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The Relationship Between Sensorimotor Integration and Social Processing

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General Abstract

To interact with the physical world, the brain must integrate information across multiple sensory and motor domains to create a stable representation of the body. Crucially, it is the effective integration of visual, tactile, proprioceptive, and motor information which creates the experience of a bodily self. The embodied cognition framework proposes that important social processes such as self-awareness, perspective-taking, and interpersonal synchrony are grounded within the bodily self. Thus, exploring the links between the senses, the body, and social processes can elucidate how humans interact, understand each other, and move in time with each other. Research investigating why certain populations show differences in how they socially interact can shed further light on the contribution of sensorimotor integration in social processing. Autism is a neurodevelopmental disorder characterised by differences in social interaction, communication, and sensory processing. Research suggests that sensory processing differences may account for the characteristic differences in social behaviour in autism. However, the exact relationship between sensorimotor integration and social processing is not fully understood.

This thesis aimed to investigate the relationship between sensorimotor integration and social processing in autistic and non-autistic individuals. Chapter 2 found evidence to suggest that an internal representation of the body, built upon multisensory integration may be implicated in self-referential processing in non-autistic adults. Chapter 3 found evidence that whilst autistic adults exhibit self-referential processing it may not be related to sensorimotor integration and the body schema. These findings suggest that whilst non-autistic self-conceptualisation is intertwined with body representations, autistic self-conceptualisation may not. Chapter 4 found that altering the experience of self-location did not impact visual perspective-taking performance in non-autistic adults. Moreover, visuo-proprioceptive-motor

integration was not found to relate to the ability to take another person's perspective. This finding elucidates the role of sensorimotor integration and internal representations of the body in visual perspective-taking. Chapter 5 found that sensorimotor and joint action processes facilitate interpersonal synchrony and subsequent social bonding in typically developing children and adults. Importantly, these findings suggest that sensorimotor processes are key for developing the ability to move in time with another person and benefit from subsequent social bonding. Chapter 6 found that autistic adults experience sensory fluctuations across multiple modalities and that these sensory differences have a significant impact on their daily lives, including social well-being. Together, the present thesis evidences the intertwined relationship between internal representations of the body, sensorimotor integration, and how we understand and interact with others. Importantly, it also demonstrates the crucial roles of multisensory experience, and body representation, in the mental, physical, and social well-being of autistic adults.

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Dedicated to Tina, who told me to lead a big life.

Table of Contents

Author's Declaration

I declare that this thesis is a presentation of original work completed by the author, Ellen M. Howard, under the supervision of Dr. Danielle Ropar and Dr. Roger Newport. The research presented in the current thesis was supported by a 1+3 PhD scholarship from the Economic and Social Research Council [grant number ES/P000711/1] at the University of Nottingham. This work has not previously been presented for an award at this, or any other university. All sources are acknowledged as References.

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List of Figures

List of Tables

Glossary of Terms

Term	Definition
Bodily Self/ Bodily Self-Consciousness	The experience of having a body. It emerges through bottom-up sensory signals and top-down cognitive processes.
Body Image	Representation of the body relating to the perception and conceptualisation of the body in addition to thoughts and emotions consciously generated about the body.
Body Representation	How the body is internally represented. Body schema and body image are body representations.
Body Schema	Representation of the body which dynamically integrates different body positions and movements in relation to the environment through sensorimotor integration.
Multisensory Integration	Process by which the brain combines sensory information from multiple modalities.
Neurotypical	An individual who is not autistic or who is otherwise not neurodivergent.
Representation of Bodily Self	How the experience of having a body is internally represented. Comprises of body image and body schema.
Sensorimotor Integration	Process by which the brain combines sensory and motor information.

Table of Abbreviations

AIC	Akaike Information Criterion
APA	American Psychiatric Association
BIC	Bayesian Information Criterion
d’	d-prime – Memory Sensitivity Measure
DHT	Disappearing Hand Trick
DSM-5	Diagnostic and Statistic Manual (5th edition)
fMRI	Functional Magnetic Resonance Imaging
FBI	Full Body Illusion
HLJT	Hand Laterality Judgement Task
IoS	Inclusion of Other in Self
LMM	Linear Mixed Modelling
MSI	Multisensory Integration
NICE	National Institute for Health and Care Excellence
OBT	Out of Body Task
RHI	Rubber Hand Illusion
RT	Reaction Time
SIFI	Sound Induced Flash Illusion
SPT	Self-Prioritisation Task
TBW	Temporal Binding Window
VPT1	Level One Visual Perspective Taking
VPT2	Level Two Visual Perspective Taking

Chapter 1: General Introduction

1.1 Chapter Overview

The integration of sensory and motor information provides the basis for the sense of bodily self and allows us to understand and interact with the world (Iarocci & McDonald, 2006; Tsakiris, 2010, 2017). For example, to interact with another person we may combine auditory information from their speech and visual information from seeing the way their lips move to understand *who* is speaking and *what* they are saying. Importantly, holding a representation of the bodily self reinforces that we are physically distinct from other people, which is the precursor to understanding that other people have distinct thoughts and views from our own (Meltzoff, 2007; Schütz-Bosbach et al., 2006). The embodied cognition framework postulates that crucial social processes are grounded within the body (Barsalou et al., 2003; Costa et al., 2013; Goldman & de Vignemont, 2009). Indeed, the bodily self is thought to relate to essential social functions such as self-related processing, visual perspective-taking, and interpersonal synchrony (Baier & Karnath, 2008; Chartrand & Bargh, 1999; Drewing et al., 2006; Kessler & Thomson, 2010; Mills et al., 2019; Penton, 2020; Sun et al., 2016; Surtees et al., 2013a, 2013b). Investigating how sensorimotor integration and the body are implicated in social processing can provide insight into how humans understand and interact with others. Further insight into the contribution of sensory integration in social processing can be gained from investigating why certain populations show differences in how they socially interact.

Autism is a neurodevelopmental disorder characterised by differences in social processing in addition to hyperreactivity and hyporeactivity to sensory input (American Psychiatric Association, 2013). There is growing evidence to suggest that differences in how sensory information is integrated may underpin differences in social processing in autism.

Specifically, the integration of visual, proprioceptive, and tactile information is disrupted in autism (Cascio et al., 2012; Greenfield et al., 2015; Paton et al., 2012; Ropar et al., 2018). As such, differences in how the brain integrates sensory information and forms internal representations of the body may impact upon how autistic individuals interact with others (Frith & Happe, 1994; Lombardo et al., 2007; McNaughton & Redcay, 2020; Pearson et al., 2013, 2014). Research investigating social behaviour in autism can therefore elucidate the links between sensorimotor integration and social processing.

The present chapter will first provide an overview of how the brain forms a representation of the bodily self through multisensory integration. Utilising an embodied cognition framework, the role of the body schema and sensorimotor integration in social interactions will be discussed. Specifically, the link between sensorimotor integration and self-related processing, visual perspective-taking, and interpersonal synchrony will be outlined. To further understand the links between sensorimotor integration and social processing, discussion will be made about how differences in multisensory integration may be implicated in autism. Lastly, the importance of representing the perspectives of autistic individuals in psychological research will be outlined, focussing on how qualitative work can contextualise quantitative research findings to ensure theoretical viewpoints represent autistic experience. The above themes will be summarised in the context of the central research questions addressed within the thesis, specifically how the experimental chapters will contribute to understanding the link between sensorimotor integration and social processing.

1.2 The Sense of Bodily Self

Historically, the sense of 'self' has been debated from psychological and philosophical perspectives. William James in the late 19th Century categorised the self into concepts of the physical self, mental self, spiritual self, and the ego (James, 1890). More recently, the experience of the physical self has been thought to be grounded within the body (Gallagher, 2000). Bodily self-consciousness (in the current thesis used interchangeably with bodily self), that is, the sense of having a body, is thought to be underpinned by four key components; ownership (Blanke, 2012), agency (Kalckert & Ehrsson, 2012), self-location (Blanke & Metzinger, 2008), and perspective (Serino et al., 2013). Ownership is the experience of knowing that one's body belongs to you, and it is distinct from other's bodies (Gallagher, 2000), agency is the feeling of being in control of one's body (Gallagher, 2000), self-location is the experience of where one feels to be in space (Blanke, 2012), whilst perspective relates to experiencing the world from where one perceives it, typically within the self-located space (Blanke & Metzinger, 2009). Importantly, these components are thought to be distinct from each other and offer unique contributions to the formation of a bodily self (Serino et al., 2013). It is the convergence of these components that gives us the experience of a sense of bodily self.

Neurocognitive models propose that bodily self-consciousness comprises of two distinct concepts: body image and body schema. The body image is an internal mental representation based on top-down knowledge about the body and emotional attitudes towards it (Gallagher, 1986). By comparison, the body schema is a dynamic representation of the body in the brain, informed by body positions and movements in relation to the surrounding environment (de Vignemont, 2011; Matsumiya, 2022; Paillard, 1999). The body schema is primarily constructed from bottom-up sensory information from multiple sensory modalities originating from multiple body parts (de Vignemont, 2011; Longo et al., 2010; Medina &

Coslett, 2010; Riva, 2018). Thus, it is both rich sensory and motor input and knowledge about what our bodies look and feel like that builds the experience of the bodily self. As such, the experience of a bodily self is created through the convergence of bottom-up sensory signals and top-down cognitive inputs.

Having a stable sense of bodily self is inherently intertwined with optimal interaction with the world. For example, self-generated action towards an object (e.g., picking up a cup of coffee) requires the brain to understand what your body is (i.e., ownership), experience control over the body parts carrying out the action (i.e., agency) and be able to bring the cup to your mouth (i.e., self-location and perspective). Additionally, a stable sense of bodily self lays the groundwork for the experience of self-awareness - that we are our own 'self' that is distinct from others (Tsakiris, 2017), in turn, underpinning our ability to identify, distinguish, and compare ourselves to others (Meltzoff, 2007; Schütz-Bosbach et al., 2006). Importantly, this allows us to infer the perceptions, emotions, and intentions of others by comparing another's actions to our own previous experiences (Meltzoff, 2007). For example, 12-month-old infants will look towards a visual target for longer when an adult is directed towards the target with their eyes open compared to having their eyes closed (Brooks & Meltzoff, 2002). This exemplifies how our own past sensory experience shapes how we interpret others' actions and behaviours. Holding a stable self-other representation is fundamental for higher-order social processes such as visual perspective taking and empathy, as one must represent themselves as distinct from others, to understand that others may hold different perspectives and beliefs (Bird & Viding, 2014; Meltzoff, 2007; Steinbeis, 2016; Tsakiris, 2017). Indeed, reinforcing self-other distinctions can facilitate empathic responses (de Guzman et al., 2016). Moreover, establishing a representation of the body allows for the effective execution of action which provides the foundation for action understanding (Gerson & Woodward, 2014). In turn, the ability to understand others' actions allows for imitation, mimicry, and interpersonal synchrony, which are key elements of social bonding (Chartrand & Bargh, 1999; Hove & Risen, 2009; Tunçgenç & Cohen, 2018; Wang & Hamilton, 2013). Therefore, internal representations of the body, formed through the convergence of top-down knowledge and bottom-up sensory and motor input are crucial for interacting with other people.

As the sense of bodily self has such an important impact on how we navigate the world and interact with others, it is important that we understand the principles which govern its formation. There has been increasing research using experimental methods to manipulate the sensory experience of individuals, to better understand the contribution of sensory input in experiencing a sense of bodily self. The following section will outline research which has sought to understand how multisensory integration is implicated in the formation of internal representations of the body.

1.3 The Role of Multisensory Integration in Body Representation

The experience of a bodily sense of self is thought to be underpinned by multisensory integration (MSI) – the process of combining sensory information to compute a representation of the world (Iarocci & McDonald, 2006) which arises through the combination of sensory inputs from multiple modalities (de Vignemont, 2011). Sensory inputs can originate from outside the body through external signals (e.g., touch and vision) (Ehrsson et al., 2005; Tsakiris & Haggard, 2005) as well as from within the body through internal signals (e.g., proprioception, vestibular sense, interoception) (Longo et al., 2010; Suzuki et al., 2013). Additionally, the brain dynamically weights and integrates sensory and motor information through sensorimotor integration. Through this integration, a stable representation of the body is formed, known as the body schema (Blanke, 2012; Makin et al., 2008; Nava et al., 2014; Schütz-Bosbach et al., 2006; Tsakiris, 2010, 2017), see Figure 1.1.

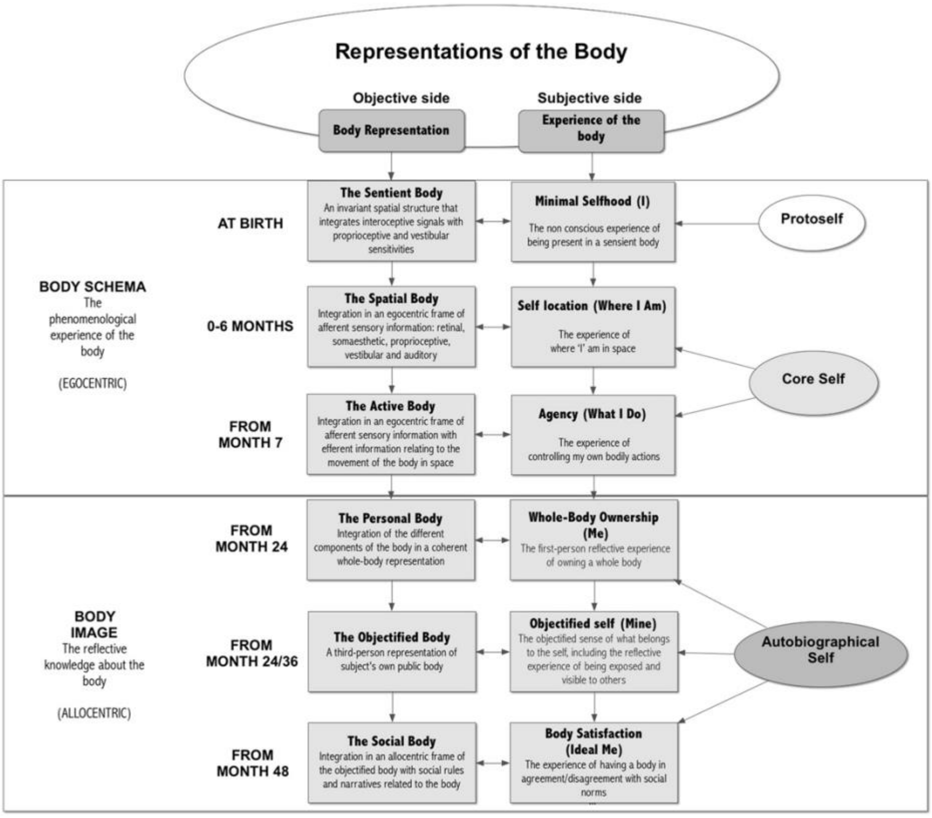

Figure 1.1. From Riva, 2018.
Schematic of representations of the body compromise of the body schema and the body image, informed by bottom-up signals and top-down knowledge about the body.

Important insight into how the brain integrates sensory information to form the body schema can be gleaned from multisensory illusions. One of the most commonly studied is the Rubber Hand Illusion (RHI), whereby participants typically experience a sense of ownership over a rubber hand when it is stroked in temporal and spatial synchrony with their own hand, hidden from view (Botvinick & Cohen, 1998). The induction of embodiment over the rubber hand, whereby individuals feel the sensation that the rubber hand is part of their body, is dependent on the optimal integration of visual, proprioceptive, and tactile information. As such, the illusion is typically not experienced, or not as strongly experienced, when the tactile and visual strokes are administered asynchronously in time, incongruently in space or when there is significant proprioceptive incongruency. Outcome measures of the illusion are classically behavioural (proprioceptive drift, i.e., mislocalisation of the hand towards the rubber hand), subjective (e.g., questionnaire items), or physiological (e.g., skin conductance response) (Armel & Ramachandran, 2003). Overall, stronger embodiment of the rubber hand is characterised by greater proprioceptive drift and higher subjective ratings of ownership.

For multisensory integration to occur, inputs across modalities must be processed as synchronous and unified. As such, the binding of sensory information is dependent on temporal constraints (Costantini et al., 2016; Gick & Ikegami, 2008; Stevenson et al., 2018). This processing must be flexible enough to allow for sensory inputs to occur in slight succession of each other as in the real-world sensory information does not necessarily ‘reach’ the brain at the same time (Dixon & Spitz, 1980). For example, when one perceives an individual talking, the auditory input of their voice and the visual input of their mouth moving may be received by sensory receptors at slightly different times. Therefore, the brain must determine whether the two sensory inputs belong to the same perceptual event. The time period in which multisensory integration is most likely to occur is referred to as the temporal binding window (TBW)

(Colonius & Diederich, 2004). Applying this to the RHI, this means that visual and tactile inputs must occur within the TBW for the inputs to be appropriately integrated and for the illusion to be induced.

Beyond bottom-up constraints such as timing, neurocognitive models of ownership argue that sensory inputs converge with top-down stored internal models of the self (i.e., body image) to mediate the experience of the body (Tsakiris, 2010, 2017). This is reflected in work using the RHI, as top-down inputs of visual appearance (Tsakiris et al., 2010), postural orientation (Gottwald et al., 2019), and spatial location (Kalckert et al., 2019) influence embodiment of the rubber hand. Multisensory integration of inputs is therefore constrained by top-down knowledge of how the body is typically represented. We cannot, therefore, feel embodiment over a wooden block, even if the block is stroked in temporal and spatial congruency with our own hidden hand (Tsakiris et al., 2010). Consequently, we experience our body both through sensory inputs and through the knowledge of what our body should look and feel like.

Advancements in technology have afforded researchers the valuable opportunity to make significant progress in the understanding of the multisensory nature of the bodily self. The availability of immersive virtual and augmented reality techniques has provided a non-invasive approach to manipulate sensory input and evaluate behavioural and perceptual outcomes (Newport et al., 2010, 2015; Newport & Gilpin, 2011). Virtual reality has allowed individuals to experience embodiment over a virtual body in a completely virtual environment, typically using head-mounted displays and computer-manipulated immersive environments (Aspell et al., 2009; Cowie et al., 2018; Lenggenhager et al., 2007). Additionally, mediated reality can be utilised to display virtual information within a real-world setting, for example viewing hands under either blue or red light can alter temperature perception of the hand (Ho et al., 2014). Body illusions using these techniques can offer unique advantages from classic RHI paradigms as they can utilise images of the individual's body, meaning ownership over a fake limb or body does not need to be extensively induced. Instead, participants can almost instantly embody a virtual body that visually looks identical (or very similar) to their own. This means that individuals do not need to cognitively overcome the knowledge that the rubber hand is not part of their body and thus the top-down load of these techniques is reduced. As such, these methods can be utilised to dissociate the contributions of bottom-up and top-down inputs of bodily self-consciousness.

The Full Body Illusion (FBI) is an innovative technique in which participants view a virtual image of their own body (Lenggenhager et al., 2007). Using a head-mounted display, participants are shown a video image of their own body through a camera situated two meters behind them. This means that individuals view an image of the back of their own body as if it is two meters in front of them. When the virtual body is seen to be stroked in temporal synchrony, participants experience a shift in self-location towards the virtual body (Lenggenhager et al., 2007). As such, self-location of the entire body relies, at least in part, on visuo-tactile-proprioceptive integration. However, when the virtual body is replaced by a non-corporeal object (i.e., a grey box) participants no longer exhibit a drift in self-location towards the object, despite synchronous visuotactile inputs. Moreover, participants report greater self-identification (i.e., the experience of full-body ownership) over a virtual body compared to the virtual non-corporeal object. This exemplifies the convergence of bottom-up and top-down processes, that multisensory integration modulates the bodily experience within a framework of knowledge about what bodies look like.

Further work has utilised the FBI to investigate the contribution of MSI in the development of the bodily self in childhood (Cowie et al., 2018). Children (aged 6-7, 8-9, 10-11 years) and adults viewed a live video image of their own back which was either synchronously or asynchronously stroked. Following stroking, three aspects of bodily self-consciousness were measured: drift in perceived self-location, self-identification with the virtual body, and touch referral to the virtual body. It was found that self-identification with the virtual body was present at 6-7 years old, with all age groups exhibiting a significantly higher self-identification with the virtual body following the synchronous condition compared to the asynchronous condition. Only 10-11-year-old children and adults exhibited significantly greater touch referral to the virtual body in the synchronous condition compared to the asynchronous condition. Lastly, only adults demonstrated a drift in perceived location towards the virtual body, with all other age groups showing no significant difference in perceived location between synchronous and asynchronous conditions. These findings evidence a maturational link between multisensory integration and bodily self-consciousness. Crucially, whilst subjective feelings of ownership and touch referral may develop earlier in childhood, optimal visuotactile integration to experience self-location appears to be a process that matures by adulthood.

Research using mediated reality has additionally offered novel contribution to understanding the role of MSI in body representation. The mediated reality system MIRAGE has been used to create the sensation of a missing limb (Newport & Gilpin, 2011), the feeling of an elongated finger (Newport et al., 2015) and even the feeling of owning multiple left hands (Newport et al., 2010). When participants put their hand into the MIRAGE device, they can no longer see their actual hand; instead, they see live footage of their hand in the same spatial location, depth plane, and from the same visual perspective as their 'real' hand (see Section 1.9

for full method description). Research using this technology has found that synchronous active stimulations can induce near-instantaneous embodiment over a virtual limb (Newport et al., 2010). Thus, this experimental technique offers a valuable method to further understand the contribution of MSI in bodily self-consciousness.

The MIRAGE system has been used to investigate how flexibly adults can embody virtual limbs (Newport et al., 2010). In this study, participants were shown two identical visual representations of their left hand, spatially offset on either side of their real hand location (Newport et al., 2010). Seen and felt touch was either synchronous for the left virtual hand, the right virtual hand or both. The virtual hands were then hidden from view and participants were asked to make a pointing movement towards a central target. When the left virtual hand had been temporally synchronous, participants moved their hand in a rightwards direction, reflecting an embodiment of the left virtual hand. The reverse was found when synchronous visuotactile input was applied to the right virtual hand. Subjective questionnaire measures found that when visuotactile inputs were synchronous for one hand, ownership was felt for only that hand. Thus, feelings of ownership and embodiment of a virtual hand can be induced quickly and flexibly when sensory inputs are congruent in space and time. This study also explored whether two virtual hands could be embodied and subjectively owned when visuotactile inputs were synchronous for both hands. During the reaching task, participants were required to reach towards a target whilst also avoiding a visual barrier. If a participant embodied both virtual hands, then their movement would be towards the target whilst also ensuring both hands avoid the barrier. When visuotactile inputs were synchronous for both hands, only one was embodied. That is, participants only executed movement which navigated *one* hand around the barrier. By comparison, participants reported experiencing subjective ownership over *both* hands when visuotactile inputs were synchronous for both virtual hands.

This finding suggests that whilst multiple left hands could be incorporated into the body image, only one could be incorporated into the body schema. Thus, whilst subjective experience of the body is flexible enough to experience multiple lefts hands, the body schema is limited by top-down knowledge of what the body should look like.

A notable advantage of using technology such as MIRAGE is that, unlike the classic RHI paradigm, the real and virtual hands can be spatially congruent. This allows for contributions of temporal synchrony and spatial congruency in MSI to be isolated from one another. This has proven particularly important in research aiming to understand how optimal MSI develops in childhood. Previous work using the RHI has found that children aged four to nine years will perceive their hand position to be closer to the rubber hand, irrespective of the synchrony of the brushstrokes (Cowie et al., 2013, 2016). This result suggests that young children are more likely to integrate spatially, and temporally incongruent sensory input compared to older children and adults. There are three explanations for this result, that young children are less sensitive to the spatial constraints of the illusion, they have longer TBWs, or they have both spatial insensitivity and wider TBWs. However, the classic RHI paradigm cannot distinguish between these explanations as the paradigm relies upon having a proprioceptive incongruency between the real and fake hand. As the MIRAGE system can manipulate the proprioceptive incongruency between the real and virtual hand, research using this technology has been able to clarify these findings.

Greenfield and colleagues (2017) used the MIRAGE system to manipulate spatial congruencies between the virtual and real location of the hand in children. Children as young as 4 years old were accurate at detecting spatial incongruencies and this ability was found to improve as the degree of spatial incongruency increased. Put simply, the larger the distance between the location of the seen hand and the real hand, the easier it was for children to detect the discrepancy. In a second experiment when a visual delay was applied to the virtual hand, children were found to become increasingly better at detecting visuotactile asynchrony as the delay was increased (Greenfield et al., 2017). Across both experiments, children improved their detection of spatial incongruencies and temporal asynchronies as they got older. Together, these results suggest that spatial and temporal processing of visual and proprioceptive information becomes increasingly more refined between the ages of 4-11-years old (Greenfield et al., 2017). Subsequently, this clarifies the results of previous work, to suggest that younger children have both a reduced sensitivity to spatial constraints and longer TBWs compared to older children and adults (Cowie et al., 2013, 2016). Optimal MSI, therefore, relies upon both efficient temporal binding of sensory inputs and sensitivity to spatial constraints of sensory information.

In summary, bodily self-consciousness relies upon the efficient integration of sensory information across multiple modalities converging with top-down knowledge about the body. Specifically, the body schema is an internal representation of the body formed through sensorimotor integration and is a key component of the bodily self. Holding a representation of the body is thought to be foundational for social cognition (as discussed in Section 1.2), thus it is important to understand how MSI might be disrupted or delayed in certain populations. The following section will outline how differences in MSI may be implicated in autism.

1.4. Multisensory Integration in Autism

Autism is characterised by differences in social processing and communication (American Psychiatric Association, 2013). Historically research has typified autism to include deficits in key social functions such as empathy, Theory of Mind (ToM), and social comprehension (Frith, 2007; Frith & Happe, 1994). However, more recent work has sought to move away from deficit models of autism and understand how social differences occur as part of a dynamic interaction between autistic and non-autistic individuals (Bird & Viding, 2014; Milton, 2012). For example, interactions of autistic dyads report higher rapport than autistic/non-autistic pairs (Crompton et al., 2020). Thus, difficulties in communication may lie in the interaction and not the individual. Crucially, anecdotal reports have highlighted differences in sensory experience as being a significant aspect of autism (Bogdashina, 2003; Elwin et al., 2012; MacLennan et al., 2021; Smith & Sharp, 2013). For example, sensory experience can directly impact upon the expression of empathy, and how it is recognised by non-autistic individuals (see Fletcher-Watson & Bird, 2020). As such, theoretical perspectives of social behaviour can benefit from investigating the sensory experiences of autistic individuals.

Research has theorised that autistic individuals may experience differences in how sensory information is processed. Importantly, research has demonstrated that whilst unimodal processing is intact or even superior in autism, multimodal sensory processing is disrupted compared to non-autistic individuals (Ainsworth et al., 2021; Iarocci & McDonald, 2006; Marco et al., 2011; Pellicano et al., 2005). Sensory differences in autism are therefore thought to pertain to MSI. A key aspect of MSI is temporal processing, in which sensory events that occur proximally in time, within the TBW are bound together into a single sensory event. As discussed in Section 1.3, this window is thought to narrow through development, such that older children and adults are less likely to incorrectly bind together sensory inputs separated by a temporal delay (Hillock-Dunn et al., 2016). It has been postulated that autistic individuals exhibit a delay in the narrowing of the TBW resulting in extended sensory binding across domains (Foss-Feig et al., 2010).

A central approach to investigating the temporal nature of multisensory integration is by utilising sensory illusions. The sound-induced flash illusion (SIFI) has been used to evaluate the integration of visuo-auditory information. In the SIFI, a single visual flash is presented simultaneously with multiple auditory beeps. When multiple beeps are presented, this can result in the perception of multiple visual flashes. Therefore, the SIFI can be used to infer lower-level audio-visual multisensory integration (Hirst et al., 2020). Autistic children have been shown to be more susceptible to the SIFI at longer stimulus onset asynchronies compared with age and IQ-matched neurotypical children (Foss-Feig et al., 2010). Thus, autistic children are more likely to bind visual and auditory input together at wider temporal delays compared to non-autistic children. This has been further corroborated by work using a temporal order judgement task, in which participants judge which out of two sensory inputs is displayed first (Kwakye et al., 2011). Unisensory temporal acuity was comparable in autistic and non-autistic children, but importantly, the autistic children showed better performance on multisensory temporal judgements when temporal intervals were wider. This reinforces previous work suggesting that TBWs are extended in autistic children and demonstrates that sensory differences in autism pertain specifically to multisensory integration and not unisensory processing. Yet, autistic adults exhibit typical integration of visuo-auditory information, being similarly susceptible to the SIFI as neurotypical adults (Keane et al., 2010; Van Der Smagt et al., 2007). This suggests that visuo-auditory processing may only be developmentally delayed and not fully disrupted in autism.

In addition to audio-visual integration, research has investigated visuo-tactile-proprioceptive integration. One study modified the classic RHI to reveal if autistic adults exhibit an over-reliance on proprioception (Paton et al., 2012). Participants wore a head-mounted display that showed the fake hand in the sample spatial location as the real hand (i.e., congruent) or in a different spatial location (i.e., incongruent). As in the classic RHI paradigm, the fake hand was either stroked synchronously or asynchronously in time with the real hand that was hidden from view. Both autistic and non-autistic adults reported greater embodiment of the fake hand in the synchronous versus asynchronous conditions. Notably, non-autistic adults showed a greater embodiment of the fake hand when it was shown to be in the same spatial location as their own, hidden hand. By comparison, autistic participants showed no increase in embodiment when the fake and real hands were spatially congruent. Moreover, autistic adults were less likely to experience proprioceptive drift towards the fake hand compared to non-autistic adults. The authors argued that autistic adults relied more heavily on proprioceptive input rather than integrating their proprioception with the visuotactile inputs. However, it is unclear if this finding is a result of a general over-weighting of proprioception or reduced visuo-tactile-proprioceptive integration in autism.

Research using mediated reality has played a central role in differentiating between these explanations. Indeed, using the MIRAGE mediated reality system, autistic and non-autistic children viewed two identical live video images of their own right hand (Greenfield et al., 2015). One hand was spatially congruent with the real hand, and one was displaced to the left or right of the real hand location. Whilst tactile input was provided via brushstrokes to the participant's real hand which was hidden from view, one of the virtual hands was seen to be stroked synchronously and the other with a temporal delay. Participants then had to select which hand they thought was their own. Results showed that synchronous visuotactile input overrode the incongruent spatial information in the non-autistic children, such that they selected the synchronous hand as their own despite the spatial incongruency. Conversely, autistic children did not consistently select the synchronous hand at short delays (60ms), even when that hand was spatially congruent. This suggests that autistic children were less able to identify the short delays due to having longer TBWs and thus atypical visuotactile integration. This finding provides evidence to suggest that differences in MSI in autism relate to the temporal binding of sensory information and not merely an over-reliance on proprioceptive information.

Additional research has used the MIRAGE system to further elucidate how atypical MSI may be implicated in autism (Ropar et al., 2018). Autistic children and adolescents viewed two identical video images of their own hand inside the MIRAGE system. Similarly, to previous work (Greenfield et al., 2015), one image was spatially congruent to their real hand and the other was displaced horizontally. Whilst the real hand was stroked, participants viewed one hand in temporal synchrony and the other in asynchrony. Both virtual hands were then hidden from view and participants were asked to point towards a visual target. The direction of pointing indicated which hand had been embodied. Autistic children showed reduced embodiment of a spatially incongruent but temporally congruent virtual hand. Further evidencing that the development of visuotactile integration may be delayed in autism. Importantly, these findings clarify that behavioural differences in the RHI may not simply be explained by an over-reliance on proprioception in autism (Paton et al., 2012), instead suggesting that autistic individuals may respond differently to the RHI due to atypical sensory integration.

Differences in visuotactile integration appear to persist into adulthood, with autistic adults showing reduced susceptibility to the full-body illusion (FBI) (Mul et al., 2019). In the FBI, participants wear a head-mounted display showing a view of their own virtual body either being stroked synchronously or asynchronously. Findings show that autistic adults exhibit reduced drift in perceived self-location and self-identification towards the virtual body following synchronous stroking (Mul et al., 2019). Thus, differences in visuo-tactile-proprioceptive integration appear to have a distinct impact on how autistic individuals represent their bodily self. Interestingly, this work also found that degree of self-identification (i.e., whole body ownership) with the virtual body was negatively correlated with the number of autistic traits and positively correlated with empathy scores. These findings indicate that altered bodily self-consciousness and disruption of visual-tactile-proprioceptive integration could be implicated in autism and importantly, relate to social cognitive skills.

In summary, multisensory integration is crucial for having a body schema, which is a significant component of bodily self-consciousness. In turn, internal representations of the body are fundamental for navigating the physical world and the social world. Research has suggested that the integration of sensory information may be disrupted in autism, and this may link to differences in social behaviour. Thus, research investigating social behaviours in autism can provide insight into the contribution of sensorimotor integration in social processing. The remaining sections of this introduction will adopt an embodied cognition framework to discuss how sensorimotor integration may be linked to social processing in autistic and non-autistic individuals.

1.5 The Body as a Social Entity

The embodied cognition approach has provided a framework to understand the connection between the body and social interactions. This approach proposes that cognitive processes are deeply rooted in the body and its interactions with the world (Wilson, 2002). As such, social processes can be influenced by states of the body and vice versa, creating a bidirectional relationship between cognitive states and body states (Goldman & de Vignemont, 2009; Wilson & Golonka, 2013). Importantly, in the embodied cognition framework, the body is not merely *associated* with cognition, but may actually partially replace complex mental processes, making processes optimal (Wilson & Golonka, 2013). Thus, the function of the body in cognition may be to make complex processes easier and more efficient. The connection between the body and cognitive states has been explored with both neural and behavioural research. The former will be briefly discussed; however, the current section will focus on the behavioural studies of embodied cognition to reflect the behavioural methods utilised in the current thesis.

Neural research has focussed on the contribution of mirror neuron circuits as part of the embodied cognition framework. The basic principle of the mirror neuron theory stipulates that brain circuits which are activated during executed action and emotion are similarly activated during observed action or emotion (Gallese & Sinigaglia, 2011). Brain stimulation studies have suggested action observations lead to highly specific modulations in the human motor cortex (Cattaneo et al., 2009; Maeda et al., 2002), thus areas implicated in action execution and observation are shared. Moreover, a meta-analysis of 139 neuroimaging studies concluded that the fusiform, posterior temporal, parietal, and premotor brain areas were implicated in both action observation and imitation (Caspers et al., 2010). Therefore, evidencing a neural 'mirroring' between performing an action and watching another person execute an action.

Moreover, research has found that observing faces expressing disgust and feeling disgust activate the same areas in the anterior insula (Jabbi et al., 2008; Wicker et al., 2003). Thus, it is argued that comprehension of others' actions and emotions is grounded within sensorimotor representations (Cattaneo et al., 2009).

Behavioural studies have indicated that body states can influence emotion and cognition. Indeed, contracting forehead muscles into a frown can predict the degree of perceived hard work on a task, whilst an upright posture can predict feelings of pride upon completing a task (Stepper & Strack, 1993). Moreover, nodding one's head can increase agreement with another person's argument (Wells & Petty, 1980) and can increase the desire to purchase positively associated consumer goods (e.g., a chocolate bar) (Förster, 2004), through increasing confidence in one's own opinions (Briñol & Petty, 2003). Together these findings suggest that the way we move our bodies can impact upon the way we think and the way we interact with others. A proposed mechanism of the link between body states and cognition is that embodied representations of familiar situations become established in memory (Barsalou et al., 2003). Taking the nodding example, one may have previously agreed with another person during a social interaction, experiencing positive affect and nodding to signal agreement. When part of this embodiment occurs again (e.g., nodding) associated effects might be produced (e.g., positive emotion) as well as associated cognition (e.g., agreement). This demonstrates how the body, and its actions, can shape and be shaped by social interactions.

Environmental factors can similarly impact upon the psychological perspectives of individuals. Research has proposed that the clothes an individual wears can influence attentional effects. Indeed, when participants wore a lab coat and were informed it was a doctor's lab coat, they exhibited increased sustained attention compared to when the coat was described as a painter's coat (Adam & Galinsky, 2012). Interestingly, this shows how both the top-down influence of the symbolic meaning of the coat and the physical experience of wearing the coat converge to influence cognition, further highlighting the bidirectional relationship between the body and cognition.

Advances in technology have furthered the field of embodied cognition by allowing the embodiment of virtual bodies. The embodiment of avatars who were characterised as inventors compared to neutral avatars significantly improved the fluency and originality of ideas of engineering students in a subsequent brainstorming session (Guegan et al., 2016). This demonstrates how preconceived ideas about the symbolic meaning of an inventor can interact with embodiment to boost cognition associated with creativity. Similarly highlighting how environmental factors pertaining to the body can influence cognition.

Further research has adopted virtual reality techniques to highlight the role of embodiment in complex social dynamics. Research has found that when light-skinned individuals embody the virtual body of a dark-skinned avatar, implicit biases towards Black individuals were immediately reduced and sustained for a week (Banakou et al., 2016). Moreover, following embodiment of a dark-skinned avatar, light-skinned individuals were more likely to mimic another digital avatar with dark skin (Hasler., 2013). These findings are notable as they demonstrate the role of the body in attitude and behaviour change towards social out-groups. Thus, exemplifying how the body is implicated in perceptions of and interactions with others.

Collectively the discussed research provides a foundation of understanding for how the body, and how it is represented, is implicated in cognition, and importantly, social cognition.

Notably, research has demonstrated that sensorimotor integration is paramount to internally representing the body and thus experiencing a sense of bodily self. What then, is the relationship between sensorimotor integration and social processing? The following sections will outline research investigating the contribution of sensorimotor integration in self-related processing, visual perspective-taking, interpersonal synchrony, and lived experience in autism. Literature relating to autism will be discussed where relevant to provide a deeper context of the research questions that pertain to each empirical chapter. Figure 1.2 provides a schematic of how sensorimotor integration contributes to the experience of bodily self-consciousness and how this may additionally relate to social cognition. The remaining sections of Chapter 1 will describe how sensorimotor processes are related to social cognitive processes such as self-awareness, visual perspective taking, interpersonal synchrony, and wider social functioning.

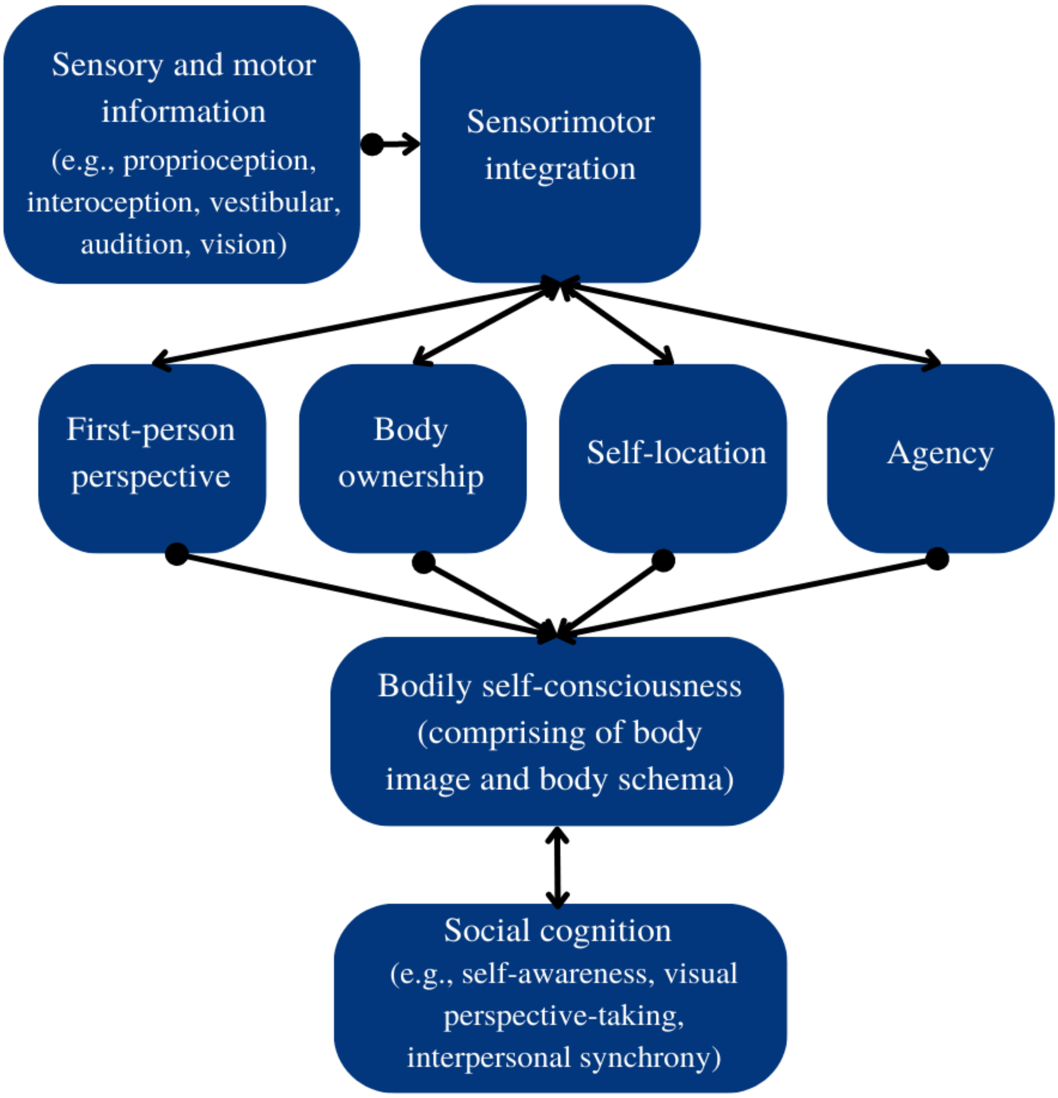

Figure 1.2. Schematic of the theoretical concepts outlined in the current thesis thus far. The arrows represent the directional nature of the concepts. For example, social cognition can be influenced by *and* influence the sense of bodily self. As such, the arrows linking these concepts are bidirectional.

1.6. Self-related Processing

Self-awareness is the state in which we become the object of our own attention (Morin, 2006). In this state we can actively identify, process, and store information that relates to the self (Duval & Wicklund, 1972). An individual can perceive aspects of the environment without explicitly knowing that they are doing so (e.g., recognising the colour of an object), but they may become self-aware if they reflect on the experience of perceiving and processing that information (e.g., I can see a red object and I want to pick it up). Notably, self-awareness can be both implicit as well as explicit (Morin, 2006). Self-awareness is closely intertwined with social interactions as we must be able to hold a mental representation of our own mental state and understand it may be distinct from the mental states of others. Indeed, self-awareness is related to Theory of Mind (ToM), the ability to attribute goals, intentions, emotions, and beliefs to others (Gallagher & Frith, 2003), which in turn is argued to be a keystone of wider social cognition (Malle, 2012). The directional link between self-awareness and ToM has not been unanimous, researchers have argued that self-awareness precedes ToM (e.g., Goldman, 2006), whilst others argue the ability to read other's minds allows us to be self-aware (e.g., Carruthers, 2009). Irrespective of this directionality, self-awareness is implicated in social cognition and thus plays a valuable role in human social interactions.

Insight into self-awareness can be gleaned through examination of how humans internally represent the self and how this influences how information is processed, perceived, and remembered. Indeed, self-referential memory is the idea that individuals have a natural propensity to remember information that relates to the self (Rogers et al., 1977). In self-referential trait memory paradigms, participants are presented with personality traits (e.g., caring, clever, arrogant) under two encoding conditions: self-referential and other-referential. In the self-referential condition, participants process the trait adjective in relation to themselves (i.e., “Are you caring?”), conversely in the other-referential condition participants process the adjective in relation to another person, usually a celebrity or well-known figure (i.e., “Is Liz Truss trustworthy?”). Several studies have demonstrated that recall and recognition of trait adjectives related to the self are superior compared to other-related traits (Rogers et al., 1977; Symons et al., 1997).

The neural basis of this self-bias advantage is reflected in the activation of a network which supports attentional, reward, and motor processing. The self-referential memory effects have been associated with brain activity in the prefrontal cortex (Turk et al., 2011), a region of the brain thought to contribute to the conscious reflection of oneself (Northoff & Bermpohl, 2004; Schmitz & Johnson, 2007). Therefore, self-referential processing is thought to closely relate to self-awareness. Indeed, it has been proposed that self-reference effects originate in an implicit fashion linked to a subjective representation of the self, in which low-level self-awareness biases attention, perception, and memory without relying on explicit thought about oneself (Cunningham et al., 2008). For this to be the case, self-reference effects need to be demonstrated in paradigms in which deeper evaluative judgements about the self are not required. This has been explored in studies utilising an incidental trait encoding paradigm in which trait adjectives are displayed above or below the participant’s own name or a celebrity’s name (Cunningham et al., 2014; Lind et al., 2019; Turk et al., 2008). Results show that a significant self-reference effect remains even when lower-level processing of the information is engaged as opposed to deeper-level semantic thought about the self (Cunningham et al., 2014; Lind et al., 2019; Turk et al., 2008). These findings are significant as they demonstrate that implicit representations of the self can form connections with external stimuli.

A methodological issue with using trait memory paradigms to understand self-biases in attention and memory is that self-related information (e.g., own name or face) is often more salient or familiar and the trait adjectives used can elicit emotional responses. This has been overcome by using a self-tagging paradigm in which participants learn pairs of person-related labels (i.e., self, friend, and stranger) and simple geometric shapes (i.e., circle, square, and triangle) (Sui et al., 2012). This paradigm allows investigation into the processing of self-relevant content whilst also providing further understanding of self-awareness. Moreover, by associating previously neutral stimuli with the self, conclusions can be drawn about self-prioritisation (preferential processing of self-related information) without the influence of well-learned stimuli such as one's own name. Using this paradigm, work has found that irrespective of length, familiarity, or concreteness of the words used, participants are faster and more accurate at responding to self-related pairs (Sui et al., 2012; Sui & Humphreys, 2015b, 2017). Importantly, these findings evidence that even without using highly salient stimuli such as an individual's name, self-related information is implicitly prioritised. This has significance for how we understand self-concept by demonstrating that an internal representation of the self can bias the processing of perceptual information (Sui & Humphreys, 2015a).

As self-related processing is thought to pertain to an internal representation of self, similarly to self-awareness, it has likewise been related to how individuals socially interact. Empathy is believed to comprise of the ability to represent and understand the experiences of self and other, whilst maintaining a self-other distinction (Bird & Viding, 2014; Decety & Lamm, 2006; Steinbeis, 2016). Self-related processing may cement this self-other distinction, thus allowing for mentalisation of the states of others. This has been reflected in work that has investigated the role of self-referential memory in empathy and ToM (Dinulescu et al., 2021). In this study, participants completed the trait adjective memory task, in the *Self* condition they viewed trait adjectives and categorised them based on whether they described themselves or not. In the *Other* condition, participants categorised these adjectives based on whether they would be desirable or undesirable to others. Participants then completed the recognition phase, where they were presented with new and old trait adjectives and had to respond as to whether they had viewed them in the encoding phase. Additionally, participants completed tasks to assess their empathic ability by rating the emotions of actors in short video clips and ToM through the Reading the Mind in the Eyes Test (Baron-Cohen et al., 2001). Accuracy in the self-referent condition of the memory task was found to be positively associated with empathy and ToM (Dinulescu et al., 2021). The stronger an individual's self-bias, the greater their ability to understand the mental states of others and empathise with them. This finding may suggest that a tendency to prioritise the processing of self-related information may be related to a stable internal representation of the self which allows for a clear self-other distinction and thus a better understanding of other's unique thoughts and emotions. Further evidence for the social nature of self-related processing has been reflected in neuroimaging studies, which have found overlap in the neural activation associated with engaging the self and understanding the mental states of others (Ames et al., 2008; Mitchell et al., 2005). Thus, there is strong evidence to suggest that self-biases in processing may relate to how we understand and empathise with others.

Considering the social role of self-related processing, research has sought to understand the mechanism underpinning self-prioritisation. The Integrative Self hypothesis postulates that an internal representation of the self serves as an integrative hub to process information (Sui & Humphreys, 2015a). As such, providing a form of associative 'glue' for perception and memory, making it easier to bind together different types of information. This has been evidenced by the finding that not only is recognition and recall of self-related information better, but the memory of associated episodic memories is also better (Leshikar et al., 2015).

Subsequently, it is argued that self-reference effects enhance the binding of different forms of information (Sui & Humphreys, 2015a). Moreover, work has found that individuals are better at categorising images of their own face compared to friend, and stranger faces, even when the faces are inverted (Keyes & Brady, 2010). Importantly, whilst there is an advantage of friend faces over stranger faces too, this only sustains when the faces are upright (Keyes & Brady, 2010). Therefore, self faces benefit from enhanced integration of global and local feature processing. This finding corresponds to the Integrative Self hypothesis by demonstrating that it is uniquely self-reference (and not reference to close others) which can facilitate the binding of perceptual information.

Beyond a cognitive network of the self, a model involving the body has been proposed to explain self-reference effects. The Bodily Self-Consciousness model (BSC) (Park & Blanke, 2019) compliments the Integrative Self hypothesis, affirming that an internal representation of the self is key to cognitive processes, but expands this by suggesting that the body can also act as a behavioural tag for memory consolidation (Bréchet et al., 2020). Indeed, work utilising the Full Body Illusion (FBI) has suggested that the conceptual representation of self and bodily representation of self are closely tied (Canzoneri et al., 2016). Typically, when spatially proximal and psychologically proximal words are paired together (e.g., Us-Near) they are processed faster than spatially distanced and psychologically proximal pairs (e.g., Us-Far) or spatially proximal and psychologically distanced pairs (e.g., Them-Near). However, when participants experienced a shift in self-location towards a virtual body in the FBI, the typical faster processing of the Us-Near pair was only exhibited when the pair was displayed towards the virtual body. This suggests that the processing of conceptual information related to the self is affected by the experience of self-location, which is a key component of bodily self-consciousness (Aspell et al., 2009; Blanke, 2012; Blanke & Metzinger, 2009). Put simply, the spatial representation of where you feel your body is located in the world can influence how you process information related to the self. Further research has suggested that a representation of the bodily self may influence self-related processing of perceptual information. Sun and colleagues (2016) utilised Sui et al.'s, (2012) perceptual matching task to investigate the role of an embodied representation of self in self-related processing. Participants were asked to learn pairs of person labels (i.e., self, friend, and stranger) and colours. The colours were presented on avatars either adopting a first-person or third-person perspective. In addition, the avatars were either presented in a socio-communicative context (facing each other) or facing away from each other. When two avatars were presented, *Self* and *Friend* trial performance was shown to be boosted when the target colour was presented from a first-person perspective. The authors suggest that the activation of a representation of an embodied self, from a first-person perspective, enhances attention towards both *Self* and *Friend* stimuli. Furthermore, this effect was also salient within a socio-communicative context. Such evidence suggests that self-related perceptual processing is both mediated by social contexts and related to an embodied representation of self. This finding provides a foundation for research to explore the contribution of the bodily self in self-related processing, to fully understand the links between the conceptual self and the physical self.

Self-related processing provides an important insight into how the self is represented and how humans are able to interact with each other. To further understand the mechanisms underpinning self-related processing, research can investigate how internal self-representation may present differently. Research has proposed that differences in social function in autism may pertain to how the self is conceptualised. Specifically, it has been argued that differences in mentalising and perspective-taking may be due to a diminished conceptual representation of the 'self' (Frith, 2003; Frith, 2007; Frith & Happe, 1994; Lombardo et al., 2007; Lombardo &

Baron-Cohen, 2010; Uddin, 2011). Indeed, it is claimed that autistic individuals may have reduced self-awareness and thus reduced ability to understand the mental states of others (Frith, 2003; Frith & Happe, 1994; Lombardo et al., 2007; Lombardo & Baron-Cohen, 2010). To test this theory, self-reference effects can be explored in autism. If autistic individuals have reduced self-awareness, it could be predicted that they will exhibit a reduced tendency to prioritise the processing of self-related information.

Lombardo and colleagues (2007) investigated self-related processing in autistic and non-autistic individuals using the trait memory task. Participants associated trait adjectives with either themselves, a close friend, or a non-close other, they were then asked to recognise these adjectives in a test phase. Autistic individuals showed reduced memory performance for self-related traits, compared to neurotypical adults, although this was not significantly different. Interestingly, individual differences in the size of the self-bias effects were related to mentalizing ability and the number of autistic traits. The authors argue that differences in self-referential cognition in autism are intrinsically linked to core features of autism and social processes such as empathy. They further argue that their findings provide support for the theory of an “absent self” in autism (Frith, 2003).

If reduced self-awareness is a deficit in autism, then it would be expected that autistic children will similarly show reduced self-reference effects compared to non-autistic children. Again, using the explicit trait memory paradigm, one study compared the memory performance of autistic children and non-autistic children (Henderson et al., 2009). Autistic children showed comparable memory effects for self- and other information, compared to non-autistic children who exhibited a self-bias in memory performance. Additionally, for all children, enhanced self-referential memory performance was associated with better social cognition. This result has been corroborated more recently, in work similarly using the explicit trait paradigm in autistic children (Burrows et al., 2017). Interestingly, this work also found that atypical memory performance did not differ on the basis of valence of the encoded adjectives. This suggests that autistic individuals show a global difference in self-referential memory, irrespective of whether the information is positive or negative. Together, these findings suggest that autistic children exhibit diminished self-referential memory which may correspond to differences in the internal representation of self and thus social cognition.

However, it has been argued that the discussed results reflect a difficulty in making explicit evaluative judgements about the self (as required by the explicit trait memory paradigm) rather than self-related processing (Lind, 2010; Williams et al., 2018). Indeed, work has found that autistic adults show typical self-related processing when this self-evaluative element is removed (Williams et al., 2018). In this research, participants completed the self-tagging paradigm in which they learned pairs of person-related labels (i.e., self, mother, and stranger) and simple geometric shapes (i.e., circle, square, and triangle) (Sui et al., 2012). Autistic and non-autistic adults showed a bias in remembering self-related pairs compared to mother- or other-related pairs. The number of autistic traits in the neurotypical participants also did not relate to the size of the self-bias in the self-tagging task. Thus, these findings may reflect typical self-related processing in autism - when explicit evaluative judgements about the self do not have to be made.

Further work has aimed to disentangle the contributions of implicit and explicit encoding in self-reference memory. Across three experiments, Lind and colleagues evaluated the effect of incidental and explicit self-referential recognition memory in autistic and neurotypical adults and children (Lind et al., 2019). The authors employed a modified trait memory task whereby participants judged whether a trait word had appeared to the left or the right of a name (either the participant's or a celebrity's). Participants were instructed not to pay attention to the name or the adjective and only to attend to the spatial location of the trait. The typical trait memory paradigm was then used as the explicit condition. In the first experiment, neurotypical adults reliably recognised more self-paired trait words in *both* the implicit and explicit conditions. The number of autistic traits was not associated with self-bias in either the implicit or explicit conditions. In experiment two, autistic and non-autistic adults completed the implicit and explicit trait memory tasks. They found no evidence of diminished self-bias in autistic adults in either the implicit or explicit conditions. Lastly, in experiment three, autistic adolescents showed typical self-bias in both the implicit and explicit conditions. Conversely, to what has previously been suggested, these findings suggest that autistic adults and adolescents have typical self-related processing and thus a typical internal representation of the self.

Although previous work has suggested disrupted self-referential memory in autistic adults (Lombardo et al., 2007), recent work has provided evidence to the contrary (Lind et al., 2019). Taking a closer look at Lombardo et al.'s study, although autistic individuals showed a reduced memory performance for self-related trials compared to neurotypicals, they still exhibited a self-bias effect that was not significantly different to the matched controls. Thus, these findings appear to evidence typical self-related processing in autism that is not significantly diminished compared to neurotypical adults. Together, these findings suggest that autistic individuals exhibit typical self-referential cognition in both explicit and implicit contexts (Lind et al., 2019; Lombardo et al., 2007; Williams et al., 2018).

Considering the results in adolescents, Lind et al. (2019) suggest that the discrepancy between their findings on explicit self-bias and previous literature (Burrows et al., 2017; Henderson et al., 2009) may be due to the age of participants and the group matching across the studies. For example, Burrows et al.'s (2017) study did not match autistic and non-autistic children by chronological age. As self-biases typically increase through childhood, it is unknown if this would have contributed to the group differences (Sui & Zhu, 2005).

Crucially, the discussed findings do not consistently evidence reduced self-related processing in autism. Thus, research in this area does not support an "absence of self" in autism, contrary to what has been previously argued (Frith, 2003, Lombardo et al., 2007). Instead, it appears that autistic adults may hold similar conceptual representations of the self to neurotypicals, evidenced by intact self-referential processing.

What research is yet to uncover, is whether the mechanisms underpinning self-related processing are similar in autistic and non-autistic individuals. As discussed in Section 1.5, the Bodily Self Consciousness theory postulates that self-referential processing relies upon the internal representations of the body (Park & Blanke, 2019). Moreover, previous work has suggested that self-related processing may correspond to an embodied representation of the bodily self (Sun et al., 2016). Autistic individuals show differences in how they integrate sensory information and represent their bodies (Cascio et al., 2012; Greenfield et al., 2015; Mul et al., 2019; Paton et al., 2012; Ropar et al., 2018), which may modulate the relationship between the internal representation of the body and how self-related information is processed. The current thesis will seek to explore the relationship between sensory integration, body schema, and self-related processing in autistic and non-autistic individuals in Chapters 2-3.

1.7. Visual Perspective Taking

Understanding how other people view the world is essential for navigating social interactions. Beyond understanding what other people might be *thinking*, it is also important to understand what others might be *seeing*, known as visual perspective taking (VPT). It is thought there are two dissociable perspective-taking processes, level 1 (VPT1) and level 2 (VPT2). The former is described as the ability to understand what someone else can see through one's own 'line of sight', whilst the latter is the ability to mentally adopt another person's spatial point of view (Kessler & Rutherford, 2010). We intuitively use VPT1 and VPT2 commonly in everyday life. For example, if a person sitting across from you is trying to locate a saltshaker on the table, you might be able to see that it is occluded from their vision by a plant pot. Thus, you can understand *what* they can see from their viewpoint (VPT1). VPT2 plays an equally important role in our everyday lives. For example, to help the person sitting across from you find the saltshaker, you might describe its location using their spatial reference frame, i.e., using their left and their right. This is an example of understanding *how* the other person sees the world. Therefore, when socialising, we instinctively, and often unconsciously, consider what the other person can see and how they see it.

VPT1 and VPT2 are dissociable processes which are thought to have different underlying mechanisms. VPT1 can be accomplished through simple line of sight to understand what another person sees (Surtees et al., 2013b). Conversely, VPT2 is thought to involve egocentric transformations of self 'into the shoes' of the other person (Devlin & Wilson, 2010; Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Surtees et al., 2013b), whereby an individual must imagine the rotation of their own body into the space of another person. This distinction is reflected in imaging work which has investigated the neural substrates of VPT1 and VPT2. Indeed, VPT2 is associated with increased blood-oxygen-level-dependent signals in areas linked with social cognition such as the temporoparietal junction (TPJ) and medial prefrontal cortex (David et al., 2006; Mazzarella et al., 2013). By comparison, VPT1 is associated with the mesial cortical areas which are related to visuospatial processing and decision-making (Vogeley et al., 2004). Thus, VPT1 and VPT2 at least partly rely on distinct neural networks.

VPT1 and VPT2 also exhibit different developmental trajectories (Kessler & Rutherford, 2010). Work has found that very young children hold an awareness of what others can see (VPT1). For instance, work has utilised implicit measures of VPT1 where the looking time of infants is used as an indication that an expectation about the world has been violated, whereby longer looking time indicates recognition of this violation. Indeed, 14-month-old infants spend more time looking at pictures in which a person is reaching for and grasping an object which is visually occluded to the person, compared to when the object is in sight of the person (Sodian et al., 2007). Thus, young children expect that a person should not be able to reach for an object that is visually occluded and thus look longer at a picture that depicts this. Moreover, 18-month-old children will orient themselves to allow another person to see a picture they are holding (Lempers et al., 1977). These findings suggest that having an understanding of what other people can see develops early in childhood.

By comparison, VPT2 is a more sophisticated process which is thought to develop later in childhood. Work by Piaget using the classic "Three Mountains Task" instigated the understanding of how VPT2 develops in children (Piaget & Inhelder, 1956). In this task, a child is presented with a model of three mountains which they view from different angles. A doll is placed at different points around the scene and the child selects how the mountains will look to the doll. Early work found that 4-year-olds would select the view from their own perspective, whereas 8-year-olds could reliably select the scene from the doll's viewpoint (Piaget & Inhelder, 1956). The authors argued this evidenced a developmental shift from an egocentric view of the world to an ability to understand what others can see. Indeed, whilst three-year-olds are reliably able to perform VPT1, they are unable to perform VPT2 (Flavell et al., 1981). However, more recent work has found that when VPT2 occurs as part of social interaction, children as young as three years old can demonstrate VPT2 (Moll & Meltzoff, 2011). Indeed, when children were asked by the experimenter to make a picture look green, they would place the picture behind a yellow colour filter, such that the picture looked green from the perspective of the experimenter. The authors argue that the young children were therefore able to understand how the experimenter was viewing the picture, and therefore perform VPT2. The discrepancy in results is likely due to the level of perspective-taking required to complete the task. In previous work, children had to hold a representation of a perspective of another person and compare this to their own perspective (Flavell et al., 1981). By comparison, in the Moll & Letzoff (2011) study, the child does not need to compare their own perspective to another's, therefore making it easier to complete. Irrespective of this, VPT2 still does not appear to develop as early as VPT1. Thus, the ability to understand *what* someone sees (VPT1), and *how* someone sees (VPT2) are distinct processes with dissociable neural networks and developmental trajectories.

According to the embodied cognition framework, social cognition is grounded within the motor and perceptual systems of the body (Wilson, 2002). The body schema is an internal dynamic representation of the body in space and VPT2 is thought to engage mental transformations of the body schema into the location and orientation of another person in space (Kessler & Thomson, 2010). Behavioural evidence for the embodied nature of VPT2 has largely been provided using two methods for measuring VPT2: 1) *Own Body Transformation* tasks and 2) *Avatar-in-Scene* tasks.

In the *Own Body Transformation* (OBT) task, participants view a human figure with a salient body feature (e.g., a glove). The participants must then decide the laterality of the salient feature from the perspective of the figure. Consistent with the notion that individuals mentally transform their own body to match the perspective of the target, responses to this task are usually faster when the figure is back-facing (i.e., facing the same way as the participant) compared to front-facing figures (Gardner et al., 2013; Gardner & Potts, 2010). Not all individuals use an embodied strategy for this task. Indeed, it is possible to evaluate the laterality of the salient object on a front-facing avatar using a cognitive strategy and reversing the left and right. However, this strategy has been found to correspond to response inhibition performance, thus increasing the cognitive demands needed to use this strategy (Gardner et al., 2013). As such, embodied routes of perspective-taking are thought to minimise demands on domain-general executive function and are thus an optimal strategy. Indeed, the majority of individuals report using embodied strategies for perspective-taking in OBT tasks (Gardner et al., 2013; Gronholm et al., 2012).

The *Avatar-in-Scene* task shows an avatar looking at a spatial scene from different angles of rotation along the horizontal axis. Participants are asked to decide whether the target object in the scene is on the left or the right side from the avatar's perspective. Creating angular disparities between the participant's and target's bodies increases the time taken to take the visual perspective of the target (Kessler & Thomson, 2010). This finding indicates that participants are mentally imagining rotating their own body into the position of the target. Thus, the greater the angular disparity, the longer it takes to complete the mental rotations. Moreover, this finding is specific to visual perspective taking and not object rotation, which further suggests that typically VPT2 relies on egocentric embodied simulations of the self and not spatial rotation strategies. Such findings of angular disparities increasing the processing time of another's perspective have been robustly replicated in work since, evidencing the embodied nature of VPT2 (Kessler & Rutherford, 2010; Surtees et al., 2013a, 2013b). Collectively, there is robust behavioural evidence to suggest that VPT2 is an embodied process that is grounded within motor and perceptual systems of the body.

Building upon evidence that VPT2 is an embodied perspective, research has sought to understand how exteroceptive and interoceptive body signals contribute to VPT2. Interoception is the ability to perceive internal bodily signals (e.g., thirst, hunger, breathing) (Tsakiris, 2017). Interoception has been implicated in the experience of embodiment, particularly the experience of owning a body (Suzuki et al., 2013). When a virtual hand was seen to visually beat (i.e., gently pulse red) in time with the participant's own heartbeats, subjective and objective measures of ownership over the virtual hand were greater than when this cardio-visual information was asynchronous (Suzuki et al., 2013). This finding suggests that interoceptive signals can contribute to the feeling of owning a body and are thus implicated in the feeling of embodiment. Following the embodied cognition framework, this might suggest that an internal representation of the body (i.e., body schema), including awareness of interoceptive signals, may link to embodied social cognition such as VPT2.

The ability to detect one's own heartbeat, thought to be a measure of interoception, has been found to predict VPT2 reaction times (Erle, 2019). Indeed, the better an individual is at accurately detecting their own heartbeat, the faster their VPT2 ability. This finding suggests that the ability to simulate an egocentric transformation of the body is aided by heaving greater interoceptive awareness of the body. However, it has been argued that the heartbeat counting task is not an accurate measure of interoception as it can be completed by relying upon non-interoceptive cues (Desmedt et al., 2018). Indeed, when individuals are asked to ignore non-interoceptive signals, accuracy in the task drops to around 50% (Desmedt et al., 2018). Thus, previous findings (e.g., Erle, 2019) linking heartbeat counting and VPT2 may not reflect a relationship between interoception and VPT2.

Yet, research has demonstrated the role of interoception in VPT2 without relying upon the heartbeat counting task. Using the OBT task, the interoceptive similarity (i.e., heartbeat synchrony) between participants and the virtual avatar was manipulated to try and understand the contribution of interoceptive signals in VPT2 (Heydrich et al., 2021). This was achieved by flashing the silhouette of the avatar either synchronously or asynchronously with the timing of the participant's heartbeats. The impact of this cardio-visual synchrony was then evaluated using the reaction times and accuracy on the OBT task. It was found that reaction times were shorter when the cardio-visual information was synchronous compared to asynchronous. However, this was only found for participants with high empathy scores and not for those with low empathy scores. The authors suggest that the integration of cardio-visual information between the participant's body and the avatar makes it easier to adopt the visual perspective of the avatar but that this effect is mediated by empathy. This finding may therefore suggest that internal body awareness (i.e., interoception), VPT2, and empathy may be closely related. As such, this result may provide a starting point for research to evaluate how components of bodily self-consciousness (i.e., self-location) are implicated in VPT2 through MSI mechanisms.

Research investigating how autistic individuals show differences in the ability to take another person's perspective has further broadened our understanding of VPT2. As autistic individuals exhibit differences in MSI and how they experience a sense of bodily self (see Section 1.4), differences in VPT2 performance in the autistic population can be investigated to further understand the embodied mechanisms of VPT2.

Autistic children have been found to have difficulty performing VPT2 compared to chronological and mental aged matched typically developing children (Hamilton et al., 2009). In this study, children viewed a teddy which was covered by a pot and rotated on a platform. In the object rotation condition, participants had to report which view of the teddy they would see when the pot is lifted. In the VPT2 condition, children had to report which view of the teddy an avatar would see when the pot was lifted. Autistic children performed significantly worse on the VPT2 trials compared to the neurotypical children, however, they maintained performance on the object rotation task. These findings suggest that autistic children have a unique difficulty with VPT2 and not spatial transformations in general.

Such differences in VPT2 also appear to extend into adulthood. One study asked autistic and non-autistic adults to make judgements on objects and bodies rotated at different angles (Pearson et al., 2014). In the egocentric rotation condition, participants made laterality judgements about the bodies and objects, whereas, in the mental rotation condition, participants had to say if the target and reference images were the same or a mirror image. Results from the mental rotation task showed that autistic participants were comparably accurate as neurotypical participants. Conversely, autistic participants showed reduced performance in the egocentric condition compared to neurotypical participants. This finding may reflect the idea of a reduced ability to use the self as a reference point to perform egocentric rotations in autistic individuals.

Further work has investigated how the orientation of the other person can impact upon VPT2. Typically, VPT2 is easier to perform when making a judgement about back-facing bodies (i.e., matching the body position of the participant), compared to front-facing bodies (i.e., mirroring the body position of the participant) (Conson et al., 2015). This is because it is easier to transform the representation of one's own body into the position of a back-facing body as it more closely matches the position of one's own body. However, autistic adults show an advantage in making spatial judgements in relation to a front-facing body (Conson et al., 2015). This finding suggests that autistic adults may not use an embodied strategy to take another's perspective and instead use a non-embodied strategy. In the Conson et al., (2015) study, objects were either to the left or the right of the observer. Therefore, it is possible that autistic participants used a rule-based strategy using visuospatial cues to evaluate how the observer sees the object. It is important to note that using a non-embodied strategy in complex real-world contexts can be cognitively demanding and less efficient than embodied strategies (Gardner et al., 2013; Zacks & Tversky, 2005). Thus, a tendency to use an object rotation or mental viewpoint strategy above an embodied egocentric rotation strategy could have consequences for social interactions in the real world.

Together, the discussed research suggests that autistic individuals exhibit differences in VTP2 such that either performance is significantly reduced compared to non-autistic individuals or less optimal strategies are utilised to complete VPT2. Crucially, this may evidence the embodied nature of VPT2 by demonstrating how individuals with differences in their MSI and body schema similarly show differences in performance on an embodied social process. Indeed, research has attempted to link bodily-self consciousness and VPT2 performance in autistic individuals (Russo et al., 2018). Autistic children were asked complete a body awareness task which evaluated the children’s ability to 1) symbolically recognise body parts by pointing to the corresponding body part when asked to by the experimenter and 2) verbally recognise body parts when naming a body part the experimenter pointed to. Autistic children showed significantly poorer performance in the VPT2 task compared to non-autistic and intellectually disabled children. Importantly, there was a significant relationship between body awareness and VPT2 performance in the autistic children, such that better body awareness was associated with better VPT ability. This may suggest that variability in the ability to perform VPT2 may lie within how the body is represented, thus evidencing the embodied nature of VPT2.

In summary, understanding how other people see the world is essential for navigating social interactions. Thus, it is important to understand the mechanisms underpinning visual perspective taking. Research has provided robust evidence across neural and behavioural studies to suggest that VPT2 is an embodied process which relies upon internal representations of the body. Moreover, the discussed autism research highlights how difficulties with VPT2 may be associated with the disruption of optimal sensory integration and formation of the body schema. Whilst there is robust evidence to suggest representations of the body are implicated in VPT2, it is unknown which components of the bodily self (e.g., self-location) might be associated with VPT2. Further, despite internal representations of the body relying on MSI, it is unknown how the ability to integrate sensory information might relate to VPT2. In light of this, Chapter 4 will seek to explore the impact of manipulating self-location on visual perspective-taking ability, to better understand the link between internal representations of the body and social processing. Moreover, the relationship between sensorimotor processing and visual perspective-taking will be explored, to shed light on the role of multisensory integration in social cognition.

1.8. Interpersonal Synchrony

Interpersonal synchrony, whereby two or more people move in temporal and spatial coordination with each other is a common feature of social interactions. It can occur consciously (e.g., when shaking hands or dancing) or it can arise spontaneously (e.g., falling into step with another person). Research investigating embodied cognition has shown that synchronous interpersonal movement plays a crucial role in social bonding starting from early infancy (Trainor & Cirelli, 2015 Tunçgenç, et al., 2015; Tunçgenç & Cohen, 2016) through to adulthood (Cross et al., 2019; Reddish et al., 2013). Whilst the ability to synchronise movements with external stimuli develops in early childhood years (Kurganksy & Shupikova, 2011), relatively little is known about how sensorimotor integration might be linked to interpersonal synchrony and its subsequent social bonding outcomes (e.g., cooperation, affiliation, helping behaviour, likability, imitation).

When moving together with another person, different degrees of shared intentionality may exist among the interacting partners. For example, two individuals may be instructed to synchronise with each other (i.e., instructed synchrony), they may be instructed to synchronise with an external metronome beat and may thus end up moving synchronously with each other (i.e., incidental synchrony), or they may spontaneously synchronise their movements in the absence of any instruction on how to move (i.e., uninstructed synchrony).

Research investigating instructed synchrony has found that individuals feel more bonded to others after performing a task with them that involves synchronous interpersonal movement compared to asynchronous movement. In recent work, adults who were instructed to march in time with others exhibited greater affiliative and cooperative behaviour compared to a group who marched asynchronously (Jackson et al., 2018). Such findings extend across multiple sensory modalities. Indeed, ratings of likeability are significantly higher following synchronous movement with auditory information (originating from a partner) compared to asynchronous movement (Launay et al., 2014). Therefore, processing sensory information and successfully synchronising one's movements with it, can be extremely socially advantageous.

Instructed interpersonal synchrony is also thought to promote imitation, whereby an observer copies another person's body movements. It is important to note that imitation is distinct from interpersonal synchrony as imitation only requires the reproduction of an action, not the entrainment of it. For example, an individual attempting to synchronise with another person's movements would need to anticipate their movement to move in time with them, whereas imitation does not require this complex prediction of action and timing. Imitation is thought to be a foundational social skill that can promote group acceptance and belonging (Over & Carpenter, 2015). Furthermore, imitation during social interactions is thought to influence the experience of 'smoothness' in the social interaction (Chartrand & Bargh, 1999). Thus, if interpersonal synchrony can promote subsequent imitation during social interaction, this may further enhance social bonding between interactants. Indeed, adults are more likely to affiliate with and imitate a partner after engaging in a synchronous movement task with them as compared to after performing those movements asynchronously with their partner (Cross et al., 2021). Interestingly, the same results were not found when participants *incidentally* synchronised with each other, which suggests that the presence of a shared goal to move in time together may be key to experiencing boosted imitation following interpersonal synchrony. However, the link between interpersonal synchrony and imitation has been relatively underexplored. For example, despite humans having a natural propensity to fall in time with each other, it is unknown if uninstructed synchrony could facilitate imitation.

Research has found that pro-social effects can still be exhibited even when individuals are not intentionally synchronising with each other (i.e., incidental interpersonal synchrony). Early work found that when participants engaged in group singing, they were more cooperative with others compared to activities which did not involve synchronous movement (Anshel & Kipper, 1988). Individuals will even cooperate with others at their own financial detriment if they have previously been singing and moving in time with them (Wiltermuth & Heath, 2009). Moreover, the degree of interpersonal synchrony has been found to predict ratings of affiliation (Hove & Risen, 2009). This may suggest that a better ability to coordinate one's movements with another person, even incidentally, could elicit greater social benefit. These works show that incidentally synchronising with another person can have a significant social advantage.

Research investigating interpersonal synchrony in children can elucidate how the ability to coordinate movements with another person develops. Indeed, similar social benefits of incidental interpersonal synchrony have been found in children. When dyads of children were asked to synchronise their tapping with a bouncing ball, they rated their partner as being more similar to them and feeling closer to them when their tapping had been synchronised (Rabinowitch & Knafo-Noam, 2015). Similarly, children who incidentally synchronise with each other are more likely to exhibit helping behaviours (Tunçgenç & Cohen, 2018). Moreover, incidentally synchronising with others can even help children feel more socially bonded to children they perceive as 'out-group' members (Tunçgenç & Cohen, 2016). Thus, interpersonal synchrony can offer powerful social advantages for children.

Moving beyond instructed and incidental synchrony, humans have a natural propensity to move in time with each other, such that individuals can often spontaneously synchronise their movements (i.e., uninstructed synchrony). In adults, studies have robustly shown that people tend to spontaneously entrain to others' movements when walking (Nessler et al., 2011), swinging their legs (Schmidt et al., 1990), clapping (Néda et al., 2000) and rocking in chairs (Richardson et al., 2007). One study found that children as young as 2.5-year-olds spontaneously synchronise their drumming and do so better when performing drumming with another person compared with a robot (Kirschner & Tomasello, 2009). The authors argue that drumming with a social partner elicits a shared representation of action thus making it easier to synchronise movements. These findings suggest humans have a natural propensity to synchronise with others. Yet, it is unknown if uninstructed synchrony can foster positive social consequences. If uninstructed synchrony can promote pro-social behaviour, this may suggest that intentionally coordinating movements with another person is not necessary for social bonding outcomes of interpersonal movement. As such, research investigating the social bonding outcomes of uninstructed synchronisation in children and adults could elucidate the mechanisms underpinning interpersonal coordination.

Taken together, the discussed works show that moving in coordination with other people incurs social interaction benefits. To understand this link between interpersonal synchrony and social bonding, research has investigated the underpinning mechanisms. A prominent account explaining the link between synchrony and social bonding is the sensorimotor coupling account.

Sensorimotor coupling is defined as the process whereby an external rhythm is identified (e.g., through vision, audition, or vibration) and integrated into one's own movements (Phillips-Silver et al., 2010). Interpersonal synchrony improves when information about an external rhythm is available through multiple modalities, for example, visual and auditory (Gipson et al., 2016). This suggests that sensory integration across multiple modalities may improve sensorimotor coupling and thus the ease of interpersonal synchrony. Further, sensory information which relates to others may be easier to synchronise with. For example, viewing a biologically similar stimulus (i.e., hand), compared to a non-social, mechanical stimulus, can facilitate synchronisation (Kirschner & Tomasello, 2009), arguably due to the ease of creating motor representations of the other person's actions (Calvo-Merino et al., 2005; Iacoboni et al., 1999, Brass & Heyes, 2005; Rizzolatti, 2005; Casile et al., 2011). Subsequently, the perceptual representation of synchronised movement may be less effortful and more rewarding as neural processing costs are minimised (Koban et al., 2019). As such, a cycle facilitating interpersonal synchrony is created. Indeed, a functional magnetic resonance imaging (fMRI) study has shown the brain's reward system to be activated following synchronous, as compared to asynchronous, interpersonal movement (Kokal et al., 2011). Thus, sensorimotor coupling plays a key role in facilitating and sustaining interpersonal synchrony. If sensorimotor processes are key to experiencing the social benefits of interpersonal synchrony, then we might expect that the degree of synchronisation would predict social bonding outcomes. Yet this direct relationship between sensorimotor coupling and social bonding outcomes has not been investigated in instructed and uninstructed synchrony.

Top-down processes can also modulate how quickly sensorimotor coupling takes place. For example, merely holding the belief that the movement of non-social stimulus (e.g., a geometric shape) is being controlled by another person, can lead the stimulus to be incorporated into the individual's own motor representation in a similar way as when actually viewing human movement (Gowen et al., 2016). Beyond this, the joint action framework suggests that when individuals coordinate their actions "to bring about a change in the environment" within a social interaction (Sebanz et al., 2006), this can facilitate interpersonal synchrony. According to this framework, a shared goal and mutual knowledge that the goal is shared, unite the interaction partners' intentions, attention, and representation of the task in hand (Tomasello et al., 2005). These shared representations enable easier prediction of the other's behaviour and coordination of movements (Sebanz et al., 2006; Ramenozi et al., 2015).

Importantly, instructed, uninstructed, and incidental synchrony can occur within joint action contexts, depending on the type of shared intentions the partners hold. Prior research has found that joint action contexts facilitate synchronisation, even when individuals share a goal or intention that is not related to synchronisation. For example, individuals who shared a mutual goal to empty a box of 100 plastic balls coordinated movements more than those without a shared goal (Allsop et al., 2016). This suggests that joint action can form and facilitate interpersonal synchrony, even when the intention isn't to move in time with another person.

In terms of social bonding outcomes, work has found that dyads with a shared intentionality to move in time with each other report feeling closer to each other than those with a shared intentionality to synchronise with an auditory beat, i.e., when the emergence of interpersonal synchrony was incidental (Reddish et al., 2013). Therefore, it is a combination of synchrony and shared intentionality to synchronise that gives rise to the greatest social bonding outcomes. Furthermore, when individuals share the intention to synchronise with each other, and the salience of a social context (i.e., synchronisation with visible actors vs point-light displays) was enhanced, even less precise forms of synchronisation elicited similar levels of cooperation (Cross et al., 2016). Thus, in addition to sensorimotor coupling, the social bonding outcomes of synchrony seem to depend on whether synchronisation occurs within a salient social context in which joint action can arise.

Based on the discussed research, interpersonal synchrony can foster significant positive social consequences. However, the mechanisms linking coordination of movement and pro-social behaviour are not fully understood. In light of this, the present thesis will aim to understand the contribution of sensorimotor processes in visuomotor interpersonal synchrony in Chapter 5. This will be explored within a joint action context and investigated developmentally by comparing the sensorimotor contributions to synchrony and social bonding in children and adults.

1.9. The Sensory Experiences of Autistic Individuals

The integration of visual, proprioceptive, interoceptive and vestibular inputs is crucial to experiencing a bodily self, in particular, having a body schema (Cowie et al., 2016, 2018; Greenfield et al., 2017; Newport & Gilpin, 2011; Tsakiris, 2017). As discussed in the General Introduction thus far, sensory integration is thought to be implicated in social processes such as self-awareness, visual perspective-taking, and interpersonal synchrony. These processes are considered critical for building and maintaining social connections with others and are argued to exhibit differently in autism (Bowsher-Murray et al., 2022; Georgescu et al., 2020; Hamilton et al., 2009; Koehne et al., 2016; McNaughton & Redcay, 2020; Pearson et al., 2013; Reilly, 2020; Williams, 2010), in part due to differences in sensory processing. Indeed, the Diagnostic Manual of Mental Disorders (5th ed,; American Psychiatric Association, 2013) includes sensory processing difficulties in the symptomatology of autism and work has found 94% of autistic adults report experiencing ‘abnormal’ levels of reactivity to sensory input (Crane et al., 2009). Yet relatively little is understood about how sensory differences in visual, proprioceptive, interoceptive, and vestibular domains are reported to affect important components of daily life, including social interactions. The following section will outline quantitative and qualitative research which has investigated the sensory experiences of autistic adults. Discussion will be made of how these experiences may relate to significant aspects of life such as mental, physical, and social well-being.

Sensory differences have been commonly reported in autism from quantitative (Baranek et al., 2006; Baranek, 1999; Horder et al., 2014; Kuiper et al., 2019; O'Riordan & Passetti, 2006; Schulz & Stevenson, 2020; Tavassoli et al., 2016) and qualitative (Crane et al., 2009; Elwin et al., 2012; Jones et al., 2003; MacLennan et al., 2021; Smith & Sharp, 2013) perspectives. Autistic children as young as 9-12-months old exhibit differences in sensory processing in their observed behaviour, showing increased frequencies of aversion to social-based touch and excessive mouthing of objects compared to typically developing children or those with developmental delays (Baranek, 1999). These sensory differences maintain throughout childhood, with caregivers of autistic children reporting higher levels of sensory processing difficulties compared to caregivers of non-autistic children (Baranek et al., 2006; Dunn et al., 2002). Beyond childhood, research using self-report questionnaires reveals that sensory differences sustain into adulthood. One study using the Adult/Adolescent Sensory Profile (Brown & Dunn, 2002) questionnaire found that 94% of autistic adults report experiencing 'abnormal' levels of reactivity to sensory stimuli (Crane et al., 2009). These sensory differences can be experienced cross-modally, with autistic adults reporting sensitivity to visual, auditory, olfactory, gustatory, and proprioceptive inputs (Tavassoli et al., 2014). Importantly, these differences not only impact sensory experience but also affect the development of social behaviours (Hannant et al., 2016), mental well-being (Rossow et al., 2021), and physical health (MacLennan et al., 2021). Therefore, it is important to understand the sensory experiences of autistic people as sensory differences are widely experienced by children and adults and have a significant impact on their experience of the world.

Quantitative work aiming to understand the sensory experiences of autistic adults has typically used questionnaires. Several self-report questionnaires have been widely utilised in autism research. For example, the Glasgow Sensory Questionnaire (GSQ) (Robertson & Simmons, 2013) asks individuals about the frequency of sensory behaviours across modalities such as vision, audition, gustation, olfaction, touch, proprioception, and vestibular processing. The GSQ produces an overall score indicating sensory differences and subscales of hyperreactivity (heightened response to sensory input) and hyporeactivity (reduced response to sensory input). The GSQ has been validated in several different languages, evidencing that the scale can be used both for scientific research and for clinical practice in different cultures (Kuiper et al., 2019; Sapey-Triomphe et al., 2018; Takayama et al., 2014). Importantly, work has shown that the hyperreactivity and hyporeactivity subscales in the GSQ are both reliable and internally consistent (Kuiper et al., 2019). This has a significant clinical impact as the GSQ can appropriately distinguish between reactivity types and can therefore allow for more tailored support to be given to autistic individuals.

In a research context, work has used self-report questionnaires to show that within the non-autistic population (Robertson & Simmons, 2013) and autistic population (Horder et al., 2014; Kuiper et al., 2019), the number of autistic traits is related to the number of sensory differences experienced. Such findings highlight the close relationship between sensory processing and differences in social behaviour. Research has also sought to investigate whether sensory differences in autism are distinct from other clinical groups. One study used the Short Sensory Profile, a scale evaluating sensory processing of touch, gustation, olfaction, vision, and audition (McIntosh et al. 1999), to investigate sensory processing in autistic children, children with Fragile X syndrome and children with developmental delay (Rogers et al., 2003). Results showed that autistic children and children with Fragile X syndrome had more sensory difficulties than typically developing or developmentally delayed children. Additionally, differences were exhibited across all domains except auditory and visual sensitivity. Although the autistic children did show greater reactivity to gustation and olfaction sensitivity than the children with Fragile X syndrome. Interestingly, children with Fragile X syndrome with more autistic traits exhibited a greater number of sensory difficulties. Thus, highlighting the relationship between autism and sensory differences. Further work using the Diagnostic Interview for Social and Communication Disorders (DISCO) found that such sensory differences continue into adulthood, with 90% of autistic adults reporting sensory 'abnormalities' across multiple modalities (Leekam et al., 2007). However, in both studies (Leekam et al., 2007; Rogers et al., 2003), no comparison was made on the experience of interoception or proprioception. Crucially, research has suggested that autistic and non-autistic children differ most on sensory hyporeactivity (Ben-Sasson et al., 2009) and autistic individuals report experiencing hyporeactivity most commonly to interoception (MacLennan et al., 2021). Thus, studies which do not evaluate sensory differences across all domains may not encapsulate the full complexity of sensory experience and may draw conclusions which do not accurately represent the experiences of autistic individuals. As such, theoretical perspectives must consider the experiences of autistic individuals from a multisensory viewpoint when informing theoretical and clinical practices.

Beyond quantitative paradigms, qualitative research has been used to gain rich insight into the experience of sensory differences directly from the perspectives of autistic adults. Early autobiographical works have suggested that sensory experiences form an integral part of an autistic individual's sense of self, contributing to both pleasurable and distressing experiences (Jones et al., 2003). In self-published online accounts, autistic adults described experiencing great discomfort to hyperreactivity across vision, audition, olfaction, gustation, and touch

(Jones et al., 2003). Individuals described using positive sensory input to cope with sensory discomfort, for example, using pleasant touch to reduce the impact of hyperreactivity to a noise. Further work has aimed to create a theoretical model to understand how sensory differences are experienced, caused and coped with (Smith & Sharp, 2013). The authors suggest that sensory stress can induce the 'Stress Avalanche', whereby sensory stress can cause increased sensory sensitivity which in turn can exacerbate sensory stress. As such, sensory reactivity across multiple inputs can converge to heighten sensory difficulties, and subsequently impact upon an individual's tendency to interact with others. Put simply, sensory experience in autism occurs across multiple modalities with different sensory inputs interconnecting to inform sensory experience. The multisensory experience of sensory differences has been further demonstrated in work seeking to understand the coping strategies used to manage visual sensory reactivity (Parmar et al., 2021). Importantly, coping strategies were not reported to pertain to a single sensory domain, as visual reactivity occurred as part of a multisensory experience (Parmar et al., 2021). Vitally, research must consider how autistic individuals experience and manage sensory reactivity from a multisensory perspective.

Interactions with others have also been demonstrated to play an important role in sensory experience. From qualitative reports, autistic individuals have described using other people as a source of self-understanding and making sense of their own experience through comparison with others (MacLennan et al., 2021). For example, noting how other people appear unbothered by sensory input compared to their own experience of discomfort. Additionally, others can provide support in managing sensory experiences, particularly through close relationships (MacLennan et al., 2021; Smith & Sharp, 2013). Other people can serve as prompts to increase awareness of sensory input, for example drawing attention to physical responses to hyporeactivity such as shivering (MacLennan et al., 2021). Notably, difficulty with sensory reactivity can lead to avoidance of environments that would typically offer social interaction, therefore leading to feelings of social isolation (MacLennan et al., 2021; Smith & Sharp, 2013). These findings exemplify the bidirectional relationship between sensory and social experience and emphasise how it is important to consider the social implications of sensory differences in autism.

Despite previous literature largely focussing on the experience of hyperreactivity in autism, most autistic adults report experiencing a combination of hyperreactive and hyporeactive, rather than one reactivity type (MacLennan et al., 2021). Moreover, autobiographical accounts of sensory experience suggest individuals experience a complex combination of hyperreactivity and hyporeactivity to sensory input (Elwin et al., 2012). Through analysis of ten online autobiographies, Elwin and colleagues (2012) found that hyperreactivity was commonly experienced in vision, audition, and touch whilst hyporeactivity was experienced in interoception, proprioception, and pain perception. Interestingly, they also found that individuals can experience fluctuating reactivity to sensory input, in which participants described experiencing a temporary shift in reactivity within a sensory domain. These findings demonstrate how autistic individuals cannot simply be categorised as being hyperreactive or hyporeactive, indeed, even the experience of a sensory domain cannot be deemed as hyperreactive or hyporeactive. Instead, individuals experience both hyperreactivity and hyporeactivity across *and* within sensory domains. Sensory fluctuations are therefore a key component of sensory experience in autistic adults, yet it is unknown what the experience of sensory fluctuations is like across all sensory domains.

Collectively, the discussed research highlights how sensory inputs across multiple modalities contribute to sensory reactivity differences in autism. Importantly, it is the convergence of these inputs from internal and external sensory domains that can heighten sensory difficulties. As such, it is crucial that theoretical viewpoints and measures of sensory reactivity, account for the multisensory nature of sensory experience in autism. Moreover, these sensory differences can both influence, and be influenced by, social interactions with others. Therefore, research needs to consider how differences in sensory processing in autism may be implicated in social experience. Lastly, there is evidence to suggest that autistic individuals experience fluctuations in sensory reactivity both *across* and *within* sensory domains. However, what remains unknown is what the experience of sensory fluctuations is like from the perspectives of autistic individuals, or how these fluctuations impact upon important components of daily life such as physical, mental, and social well-being. Considering this, Chapter 6 of the current thesis will employ a mixed methods approach to investigate the sensory experience of autistic adults from a multisensory perspective.

1.1.0. Methods

The current thesis used a diverse range of methodological approaches including online and in-person research methods. The current section will outline these methods and provide details as to how they were utilised in the current thesis.

COVID impact statement

The impact of the COVID-19 pandemic was extensive and significantly impacted the methods utilised in the current thesis. Between March 2020 and June 2021, the University of Nottingham campus was closed, and I was unable to access the research labs. Thus, in this time I could not access experimental equipment to plan, design, or collect in-person data. Additionally, access to participants was significantly disrupted, even beyond formal lockdowns, as people had to slowly gain confidence to interact with the world again. Additional policies within the University of Nottingham meant that in-person testing was not feasible until August 2021. As such, soon after March 2020 I quickly adapted to using online research methods. This involved learning to use Python and Javacript programming languages to create computer-based tasks that could be hosted online. Through this adaptation process, I created online tasks which allowed for investigation into sensorimotor integration and social processing. Notably, I created a novel experimental task to evaluate sensory integration. Additionally, I taught myself the programming language R (R Core Team (2022) to efficiently process, analyse, and visualize the data. Chapters 2, 3 and 6 reflect studies which were conducted online.

Online research methods

Chapters 2 and 3 utilised the software PsychoPy (Peirce et al., 2019) to investigate the relationship between sensory integration, body schema, and self-related processing. PsychoPy is a Python-based program that allows programming of visual and auditory stimuli and recording of participant responses. The online research hosting site Pavlovia was utilised to allow online access to the experimental tasks. Chapter 6 used a mixed-methods (quantitative and qualitative) approach to investigate the sensory experiences of autistic adults. The online survey hosting platform Qualtrics was used to ask a series of closed and open-ended questions pertaining to sensory experience. Bespoke R scripts were used to process, analyse, and visualise data from all (online and in-person) empirical chapters (R Core Team (2022)).

In-person research methods

Experiments in Chapters 4 and 5 were conducted using MIRAGE, a mediated reality device (Newport et al., 2010; see Figure 1.3). The MIRAGE system uses a rectangular horizontal two-sided mirror, suspended equidistant between the work surface and a monitor above. A camera situated on the worksurface uses the mirror above to capture video images of the participant's hands, Figure 1.3A. This video is processed through a computer using a combination of custom-made hardware and software that can control visual presentation. These video images are displayed in real-time on the monitor, which is presented to participants on the reflection in the mirror (see Figure 1.3B-C). The virtual hand and the real hand are congruent in spatial location and viewed from a first-person perspective.

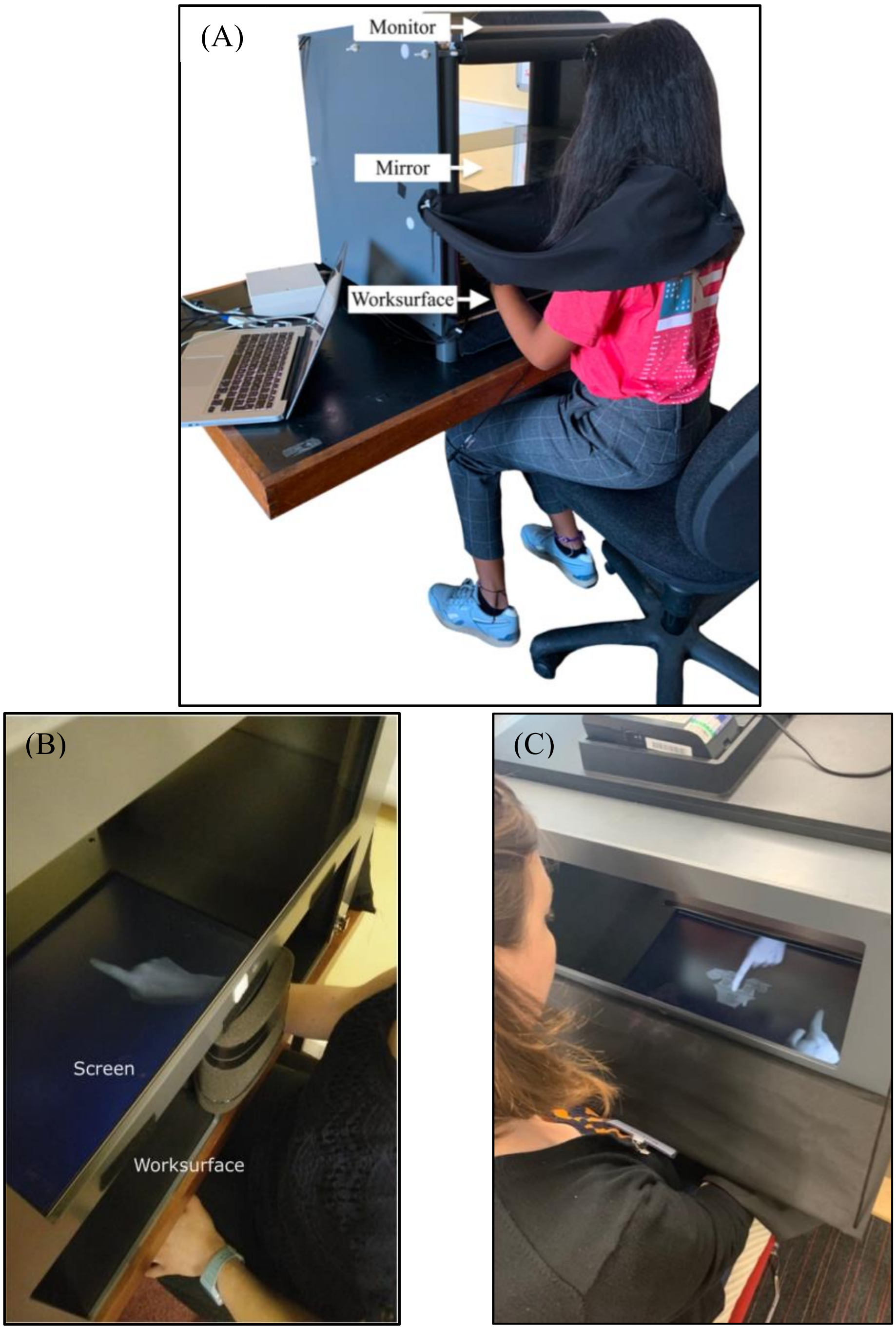

Figure 1.3.

(A) The mediated reality system MIRAGE with a participant. The camera is on the worksurface and films the participant's hand. This image is then fed to the monitor, which is reflected in the mirror such that when the participant looks down, they see a live video image of their own hand.

(B) Participant view of their hand on the MIRAGE screen when they place their hand on the worksurface. Taken from: Greenfield et al., (2017); 10.1163/22134808-00002591

(C) Participant sat with their hand on the MIRAGE worksurface, with presentation of additional visual stimuli displayed in the same depth plane as the virtual hand.

As discussed in Section 1.3, body illusions can offer valuable insight when investigating how the brain integrates sensory inputs to form internal representations of the body. Using the MIRAGE system to create body illusions has several advantages over classic methods such as the rubber hand illusion (RHI). Firstly, the virtual hand in MIRAGE looks the same as the participant's own hand and moves in real time. This means that stroking the participant's hand is not needed to induce ownership over the hand, instead, the participant can simply tap their finger. This has a significant advantage when working with autistic individuals, as soft, affective touch is often reported to be extremely uncomfortable (Crane et al., 2009, MacLennan et al., 2021) and so methods which avoid this are preferential. Secondly, the top-down load that needs to be overcome to embody the virtual hand in MIRAGE is reduced as an image of the participant's own hand is used. As such, the reported onset of illusions is reliably quick in MIRAGE and thus does not require extensive periods of sustained attention (Greenfield et al., 2017; Newport et al., 2010). Lastly, the MIRAGE can be utilised to present visual stimuli on the same depth plane as the virtual hand which can allow investigation into concepts such as interpersonal synchrony. Together, these points evidence how the MIRAGE mediated reality system offers innovative methods to investigate the contribution of sensorimotor integration in social processing in autistic and non-autistic individuals.

The representation of autistic individuals

Autism has been a research focus for many years within the field of psychology. Yet, until relatively recently, research has subscribed to the "deficit" or "medical" model that represents autism as an individual problem that needs to be "cured" (Ritvo et al, 1984). This is reflected in how the American Psychiatric Association (APA) conceptualise autism as having "difficulties with social communication and social interaction" (APA, 2013). However, reciprocity in relationships and interactions by its very definition cannot lie in just one person and yet autistic individuals bear the responsibility. The social model of disability recognises the socially constructed nature of disability through oppression, empowering disabled people to oppose the practices of the medical model (Kapp, 2013). In light of this, the current thesis will aim to represent autistic individuals appropriately by several means. Firstly, the term "autism" will be used as this is the preferential term of autistic individuals (Kenny et al., 2016). Secondly, identity-first language (i.e., autistic person) will be used throughout, again as it is the preferential language used by autistic people (Kenny et al., 2016). Thirdly, care will be taken in an attempt to acknowledge that social and communication differences in autism are just that – differences. Thus, accepting that deficits only occur within a world designed by, and serving non-autistic people. Fourthly, as a non-autistic researcher, I acknowledge that I cannot fully understand first-hand what it is like to be autistic. Subsequently, throughout this thesis, autistic consultants were engaged in the research design and application. Lastly, historically, women and non-binary individuals have been unrepresented in autism research (Lai et al., 2015; Loomes et al., 2017; Philip et al., 2012). Therefore, in the current thesis, women and non-binary autistic individuals were especially encouraged to participate in the research. Moreover, as women and non-binary individuals are often diagnosed later in life or struggle to receive a diagnosis (Zener, 2019), self-identification of autism was acknowledged as a valid diagnostic indicator in empirical chapters of the current thesis.

1.11. Summary of Studies

Chapter 2: The Role of Body Schema and Sensorimotor Integration in Self-Related Processing in Non-Autistic Adults.

When processing information, humans will typically prioritise input pertaining to the self, compared to other related information. This self-prioritisation is thought to be key for social processing as it reinforces the self-other distinction, providing the foundation for mentalising and empathy. Previous work has suggested that self-related processing might be an embodied process that relies on a bodily representation of the self. The body schema is a significant component of the bodily self, providing an internal dynamic representation of where the body is in space, formed through multisensory integration. Yet, no study has directly addressed the contribution of the body schema and sensorimotor integration in self-related processing. *Study 1* of Chapter 2 uses online methods to determine whether the body schema task performance predicts self-related processing in non-autistic adults. *Study 2* aimed to establish whether sensory integration, a precursor of the body schema, predicts self-prioritisation in non-autistic adults. Thus, Chapter 2 aimed to understand the contribution of sensorimotor integration in self-related processing.

Chapter 3: The Role of Body Schema and Sensorimotor Integration in Self-Related Processing in Autistic Adults.

Past research has suggested that differences in self-awareness may explain differences in social and communication skills in autism. Insight into conceptual self-awareness can be gained from research investigating self-referential effects. Research has found evidence of a diminished self-prioritisation effect in autism compared to non-autistic adults. Yet, more recent studies have evidenced typical self-related processing in autism. Chapter 3 sought to investigate whether autistic adults will exhibit a self-prioritisation effect in a basic perceptual processing task. Moreover, Chapter 3 aimed to expand on the findings of Chapter 2 to investigate whether body schema and sensorimotor integration predict self-related processing in autistic adults. Findings from this study may elucidate the mechanisms underpinning self-related processing in autistic adults and shed light on the contribution of sensorimotor integration in social processing.

Chapter 4: Using Mediated-Reality to Explore How Body Schema and Multisensory Integration Contribute to Visual Perspective Taking.

Level two visual perspective taking (VPT2) is an embodied process which is thought to rely on internal representations of the body. Work has found that VPT2 is disrupted in autistic individuals, which is thought to be due to differences in sensorimotor integration and how the body is internally represented. Chapter 4 sought to utilise a body illusion in the mediated reality system MIRAGE to disrupt the body schema and evaluate whether VPT2 performance is affected. Moreover, this chapter aimed to investigate the contribution of sensory integration in VPT2. Findings from this study aimed to provide important insight into the mechanisms underlying VPT2 and offer a greater understanding of how an internal representation of the body formed through multisensory integration may be implicated in the ability to understand how others see the world.

Chapter 5: The Contribution of Sensorimotor Processes in Interpersonal Synchrony and Social Bonding.

The ability to synchronise one's movements with another person has a significant social benefit. Following interpersonal synchrony, children and adults can exhibit greater cooperation, helping behaviour, and likeability to the other person. Thus, the ability to coordinate one's movements with another can be extremely socially advantageous. Interpersonal synchrony is thought to rely on sensorimotor coupling, whereby an individual must identify the rhythm of another person and integrate it into their own movement. However, the contribution of sensorimotor processes in interpersonal synchrony and its social bonding outcomes is relatively unknown. Moreover, while people readily fall in synchrony even without being instructed to do so, we do not know whether such spontaneous (i.e., uninstructed) synchronisation elicits similar prosocial effects as instructed synchronisation. In Chapter 5, investigated the role of sensorimotor integration in uninstructed and instructed visuomotor synchrony in typically developing children (*Study 1*) and adults (*Study 2*).

Chapter 6: The Sensory Experiences of Autistic Adults From a Multisensory Perspective.

Sensory differences are a key component of autism and have a significant impact on the mental, physical, and social well-being of autistic adults. Autistic individuals can experience hyperreactivity and hyporeactivity to sensory input across multiple sensory domains. Moreover, these sensory differences can both influence, and be influenced by, social interactions with others. Therefore, research needs to consider how differences in sensory processing in autism may be implicated in social experience. Notably, individuals can experience shifts in reactivity within a sensory domain, such that on one occasion a particular sensory input may cause discomfort, and, on another occasion, it does not. Yet, comparatively little research has been conducted to understand how autistic individuals experience these sensory fluctuations. Indeed, research has largely focussed on the experience of hyperreactivity to exteroceptive inputs (e.g., vision, touch, audition, olfaction). However sensory differences typically do not pertain to one modality, instead, multiple sensory domains interact and converge to inform sensory experience. Chapter 6 therefore aimed to provide insight into the experience of sensory fluctuations in autistic adults from a multisensory perspective.

See Figure 1.4 for a schematic of how each empirical chapter will link the concepts of sensorimotor integration, representations of the body, and social processing.

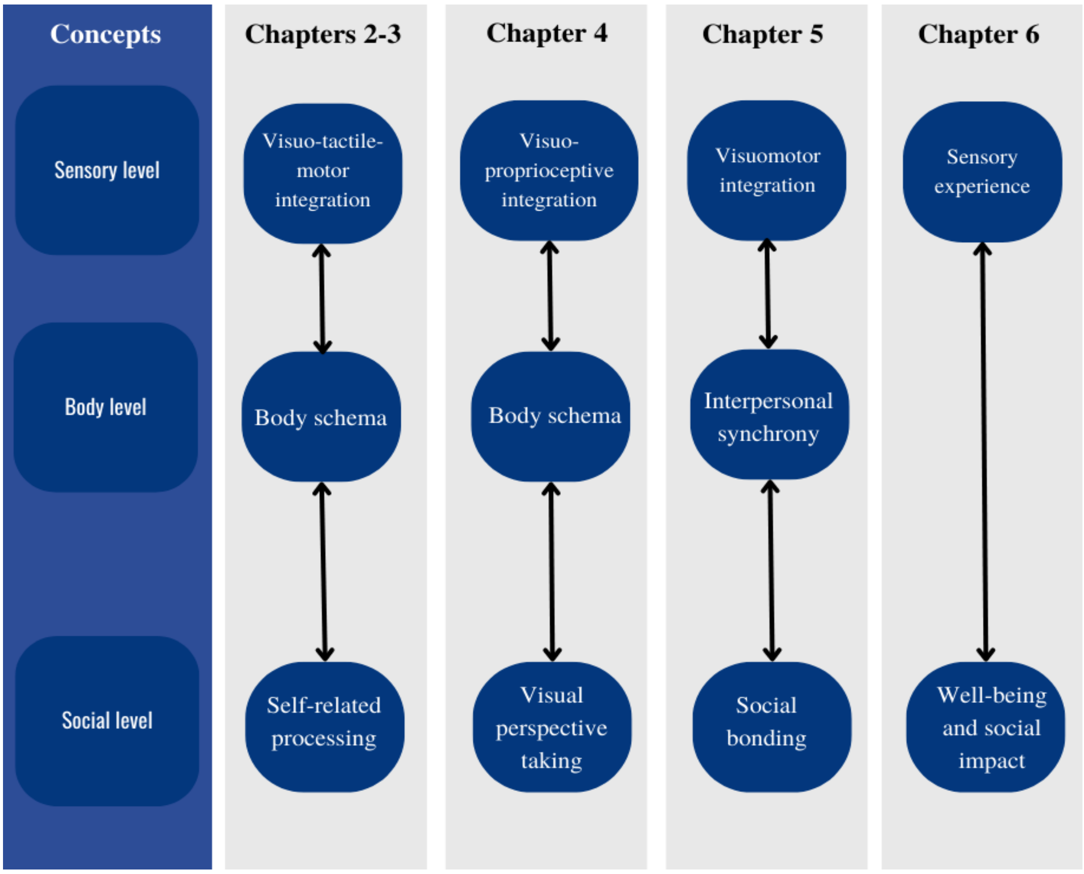

Figure 1.4. Schematic outlining how each empirical chapter in the current thesis will link the concepts of sensorimotor integration, representations of the body, and social processing.

Chapter Introduction

As outlined in Chapter 1, a core feature of social processing is the ability to understand others' mental states, emotions, and perspectives. Holding self-awareness is thought to be related to this mentalising ability. Experimentally, insight into self-awareness can be gained through the exploration of how information relating to the self is processed. As such, Chapter 2 will seek to explore the contribution of sensorimotor integration in self-related processing.

Chapter 2: The Role of Body Schema and Sensorimotor Integration in Self-Related Processing in Non-Autistic Adults

Abstract

When processing information, humans will typically prioritise input pertaining to the self, compared to other related information. Self-related processing is thought to relate to social skills such as mentalising, empathy, and theory of mind. Moreover, it is thought that self-bias in processing is associated with an embodied representation of the self. Yet, it is unknown whether an internal representation of the body formed through multisensory signals (i.e., the body schema), is associated with self-related processing. Across two online studies, we used the perceptual self-tagging paradigm (Sui et al., 2012), the Hand Laterality Judgement Task and a novel sensorimotor integration task to investigate the relationship between body schema, sensorimotor integration, and self-related processing. In *Study 1* we found that an interaction between the body schema and self-related information uniquely predicted performance on the perceptual self-tagging task. In *Study 2*, we found that an interaction between sensorimotor integration and self-related information uniquely predicted performance on the self-tagging task. These findings provide an evidence base for how self-related processing may be an

embodied function, underpinned by a dynamic internal representation of the body formed through multisensory integration.

2.1 Introduction

Having self-awareness allows us to actively identify, process, and store information that relates to ourselves (Duval & Wicklund, 1972). Importantly, self-awareness is closely intertwined with social interactions. It is thought to relate to Theory of Mind (ToM), the ability to attribute goals, intentions, emotions, and beliefs to others (Gallagher & Frith, 2003), which in turn is argued to be a keystone of wider social cognition (Malle, 2012). Insight into how this conceptual self-awareness is established can be gained from research investigating self-referential effects.

Human beings have a natural propensity to prioritise the processing of information pertaining to the self. For example, individuals are faster to respond to images of their own face compared to others' faces, even when the goal of the task is to make judgements about orientation (Keenan et al., 1999; Keyes & Brady, 2010; Sui, Chechlacz, & Humphreys, 2012; Sui, Liu, & Han, 2009). Self-related information has also been found to act as a greater attention distractor compared to other-related information (Brédart, Del-Chambre, & Laureys, 2006; Gronau et al., 2003). Additionally, there is substantial evidence to suggest memory is enhanced when individuals relate information to themselves, known as self-referential memory (Cunningham et al., 2008, 2014; Rogers et al., 1977; Symons et al., 1997; Turk et al., 2008). However, the discussed research has largely used self-related information that is incredibly salient, such as individuals' own faces or personality traits. This issue of saliency has been overcome by using a self-tagging paradigm in which participants learn pairs of person-related labels (i.e., self, friend, and stranger) and simple geometric shapes (i.e., circle, square, and triangle). Research has found that, irrespective of length, familiarity or concreteness of the words, participants are faster and more accurate at responding to self-related pairs (Sui et al., 2012; Sui & Humphreys, 2015b). Even beyond basic visual processing, work has found that self-prioritisation effects can be exhibited when learning overlaps visual and tactile modalities (Schäfer et al., 2020). Thus, self-relevance can mediate processing, perception, and memory across sensory modalities.

Giving priority to information relating to the self is thought to be important for social interaction. Across autistic and non-autistic adults, the size of self-bias effects has been found to relate to mentalizing ability (Lombardo et al., 2007). Therefore, it has been proposed that self-referential processing and the ability to understand other people's mental states are closely linked. Furthermore, recent work has demonstrated a predictive relationship between self-referential processing and social cognition (Dinulescu et al., 2021). More specifically, accuracy on self-related trials of the self-referential processing task was positively associated with accuracy on the Theory of Mind and Empathic Accuracy tasks. Therefore, self-related processing appears to be closely intertwined with the ability to understand others' thoughts, intentions, and emotions. As such, the ability to appropriately prioritise self-related information may correspond to important social behaviours.

Differences in social behaviour have also been proposed to be intrinsically linked to how self-related information is processed. It has been argued that the characteristic differences in social behaviour in autism may be associated with differences in self-referential processing (Gallagher & Frith, 2003; Lombardo et al., 2007). However, previous findings have been mixed, with autistic children showing diminished (Henderson et al., 2009) and comparable (Burrows et al., 2017) self-referential processing compared to non-autistic children. Further mixed findings have been demonstrated in adults, with autistic individuals showing reduced self-related processing compared to non-autistic adults (Lombardo et al., 2007) but more recent work shows undiminished self-referential processing in autistic adults (Lind et al., 2019; Williams et al., 2018). In the non-autistic population, it is well established that there is a continuous variation in the number of autistic traits, as measured by the Autism Quotient (AQ) (Baron-Cohen et al., 2001). This variation in the non-autistic population allows exploration of the relationship between autistic traits and other measures in adults without an autism diagnosis. As such, the relationship between autistic traits and self-related processing in non-autistic adults can be explored. If autistic individuals are thought to have diminished self-referential processing, then we might expect that the number of autistic traits in the non-autistic population would be associated with reduced self-related processing. Conversely, if there is no relationship between the number of autistic traits and self-related processing, then this may support more recent work which has suggested self-referential processing is undiminished in autism (Lind et al., 2019; Williams et al., 2018). Therefore, insight into the social function of self-related processing can be gained through evaluation of the relationship between autistic traits and self-referential effects.

Considering the significant social function of self-related processing, research has endeavoured to understand the mechanisms underpinning self-referential effects. The Bodily Self-Consciousness model (BSC) (Park & Blanke, 2019) suggests that an internal representation of the self is key to cognitive processes and that the body can act as a behavioural tag for memory consolidation (Bréchet et al., 2020). Supporting this, research has found that a representation of the body may influence how self-related information is processed. Research utilising the Full Body Illusion (FBI) has suggested that the conceptual representation of self and bodily representation of self are closely tied (Canzoneri et al., 2016). Typically, when spatially proximal and psychologically proximal words are paired together (e.g., Us-Near) they are processed faster than spatially distanced and psychologically proximal pairs (e.g., Us-Far) or spatially proximal and psychologically distanced pairs (e.g., Them-Near). However, when participants experienced a shift in self-location towards a virtual body in the FBI, the typical faster processing of the Us-Near pair was only exhibited when the pair was displayed towards the virtual body. This suggests that the processing of conceptual information related to the self is affected by the experience of self-location, which is a key component of the body schema (Riva, 2018). Thus, external information that is tied to the conceptual representation of the self, may be influenced by how the body is represented in space.

Further research utilised a perceptual matching task (e.g., Sui et al., 2012) to investigate the role of an embodied representation of self in self-related processing (Sun et al., 2016). Participants were asked to learn pairs of person labels (i.e., self, friend, and stranger) and colours. The colours were presented on avatars either adopting a first-person or third-person perspective. In addition, the avatars were either presented in a socio-communicative context (facing each other) or facing away from each other. It was found that when two avatars were presented, self and friend trial performance was boosted when the target colour was presented from a first-person perspective. The authors suggest that the activation of a representation of an embodied self, from a first-person perspective, enhances attention towards both self and friend stimuli. This effect is particularly salient within a socio-communicative context. Together, these findings may suggest that self-related perceptual processing is both mediated by a social context and related to an embodied representation of self.

An embodied representation of the self relies upon the body schema, a dynamic internal representation of the body founded on the optimal integration of sensory information from multiple modalities (de Vignemont, 2011; Longo et al., 2010; Medina & Coslett, 2010). If self-related processing is an embodied process, then we might expect that the body schema and multisensory integration would be implicated in self-referential effects. To investigate this using online research methods, computer-based tasks can be used to evaluate the body schema and sensorimotor integration.

One way to measure the body schema is using the Hand Laterality Judgment Task (HLJT). In this task, participants view images of left and right hands presented at varying angles and are asked to make judgements about the handedness of the image. Motor imagery is the most common strategy used to complete the task, in that participants are most likely to imagine their own body (or body parts) in the position of the stimulus to make laterality judgements. Individuals must therefore hold a stable representation of their body to be able to simulate it rotating into another position (Cooper & Shepard, 1975). Indeed, individuals with disrupted body schemas due to chronic pain are shown to have reduced performance on the HLJT (Ravat et al., 2020).

Behavioural markers evidencing the use of motor imagery in the HLJT come from findings that the mental processing time to calculate handedness of images of rotated hands mirrors the time taken to physically perform the rotation (Parsons, 1994) and that biomechanical constraints affect processing speed (de Lange et al., 2006). This means that the postural position of the stimuli (Sekiyama, 1982) and the postural position of the participant's body (de Lange et al., 2006) influence laterality judgement processing. The less awkward the imagined postural rotation, the quicker the laterality judgement. For example, if a right hand is rotated anti-clockwise, then judgements at 0° or 90° will be quicker than at 180° or 270° due to the biomechanical constraint of rotating the hand into that position. Thus, the difference in performance between viable and restrictive hand positions can indicate if an individual is utilising a motor imagery strategy. Whilst work has suggested that not all individuals will utilise a motor imagery strategy (Conson et al., 2013; Mibu et al., 2020), the majority of people still do and variability in the size of the biomechanical effect may reflect differences in how the body is internally represented (i.e., the body schema). Therefore, the HLJT can be used to evaluate the body schema, when utilising online research methods.

Sensorimotor integration can also be evaluated using computer-based methods. In the simultaneity judgement (SJ) task, participants are exposed to two items of stimuli across two sensory modalities and are asked to determine whether the sensory events occurred at the same time (e.g., Zampini et al., 2005). For example, participants may be presented with a flash of light and an auditory beep and be asked to judge if they were presented at the same time. Manipulating the temporal delay between the sensory events can therefore be used to evaluate temporal sensitivity when processing cross-modal sensory information. Integrating sensory information inputted from different modalities depends on them occurring within the Temporal Binding Window (TBW) (Colonius & Diederich, 2004). Extended TBWs are associated with atypical sensory processing and as such greater sensitivity to shorter temporal delays may indicate more optimised sensory integration (Foss-Feig et al., 2010; Hillock-Dunn et al., 2016). For example, using the SJ paradigm, work has found that sensitivity to visuo-proprioceptive asynchrony is greater when stimuli are viewed from a first-person perspective (Hoover & Harris, 2012). Such tasks, therefore, have the potential to be adapted online, to investigate the contribution of sensory integration in self-related processing.

Self-referential effects can offer insight into self-awareness and how the self is internally represented. In turn, self-referential effects can provide insight into the mechanisms underpinning social behaviours such as ToM, empathy and mentalising. Whilst research has suggested that self-related processing might be an embodied process, the link between the bodily self and the conceptual self is not fully understood. Across two studies, we investigated the relationships between the body schema (*Study 1*), sensorimotor integration (*Study 2*), and self-related processing using Linear Mixed Modelling (LMM). *Study 1* utilised the Hand Laterality Judgement Task (HLJT) and a self-prioritisation task (SPT) (Sui et al., 2012) to assess the relationship between the body schema and self-related processing. In *Study 1*, we made two predictions; (Hypothesis 1) participants will exhibit greater performance in the SPT for the *Self* trials compared to *Friend* or *Stranger,* (Hypothesis 2) greater performance on the HLJT will relate to better performance on *Self* trials of the SPT. Additional exploratory analysis was conducted on the relationship between autistic traits and self-related processing with no specific prediction. *Study 2* was a replication of *Study 1* with the addition of a novel sensorimotor integration task. In *Study 2*, we made one additional prediction (Hypothesis 3) that greater sensorimotor integration would positively relate to self-bias. That is, individuals with poorer visuo-tactile-motor integration would show a reduced tendency to prioritise self-related information.

Study 1

2.2 Methods

Participants

Fifty-five adults took part (38 women, 15 men, 1 non-binary M_{age}=27.09 years, *SD*=16.44, 1 missing demographic data). While simulative a priori power analysis suitable for linear mixed modelling was not conducted, a target sample size of 50 participants was set for recruitment. All participants reported having normal or corrected-to-normal vision. Informed consent was obtained before the experiment according to procedures approved by the

University of Nottingham, School of Psychology ethics committee (approval number: S1287R). Thirteen participants were removed due to missing experimental data, three participants were removed from the sample for failing to pass the attention check and a further four participants were removed due to performance errors (see Data Analysis section for further details). Therefore, the final sample consisted of thirty-four adults (24 women, 9 men, 1 non-binary, M_{age}=25.06 years, *SD*=15.06).

Materials and Measures

Participants completed the study online via Pavlovia (an online platform to host behavioural experiments) using their own personal desktops and laptops. The Autism Quotient (AQ) and demographic questions were hosted on Qualtrics.

Self-Prioritisation Task (SPT)

Three geometric shapes (circle, square, and triangle) were paired with three person labels (self, friend, and stranger) for each participant (see Figure 2.1). Participants were required to learn these pairs and then complete a recognition task. The geometric shapes were 472x410 pixels and labels were displayed 72 pixels below the shape. Shape-label pairs were presented in the middle of the screen for all trials. Half the stimuli were of correct pairs (previously learnt pairs) and half of incorrect pairs (new pair combinations). Participants had to respond whether the displayed pair was correct or incorrect. The shape-label pairs were counterbalanced across participants to control for shape saliency.

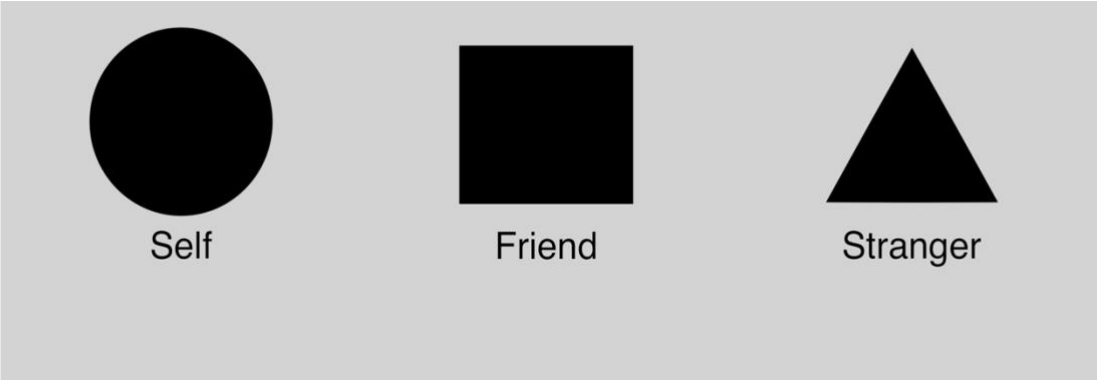

Figure 2.1. Examples of stimuli used in the self-prioritisation task.

Participants were informed of the target pairs via text instructions and were then presented with images of the shape-label pairs, each displayed for three seconds and shown one at a time. The order of this presentation was fully randomised. Participants were told to respond with the left arrow key if the pair was correct and the right arrow key if the pair was incorrect. Participants were asked to respond with their dominant hand and to keep their non-dominant hand on their desk or their lap throughout testing. Participants were told to respond as quickly and as accurately as possible. Participants completed training, practice, and experimental trials.

Training trials

Firstly, participants completed training trials to familiarise themselves with the target pairs. Participants were reminded of the correct pairs in text format before the training trials. Shape-label pairs were shown for three seconds, and participants had to respond in this time. Feedback in text form was then displayed indicating whether the previous response was correct. Feedback was displayed for two seconds after the response had been made. Participants completed a total of 12 training trials.

Practice trials

Pairs were displayed for 0.5 seconds, and participants had a total of two seconds to respond (including display time). Practice trials were terminated when participants reached 80% accuracy or a maximum of 60 trials. All participants completed a minimum number of 36 trials.

Experimental trials

Before the experimental trials, participants were reminded of which keys to respond with on correct and incorrect pair trials. Then, pairs were displayed for 0.2 seconds, and participants had two seconds to respond, including display time. Participants completed 96 trials.

Hand Laterality Judgement Task (HLJT)

Hand images were obtained from the Bank of Standardised Stimuli (Brodeur et al., 2014). Right- and left-hand images were presented at rotations of 0°, 90°, 180° and 270° either at palmer or dorsal view. The biomechanical ease of imagery was most difficult at the greatest degree of rotation. Therefore, left-hand images were rotated clockwise, and right-hand images were rotated anti-clockwise. This meant that for both right and left images, 270°would be the most biomechanically challenging angle. A total of 16 hand stimuli items were used (8 left, 8 right, with 4 rotations in palmer and dorsal view), (see Figure 2.2).

Figure 2.2. Examples of the stimuli presented in the Hand Laterality Judgement Task. Displayed respectively is a right hand in palmar view at 0°, a left hand in dorsal view at 90°, a left hand in palmar view at 180° and a right hand in dorsal view at 90°.

Participants were instructed to respond as quickly and as accurately as possible. Participants were asked to respond with the left arrow key if they thought the stimulus was of a left hand and the right arrow key if they thought it was an image of a right hand. Participants were asked to respond with their dominant hand and to keep their non-dominant hand still on their desk or lap throughout the task. Hand stimuli were displayed until participants made a response. Participants completed a total of 80 trials.

Autistic traits

Autistic traits were measured by the Autism Quotient (Baron-Cohen et al., 2001), a self-report questionnaire in which participants rate their level of agreement to 50 statements e.g., “I find social situations easy”; “I find myself drawn more strongly to people than to things”) on a four-point Likert scale (“definitely agree”, “slightly agree”, “definitely disagree” and “slightly disagree”). An attention check was administered as part of the AQ, in which participants were asked to select “slightly agree” to the statement “I am paying attention” displayed halfway through the questionnaire.

Procedure

Participants were recruited online through social media accounts and university web pages. Participants completed the entire study online on a laptop or desktop computer without the online presence of a researcher. The order of the hand laterality judgement task, self-prioritisation task, and sensorimotor integration task was randomised for each participant. The AQ was always administered last. There were no effects of order (SPT or HLJT first) or SPT version (label-shape pairs, e.g., triangle-self or square-self) on SPT performance or HLJT performance (see Appendix 2.1). Following the completion of the study, participants were given a debrief sheet and were given the opportunity to contact the researcher to ask any questions. Participants then received their inconvenience allowance.

Data analysis

Four participants did not correctly answer the attention check question within the AQ and so were removed from the analysis. In the SPT and HLJT tasks trials where reaction times less than 200ms were filtered to remove anticipatory responses (Woods et al., 2015). If a participant had more than half of their experimental trials removed due to anticipatory responses, they were removed from the analysis. Therefore, two participants were removed as more than half of their reaction times in the SPT trials were less than 200ms and therefore deemed to be anticipatory. A further six participants were removed for missing experimental data (i.e., completing training trials but not experimental trials).

Self-prioritisation

D-prime was used to assess performance in the *Self*, *Friend*, and *Stranger* trials. D-prime indicates the sensitivity to be able to accept correct pairs of stimuli and reject incorrect pairs of stimuli. D-prime values were calculated as follows (as per Sui et al., 2012):

$$\boldsymbol{d' = z(H) - z(F)}$$

Where z(H) and z(F) are the z transforms of hit rate and false alarm, respectively. Hits correspond to correct responses to shape-label matched pairs and false alarms are incorrect responses to shape-label mismatched pairs. To avoid infinite d-prime values, if z(H) or z(F) were equal to 1, the value was transformed to 0.96875. If z(H) or z(F) were equal to 0, the was transformed to 0.03125. Positive values indicate an ability to correctly identify correct pairs and reject incorrect pairs a score of 0 indicates chance performance and negative values indicate an inability to correctly identify correct pairs and reject incorrect pairs. Participants with d-prime values ≤0 in more than one SPT condition were removed from the analysis on the basis that they did not demonstrate evidence of understanding the task or appropriate responding. Three participants were excluded from the analysis on this basis. To test Hypothesis 1, paired sample t-tests were used on the d-prime values to assess whether there was a prioritisation of *Self* pairs compared to *Friend* and *Stranger* pairs.

Hand laterality judgement task

To control for speed-accuracy trade-off effects, accuracy, and reaction time (RT) measures were combined to obtain the psychological efficiency index. This was calculated by dividing the mean RTs of correct responses by the proportion of accurate responses for each participant (Townsend & Ashby, 1983; Mattan et al., 2015). This created a single score in which lower values equal better performance. Statistical analyses are reported for these combined efficiency scores only.

A manipulation check was performed to ensure the hand laterality judgement task was evaluating embodied motor imagery, and thus body schema. A behavioural marker evidencing the use of motor imagery in this task is the biomechanical constraint effect in which performance on the task is mediated by the postural position of the stimuli (Sekiyama, 1982) and the postural position of the participant's body (de Lange et al., 2006). The less awkward the imagined postural rotation, the quicker the laterality judgement. For example, a hand rotated to 270° or 180° will be more difficult to evaluate the laterality than a hand presented at 90° or 0° rotation. Stimuli presented at 0° or 90° can therefore be considered biomechanically viable and stimuli presented at 180° or 270° can be considered biomechanically restrictive. Thus, the biomechanical constraints on performance can indicate whether a motor imagery strategy was utilised. A paired samples t-test was used to assess the difference in efficiency scores between biomechanically viable and restrictive stimuli. Significantly better performance in the viable condition would evidence a biomechanical effect.

Exploratory Analysis: Autism Spectrum Quotient

The fifty-question Autism Quotient (AQ) was coded as per the coding scheme (Baron-Cohen et al., 2001). Scores range from 0-50 with a higher score indicating more autistic traits. In the current study, scores ranged from 5 to 35 (*M*=17.56, *SD*=7.97).

Linear Mixed Modelling

Mixed-effects models were run using the lme4 package in R (R Core Team (2022) to understand the predictive relationship of body schema and autistic traits on self-prioritisation. A full model was constructed that included the predictors of *Label* (self, friend, or stranger), AQ scores, *Body Schema* scores and the interaction between *Label* and *Body Schema*. The full model included random intercepts for participant ID to account for the nested structure of the data. The null model consisted of only the random effect of participant ID. The model fit of the full and null models was assessed using an analysis of variance (ANOVA). If the full model was a significantly better model fit compared to the null model, then the full model was compared to a simple main effects model to ascertain the contribution of the interaction.

2.3 Results

Manipulation checks

Hand Laterality Judgement Task

A paired samples t-test revealed a significant difference between the biomechanical condition (t(33)=-4.77, *p*<.001), with participants performing better (lower efficiency scores) in the *Viable* condition (0° and 90° rotation) (*M*=2.29, *SD*=0.997) compared to the *Restrictive* condition (180° and 270° rotation) (*M*=3.05, *SD*= 1.26) (see Figure 2.3).

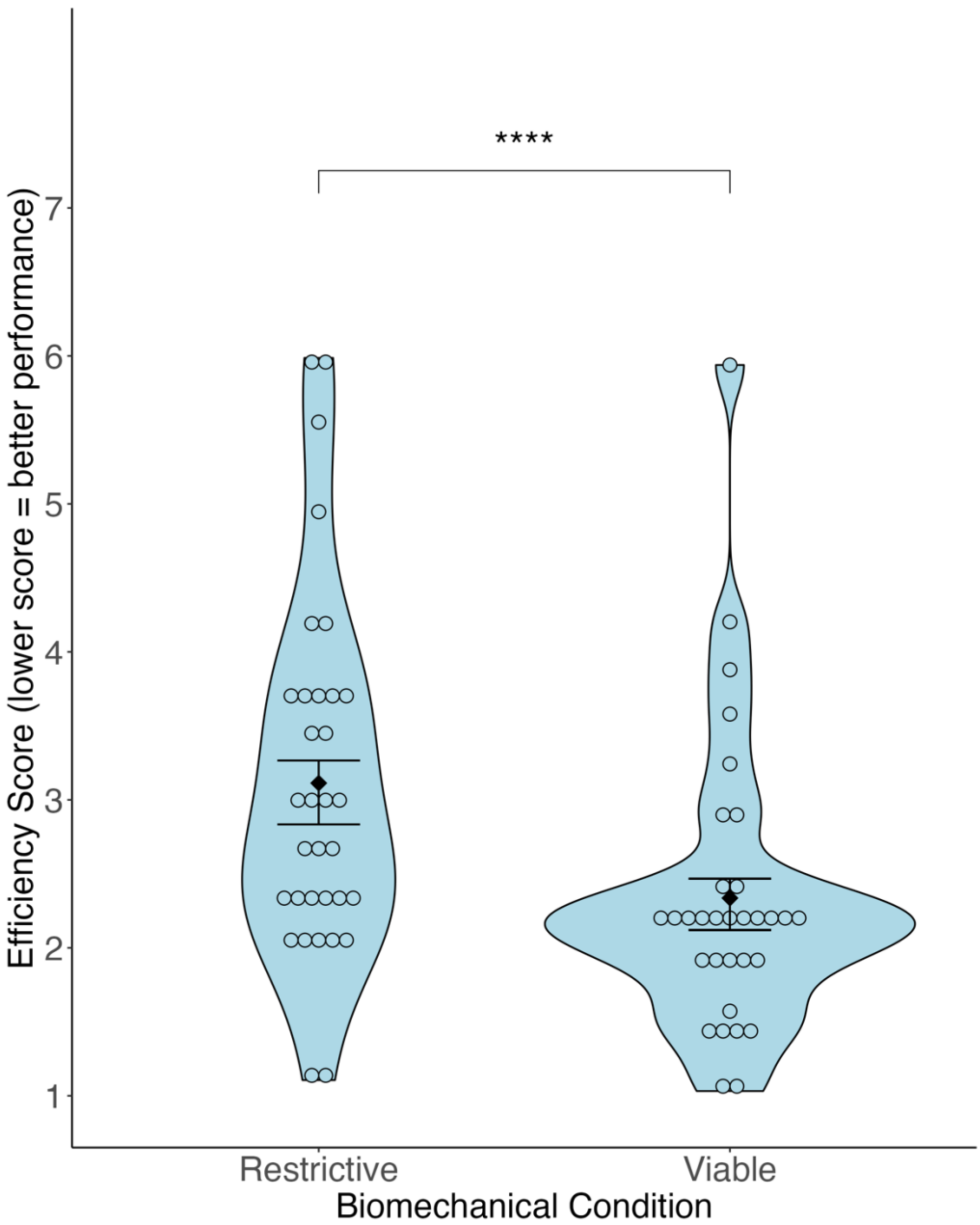

Figure 2.3. Violin plot of the mean efficiency scores on the Hand Laterality Judgement Task, split by biomechanical condition. The Restrictive condition consists of rotations at 180 or 270, the Viable condition consists of rotations at 0 or 90. The lower the score the better the performance. Coloured dots indicate individual data points and black diamonds indicate group mean.

Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ****=p<0.001.

Hypothesis 1: self-related performance will be greater than other-related performance

Two Bonferroni corrected paired samples t-tests (α=0.025) showed a significant difference in d-prime scores between *Self* and *Stranger*; (*t*(33)=3.67, *p*=.003) but no significant difference between *Self* and *Friend*; (*t*(33)=-1.03, *p*=.31). Participants performed best in *Self* trials (*M*=2.70, *SD*=0.879), then *Friend* trials (*M*=2.51, *SD*=0.780), then *Stranger* trials (*M*=2.05, *SD*=0.921) (see Figure 2.4).

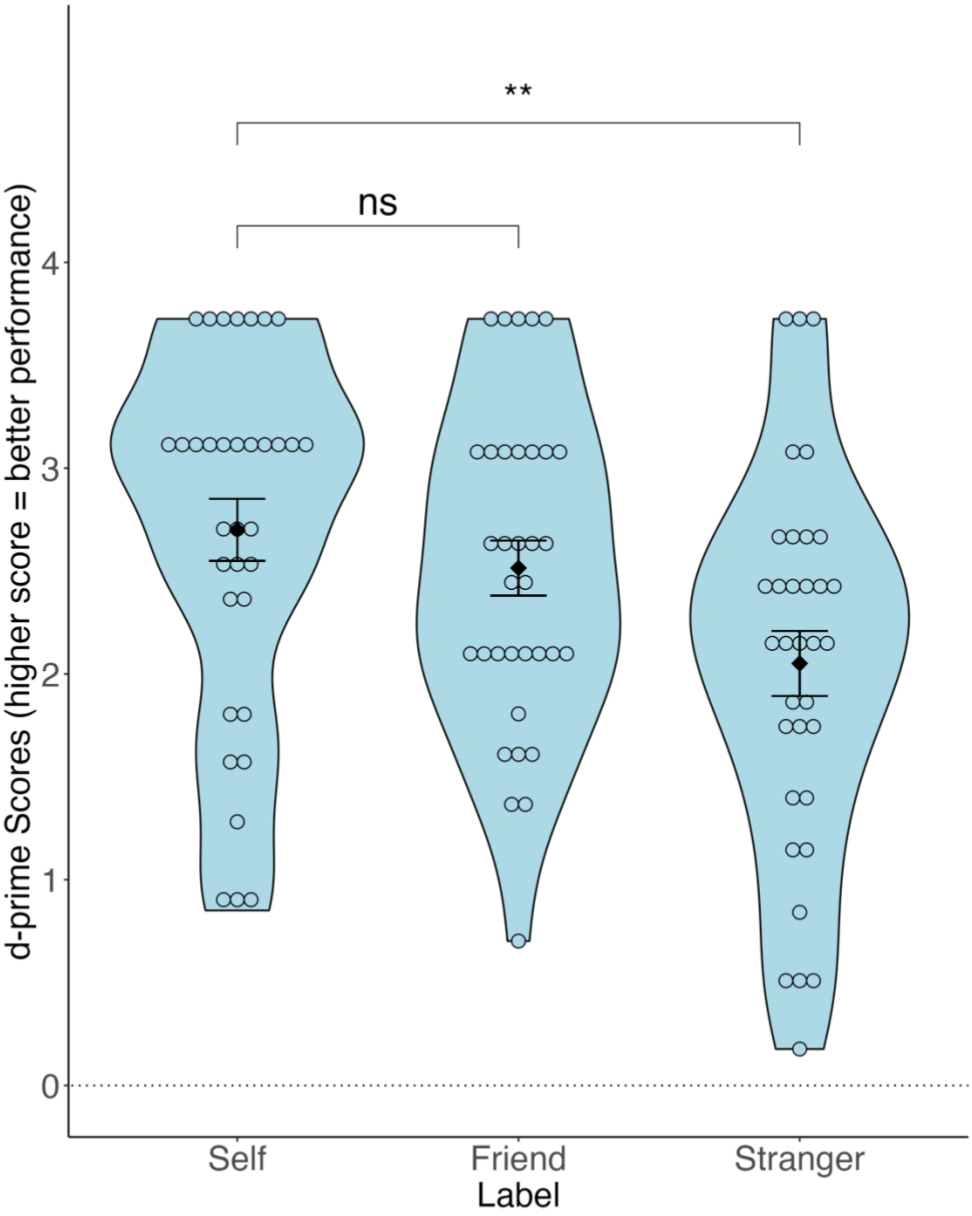

Figure 2.4. Violin plot of the mean d-prime scores for each label on the self-prioritisation task. The higher the score, the better the performance. The dotted line indicates chance performance on the SPT.

Coloured dots indicate individual data points and black diamonds indicate group means. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, **= *p*<0.01, ns=non-significant.

Hypothesis 2: body schema performance will predict self-related processing

The full model was a significantly better fit compared to the null and the simple main effects model, see Table 2.1 for model summaries and comparisons. The full model was the best fit in explaining variance in the d-prime scores on the SPT, explaining 16.8% of the variance by fixed effects and 49.4% of the variance by random effects. The *Self* label was a significant predictor of SPT performance (*p*<.001, 95% CI [0.76, 2.54]). The interaction between the *Self* label and body schema performance (*p*=.001, 95% CI [-0.87, -0.24]) was also a significant predictor of SPT performance, with performance on the *Self* trials increasing as body schema performance increased, (see Figure 2.5). The number of autistic traits as measured by AQ scores was not a significant predictor in the model (*p*=.80, 95% CI [-0.39, 0.11]).

Table 2.1: Predictors of d-prime scores on the SPT. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	266.21	274.08	
Simple Main Effects (Null + Label, Body Schema, AQ Scores)	258.66	277.04	.00369 vs Null
Full (Simple Main Effects+ Label*Body Schema)	250.82	274.44	.00268 vs Simple Main Effects

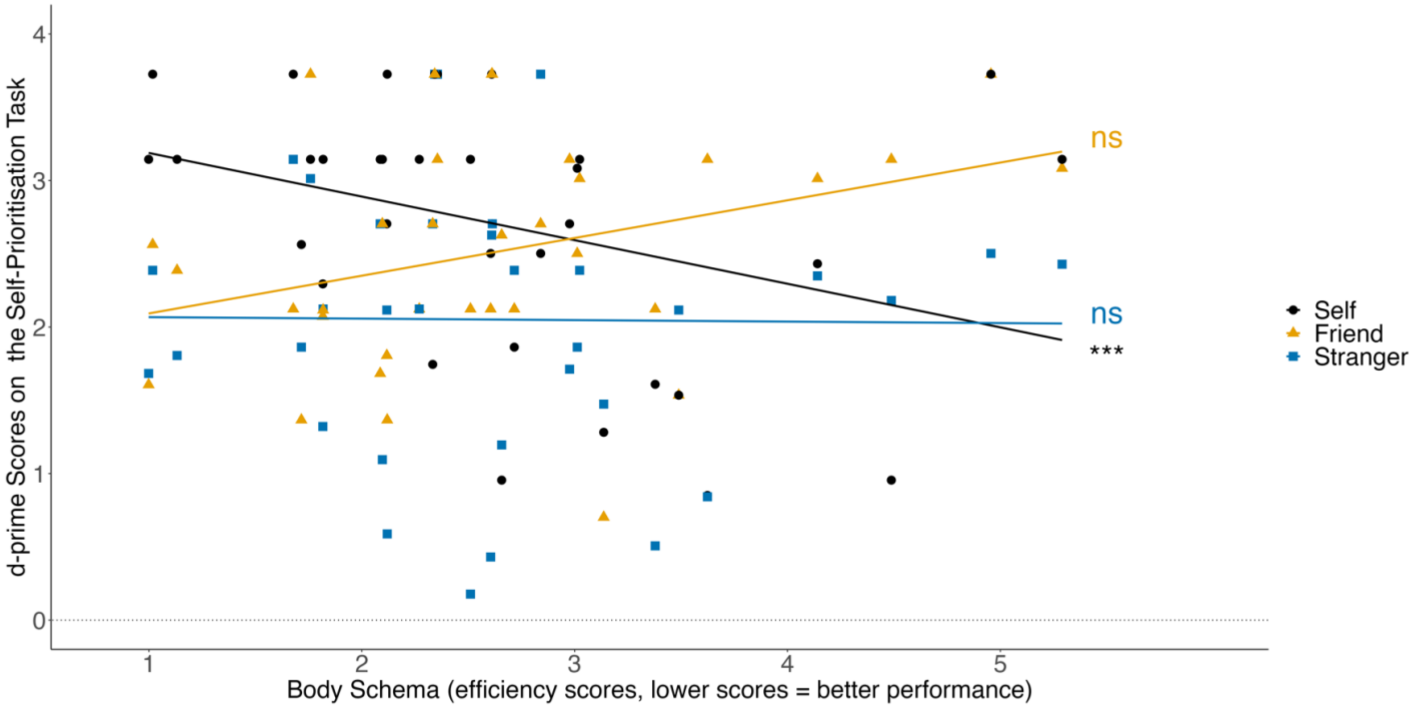

Figure 2.5. Plot showing the relationship between *Body Schema* (efficiency scores; the lower the score the better the performance) and d-prime scores on *Self*, *Friend*, and *Stranger* trials of the self-prioritisation task. Annotations show the significance level of the interactions between each label and *Body Schema* from the LMM analysis. The dotted line indicates chance performance on the SPT.

Brackets show the pairwise comparisons, ***=$p \leq .001$, ns= non-significant.

Standard error is not displayed graphically here to maintain clarity of results.

2.4 Discussion

We investigated the relationship between body schema and self-related processing. In line with Hypothesis 1, we found a significant self-bias effect in a simple self-tagging paradigm in which participants learnt pairs of labels (self, friend, and stranger) and geometric shapes (circle, triangle, square). In support of Hypothesis 2, we found that an interaction between *Body Schema* and *Self* label was a significant predictor of performance on the self-prioritisation task. In our exploratory analysis, we found that adding autistic traits to our model did not significantly predict performance on the self-prioritisation task.

As predicted in Hypothesis 1, and in line with previous works (Sui et al., 2012; Sui & Gu, 2017; Sui & Humphreys, 2015b, 2017) we found that participants were significantly more accurate at remembering self-related information compared to stranger-related information. Contrary to our prediction, we found no significant difference in d-prime scores of *Self* and *Friend* pairs. However, additional analysis did reveal a significant difference in reaction times (ms) between *Self* and *Friend*; ($t(33)=6.09$, $p \leq .001$) and *Self* and *Stranger*; ($t(33)=-11.0$, $p<.001$) with participants performing better in *Self* trials ($M=785.542$, $SD=157.618$) compared to *Friend* ($M=858.313$, $SD=164.457$) and *Stranger* ($M=887.207$, $SD=156.351$). This suggests that whilst participants were comparably accurate at processing *Self* and *Friend* trials, they were much quicker at reaching a correct response for *Self* trials. Subsequently, this evidences that participants exhibited a self-bias in the processing of the shape-label pairs.

In line with Hypothesis 2, we demonstrated that the body schema may be implicated in self-related processing. Performance on the HLJT significantly and uniquely (compared to *Friend* or *Stranger*) predicted d-prime scores on *Self-related* trials of the SPT. This means that participants with better body schema scores (lower efficiency scores on the HLJT) exhibited greater accuracy in processing self-related information. This was a unique finding of embodied facilitation in the *Self* trials, and not the *Friend* or *Stranger* trials. This result suggests that body schema performance uniquely corresponds to the ability to process self-related information, in turn providing evidence for self-related processing being an embodied process which relies on an internal representation of the body.

This finding corresponds to the Bodily Self-Consciousness model (BSC) (Park & Blanke, 2019) which stipulates that an internal representation of the self is key to cognitive processes and that the body can act as a tag for memory consolidation (Bréchet et al., 2020). As such, it is possible that an internal representation of the self, formed through multisensory integration (i.e., the body schema), may reinforce the self-other distinction, and thus promote self-related processing (Meltzoff, 2007; Tsakiris, 2017). Indeed, previous work has found that the self-prioritisation effect could be boosted when stimuli were presented within a first-person perspective (Sun et al., 2016). Thus, this suggests that self-related processing was facilitated when the representation of the perceptual information was more closely matched to the representation of the bodily self (i.e., when represented in a first-person perspective). Whilst previous work found evidence that both self and friend processing was boosted by an embodied perspective (Sun et al., 2016), the current study found that body schema only corresponded to self-related processing. This seems to show that body schema uniquely relates to perceptual processing of self-related but not friend-related information. This difference in findings is likely due to procedural distinctions in the methods used. Sun and colleagues (2016) presented stimuli on avatars in a socio-communicative positioning (i.e., avatars displayed facing each other), which may have more widely primed processing of *Self* and *Friend* trials. In comparison, we used an individual measure of body schema which would not necessarily boost the processing of friend-related information.

Importantly the current findings have implications for how we understand social cognition. Self-referential processing is thought to correspond to the conceptual representation of the self, including self-awareness. Self-awareness is closely intertwined with social interactions as we must be able to hold a mental representation of our own mental state and understand it may be distinct from the mental states of others. Indeed, self-awareness is related to ToM (Gallagher & Frith, 2003) and empathy (Dinulescu et al., 2021). Considering the current findings, this may suggest that how the body is internally represented might be associated with self-awareness and thus the ability to understand the mental states and emotions of others. However, our exploratory analysis found that autistic traits to did not relate to performance on the SPT, corresponding to previous work which also found autistic traits did not predict SPT performance within a non-autistic population (Dinulescu et al., 2021; Lind et al., 2019; Nijhof et al., 2020). This suggests that the number of autistic traits is not associated with diminished or enhanced self-bias in non-autistic adults. Theoretically, this is important, because whilst self-referential processing might be related to social cognition, variation in self-processing does not appear to account for social differences associated with autism.

Study 2

The body schema is thought to depend on multisensory integration (MSI) – the process by which the brain dynamically weights and integrates this sensory information to create a dynamic internal representation of the body (Makin et al., 2008; Nava et al., 2014; Schütz-Bosbach et al., 2006; Tsakiris, 2010, 2017). Following on from the results of *Study 1*, we aimed to evaluate the contribution of sensorimotor integration, a central aspect of the body schema, in self-related processing. *Study 2* aimed to understand the relationship between sensorimotor integration, body schema, and self-related processing.

2.5 Methods

Participants

Fifty-one adults took part (8 women, 42 men, 1 non-binary M_{age}=18.06 years, *SD*=0.24). While simulative a priori power analysis suitable for linear mixed modelling was not conducted, a target sample size of 50 participants was set for recruitment. All participants reported having normal or corrected-to-normal vision. Informed consent was obtained before the experiment according to procedures approved by the University of Nottingham, School of Psychology ethics committee (approval number: S1287R). Fourteen participants were removed for performance errors (see Data Analysis section for details). Therefore, the final sample consisted of thirty-seven adults (31 men, 6 women, M_{age}= 18.08 years, *SD*=0.28).

Materials and Measures

The same methods were used in Study 2 as in Study 1, with the addition of the sensorimotor integration task. Details for this task are given below. There were no effects of task order or SPT task version (label-shape pair combinations e.g., self-triangle or self-square) on SPT, HLJT or Sensorimotor Integration task performance (see Appendix, 2.2).

Sensorimotor Integration Task

The sensorimotor integration task used in the current study was developed to measure visuo-tactile-motor integration using online research methods. The task was adapted from simultaneity judgement tasks which have been used previously to measure the temporal binding of cross-modal sensory inputs (e.g., Zampini et al., 2005). Poorer temporal sensitivity in the simultaneity judgment task is associated with atypical sensory processing and as such greater sensitivity to temporal delays may indicate more optimised sensorimotor integration (Foss-Feig et al., 2010; Hillock-Dunn et al., 2016). Put simply, the better individuals are at detecting shorter temporal delays between sensory events, the more optimised their sensorimotor integration. In the current study the simultaneity judgement task was designed to evaluate the integration of visual, tactile, and motor information. Better performance in the task is thought to reflect more optimal integration of information across these domains.

Participants made a self-generated keypress with their dominant hand when indicated to by the appearance of a visual stimulus on the screen, (see Figure 2.6). The visual stimulus would then change to reflect movement into a new position (i.e., finger in upright position moving to downwards position) either simultaneously with the participant keypress or would move after a delay. To overcome variable computer processing times typical of computer-based tasks and online research methods, the simultaneity judgement paradigm was adapted to measure comparative simultaneity judgements. In other words, participants viewed two sequentially presented items and had to decide which one presented the visual stimulus *most* simultaneously. One item was presented simultaneously with the participant key press and the other was presented after a delay of 50ms, 150ms, 200ms or 300ms. Following this, participants had to decide whether the first or second stimulus moved in time with their keypress. The interstimulus interval and the inter-trial interval were randomly varied (200ms, 250ms, 300ms or 350ms) across trials to prevent trial timing from aiding performance on the task. Participants completed a total of 80 trials. Whether the first of second stimuli item was visually delayed was randomised such that in 50% of the trials, the first stimulus was in time with the participant key press, and in 50% of trials the second stimulus was in time with the participant key press. The order of trials was fully randomised for each participant.

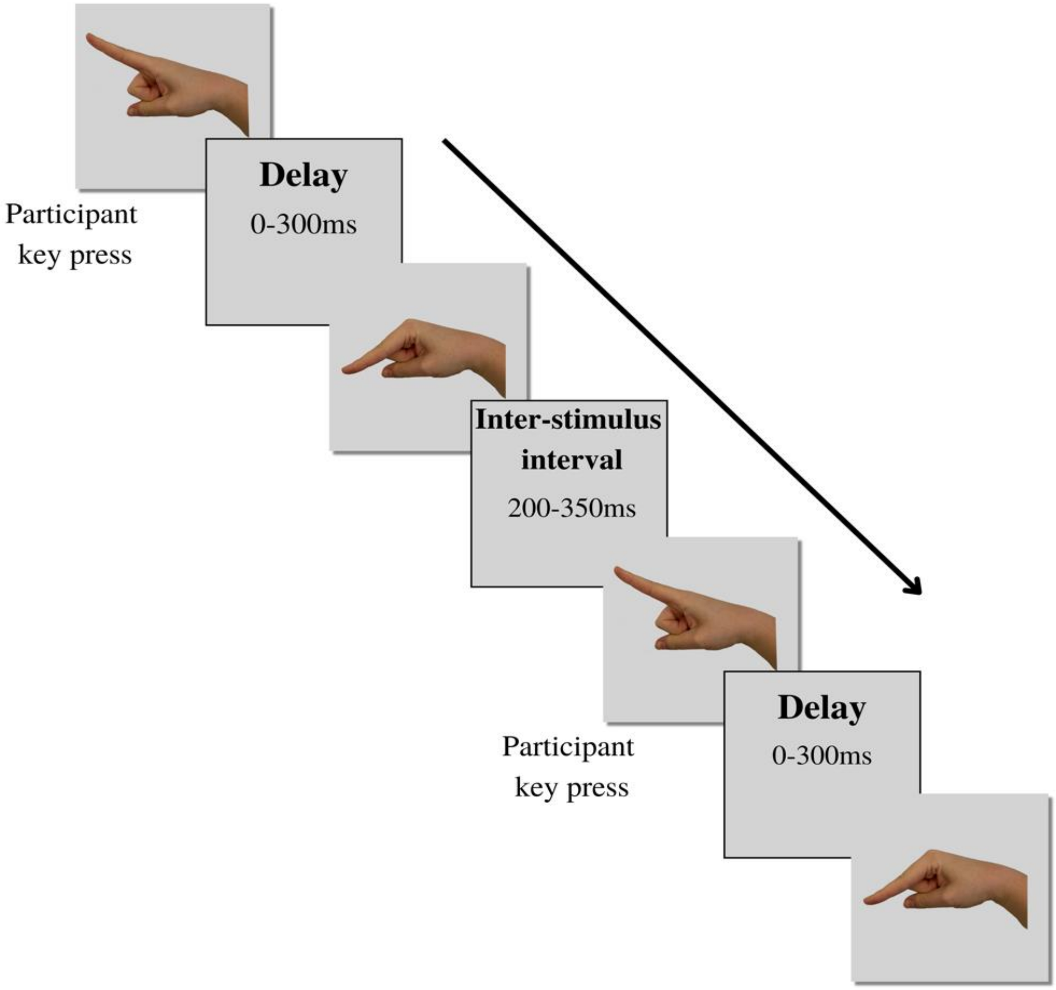

Figure 2.6. Schematic of the sensorimotor integration task procedure. Whether the delay was applied to the first stimuli pair or second was randomised across trials. The delay was either 50, 100, 150, 200 or 300ms. The inter-stimulus interval and inter-trial interval were randomly varied (200-350ms) across trials to prevent trial timing aiding performance on the task.

Data analysis

Nine participants were removed from the analysis due to over 50% of experimental trials on either the HLJT or SPT being anticipatory (≤200ms). Five participants were removed from the analysis due to having d-prime scores ≤0 in more than one SPT condition.

Sensorimotor Integration

Raw accuracy scores were used to assess performance on the *Sensorimotor Integration* task. A manipulation check was performed on the accuracy scores to ensure participants were performing as expected. As such, a repeated measures ANOVA was conducted to check that accuracy increases as the delay between participant keypress and visual stimulus increases.

Linear mixed modelling

Mixed-effects models were run using the lme4 package using R (R Core Team, 2022) in RStudio (RStudio Team, 2020) to understand the predictive relationship of *Body Schema* and *Sensorimotor Integration* on self-prioritisation. A full model was constructed that included the predictors of *Label* (self, friend, or stranger), *Body Schema* (efficiency scores), and *Sensorimotor Integration* (accuracy). The full model also included interactions between *Label* and *Body Schema* and *Label* and *Sensorimotor Integration*. The full model included random intercepts for participant ID to account for the nested structure of the data. The null model consisted of only the random effect of participant ID. The model fit of the full, simple, and null model was assessed using an analysis of variance (ANOVA). If the full model was a significantly better model fit compared to the null model, then the full model was compared to a simple main effects model to ascertain the contribution of the interaction.

2.6 Results

Manipulation checks

Hand Laterality Judgement Task

A paired samples t-test revealed a significant difference between the biomechanical condition; ($t(36)=-6.95$, $p<.001$), with participants performing better (lower efficiency scores) in the *Viable* condition (0° and 90° rotation) ($M=2.09$, $SD=0.51$) compared to the *Restrictive* condition (180° and 270° rotation) ($M=2.62$, $SD= 0.67$) (see Figure 2.7).

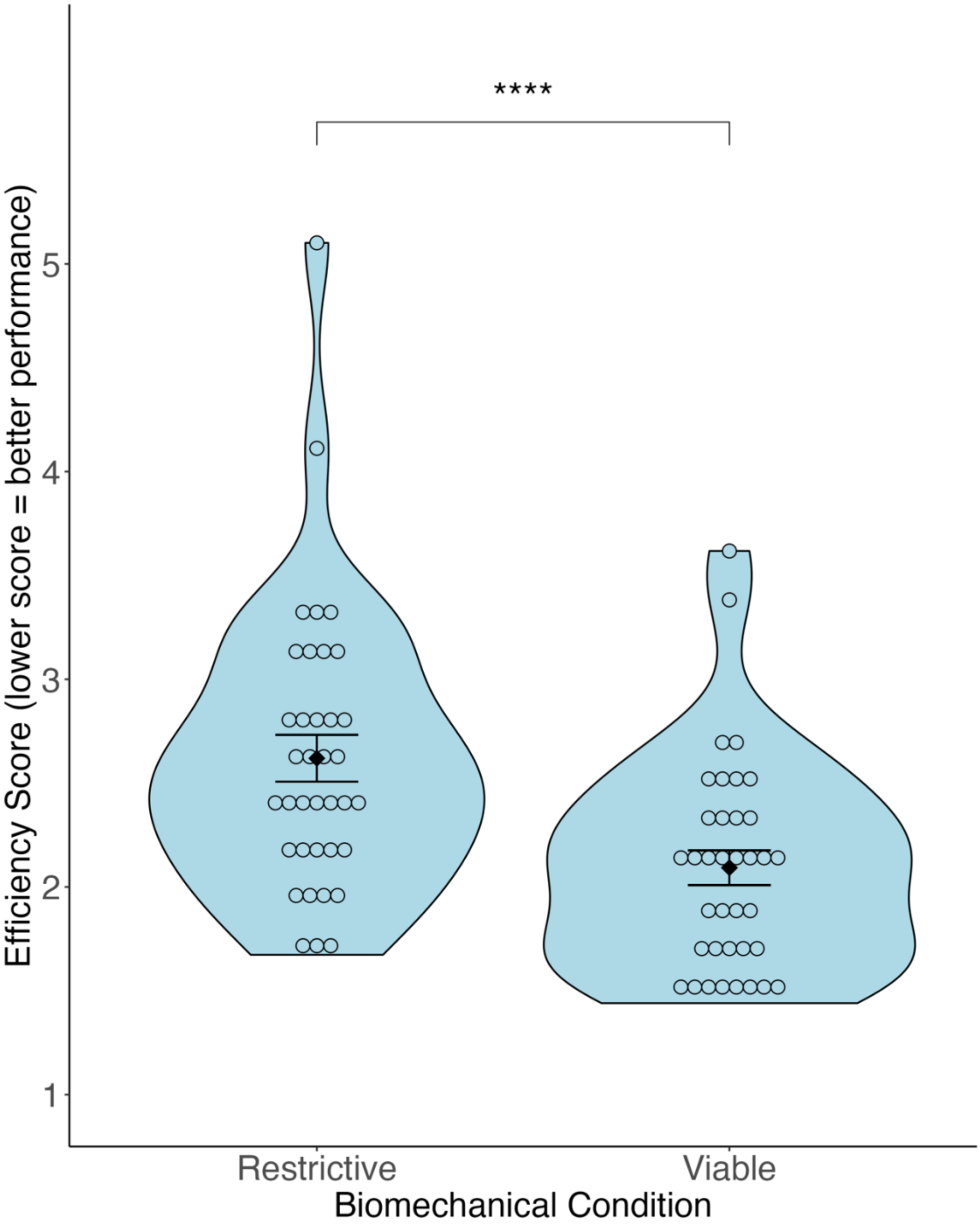

Figure 2.7. Violin plot of the mean efficiency scores on the Hand Laterality Judgement Task, split by biomechanical condition. The Restrictive group consists of rotations at 180 or 270, the Viable group consists of rotations at 0 or 90. The lower the score the better the performance. Coloured dots indicate individual data points and black diamonds indicate group mean. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ****=$p \leq .0001$.

Sensorimotor Integration task

A repeated measures ANOVA showed a significant main effect of delay; (*F*(1,183)=55.62, *p*<.001), with participants performing best in the 300ms delay condition and worst in the 50ms delay condition (see Figure 2.8). Four Bonferroni adjusted paired t-tests (α=0.125) revealed significant differences between 50 and 100ms; (*t*(36)=-5.59, *p*<.001), 100 and 150ms; (*t*(36)=-4.08, *p*=.01), and between 150 and 200ms; (*t*(36)=-4.22, *p*<.001). There was no significant difference between 200 and 300ms; (*t*(36)=-1.64, *p*=.12).

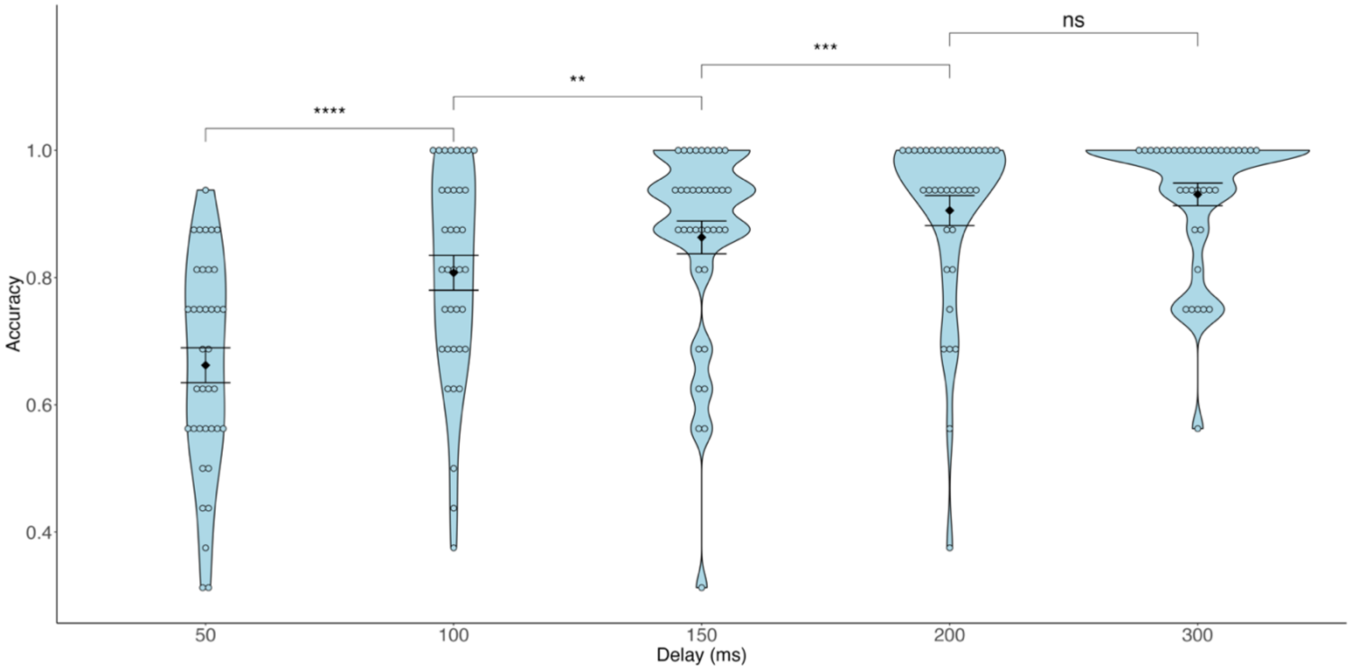

Figure 2.8. Violin plot of the mean accuracy for each delay on the sensory integration task. Coloured dots indicate individual data points and black diamonds indicate group mean. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ****=*p* ≤.0001, ***=*p* ≤ .001, **=*p*≤.01, *=*p*<.05, ns=non-significant.

Hypothesis 1: Self-related performance will be greater than other-related performance

Two Bonferroni-corrected paired samples t-tests ($\alpha=0.025$) showed a significant difference in d-prime scores between *Self* and *Stranger*; ($t(36)=5.66$, $p<.001$) but no significant difference between *Self* and *Friend*; ($t(36)=-1.49$, $p=.15$). Participants performed best in *Self* trials ($M=2.09$, $SD=0.97$), then the *Friend* trials ($M=1.90$, $SD=1.06$) and lastly *Stranger* trials ($M=1.44$, $SD=1.10$) (see Figure 2.9).

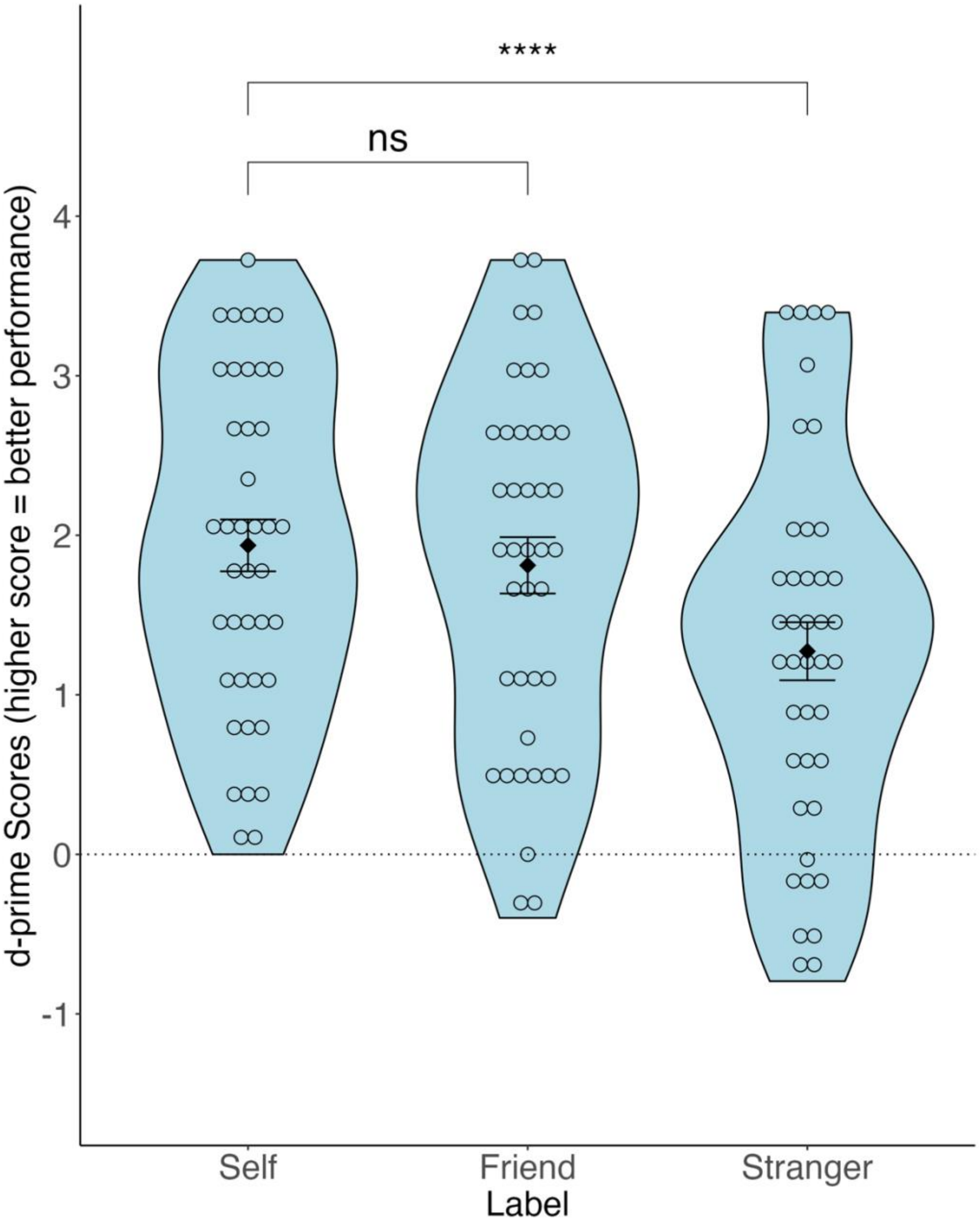

Figure 2.9. Violin plot of the mean d-prime scores for each label on the self-prioritisation task. Coloured dots indicate individual data points and black diamonds indicate group mean. The dotted line indicates chance performance on the SPT. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ****= $p \leq .0001$, ns=non-significant.

Hypothesis 2 and 3: Body schema and sensorimotor integration performance will predict self-related processing

The full model was a significantly better fit compared to the null and the simple main effects model, see Table 2.2 for model summaries and comparisons.

Table 2.2: Predictors of d-prime scores on the SPT. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	299.7	307.90	
Simple Main Effects (Null + Label, Body Schema, Sensorimotor Integration)	290.60	303.57	<.001 vs Null
Full (Simple Main Effects+ Label*Body Schema)	285.11	295.91	<.001 vs Simple Main Effects

The full model was the best fit for explaining variance in the d-prime scores on the self-prioritisation task, explaining 13.8% of the variance by fixed effects and 70.8% of the variance by random effects. The *Self* label was a significant predictor of SPT performance (*p*=.01), as was the stranger label (*p*=.032, 95% CI [-4.14, 0.58]). The interaction between the *Self* label and *Body Schema* performance (*p*=.01, 95% CI [-4.94, -0.23]) was a significant predictor of SPT performance, as was the interaction between the *Self* label and *Sensorimotor Integration* accuracy (*p*=.042, 95% CI [-1.04, 3.37]). The *Stranger* label also significantly interacted with *Body Schema* scores to predict SPT performance (*p*=.014). From Figure 2.10A it appears as though increasing *Body Schema* performance is related to, decreasing performance on the

Friend trials, whilst performance on *Self* and *Stranger* trials remains relatively stable. As such, it appears as though the divergence of performance on the *Friend* trials may be driving the significant interactions between *Self* and *Body Schema* performance and *Stranger* and *Body Schema* performance.

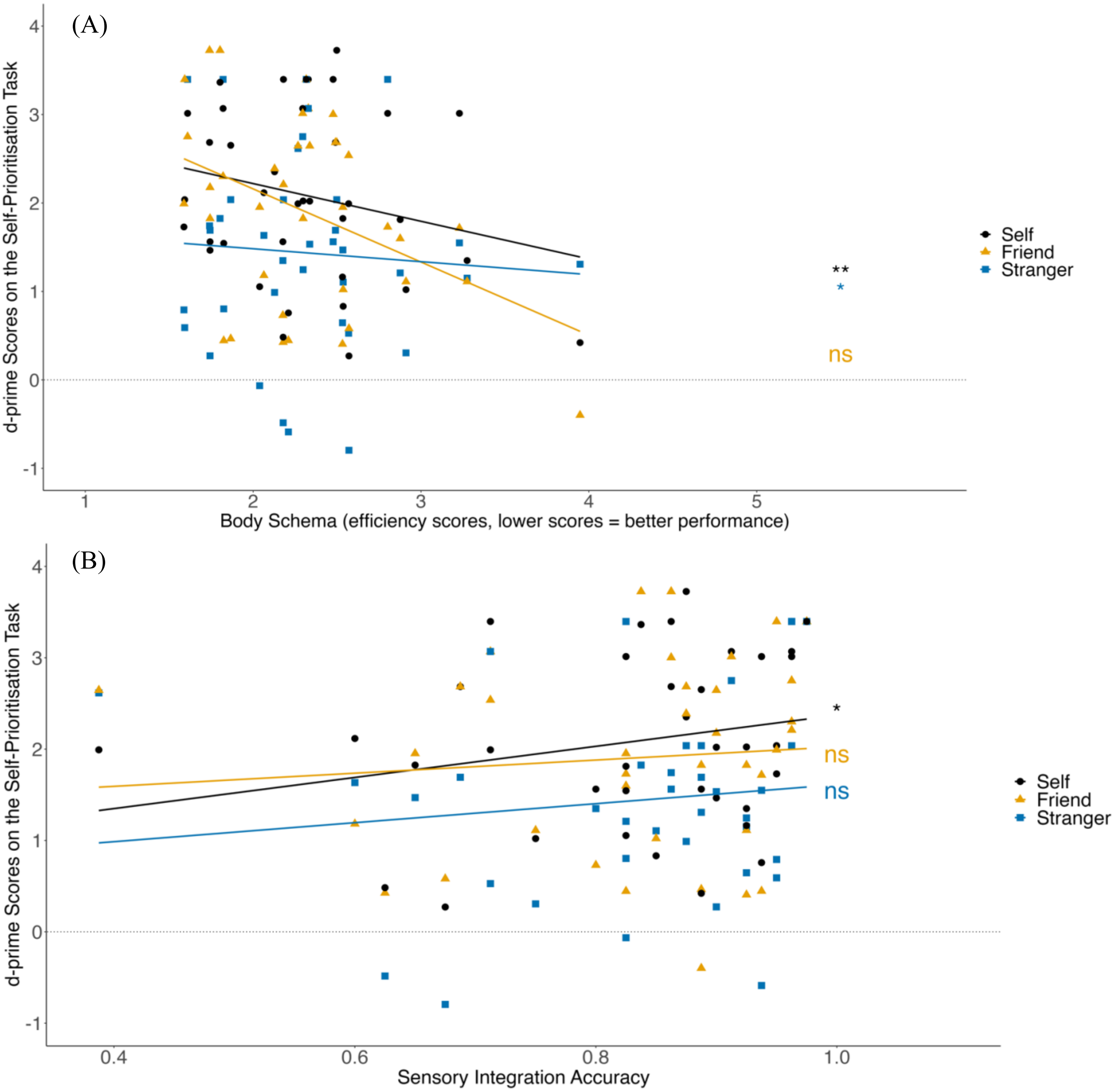

Figure 2.10. Plots showing (A) the relationship between *Body Schema* and (B) *Sensory Integration* accuracy on performance on *Self*, *Friend*, and *Stranger* trials on the self-prioritisation task. Annotations show the significance level of the interactions between each label and *Body Schema* or *Sensory Integration* from the LMM analysis. *=*p* ≤.05, **=*p*≤.01, ***=*p* ≤.001, ns=non-significant. The dotted line indicates chance performance on the SPT.

Standard error is not displayed graphically here to maintain clarity of results.

2.7 Discussion

We investigated the relationship between body schema, sensorimotor integration, and self-related processing. Similarly to *Study 1*, we found evidence that individuals exhibit a bias in performance for remembering self- and friend-related information compared to stranger-related information, as measured by d-prime scores (Hypothesis 1). Secondly, using LMM we found that a model including the interactions between *Body Schema* and *Label* and *Sensorimotor Integration* and *Label* significantly explained performance on the self-prioritisation task (Hypotheses 2 and 3).

In line with findings from *Study 1* (Hypothesis 1), we found that participants showed significantly better performance for remembering self-related information compared to stranger-related information. These findings are corroborated by previous research which has reliably demonstrated this self-prioritisation effect using the self-tagging paradigm (Sui et al., 2012; Sui & Gu, 2017; Sui & Humphreys, 2015b). However, contrary to previous work, we found no significant difference in d-prime scores between the self and friend trials of the self-tagging task. Similar to *Study 1*, we did find evidence of faster processing of self- compared to friend- or stranger-related information. Additional analysis revealed a significant difference in reaction times (ms) between self and friend; ($t(36)=4.23, p \leq .001$) and self and stranger; ($t(36)=--3.95$, $p \leq .001$) with participants performing faster in *Self* trials ($M=706.482$, $SD=120.456$) compared to *Friend* ($M=759.503$, $SD=112.057$) and *Stranger* ($M=770.951$, $SD=134.534$). Thus, participants did appear to exhibit a self-bias in the processing of basic perceptual information.

Hypothesis 3 was explored using LMM analysis, which revealed that a model including a significant interaction between *Sensorimotor Integration -Self* was the best fit for the d-prime score data. This finding provides evidence to suggest that visual-tactile-motor integration may contribute to the processing of self-related information (Hypothesis 3). We found no significant interaction between *Friend* or *Stranger* labels and *Sensorimotor Integration* accuracy, thus the ability to integrate sensory information appears to be uniquely related to self-processing. Sensorimotor integration is key to establishing a body schema (Blanke, 2012; Cowie et al., 2016, 2018; Newport et al., 2010; Newport & Gilpin, 2011; Riva, 2018; Tsakiris, 2017), thus the current finding provides evidence to suggest that integrating sensory information pertaining to the internal representation of the body (i.e., body schema), is related to how self-related information is processed. Thus, the current finding may provide evidence for the Bodily Self Consciousness model which stipulates that representations of the body can enhance the processing of self-related information (Park & Blanke, 2019).

This finding has important theoretical implications for how we understand the relationship between sensory processing and socialisation. Self-related processing is thought to be important for mentalizing (Lombardo et al., 2007), theory of mind and empathy (Dinulescu et al., 2021). As such, the current findings may suggest that the ability to integrate sensory information across multiple modalities might be associated with self-related processing and thus wider social cognition. Therefore, a disruption in sensory integration could account for potential difficulties with social skills such as ToM and empathy. To be able to understand the mental states of others, one must hold a clear distinction between themselves and others (Meltzoff, 2007; Tsakiris, 2017). Indeed, there is evidence of an overlap in the neural activation associated with engaging the self and understanding the mental states of others (Ames et al., 2008; Mitchell et al., 2005). Thus, there is a close relationship between representations of the self and understanding how others think. Concerning the current findings, an internal representation of the body built upon MSI may facilitate self-related processing, therefore further reinforcing this self-other distinction and promoting the understanding that others hold unique thoughts and emotions.

The current finding may be particularly important when understanding the social differences exhibited in autism. Previous work has demonstrated how autistic adults show differences in multisensory integration (Cascio et al., 2012; Greenfield, 2015; Greenfield et al., 2017), which may therefore contribute to differences in self-related processing and wider social cognition. Further work is needed to explore whether individual differences in sensory integration in autism may contribute to self-related processing and associated social processing.

As in *Study 1*, LMM was utilised to explore Hypothesis 2. The model predicting d-prime scores on the SPT showed that the interaction between the *Self* label and *Body Schema* and the interaction between the *Stranger* label and *Body Schema* were significant predictors in the model. Contrary to the results found in *Study 1* (Hypothesis 2), this finding suggests that body schema is not uniquely driving self-related processing, but also other-related processing. To truly understand this finding, it is important to check that the HLJT was evaluating the ability to perform embodied mental rotations of the self, and thus body schema. In the current study, visual rotation of the hand stimuli was found to significantly impact performance, which suggests that participants were using an embodied motor imagery strategy to evaluate the handedness of the stimuli. Therefore, the lack of a unique relationship between body schema performance and self-related processing is unlikely to be attributed to the HLJT not measuring embodied motor imagery.

Alternatively, the significant interactions found in the modelling analysis may be driven by the relationship between friend-related processing and body schema. Considering Figure

2.10A, the regression line of the *Friend* trials intercepts both the *Self* and *Stranger* regression lines, perhaps suggesting that *Body Schema* is related to improved performance on the *Friend* trials of the SPT. This is supported by further analyses that found a significant correlation between d-prime scores on the friend trials of the SPT and efficiency scores on the body schema task ($r(35)=-0.397$, $p=.0149$). Such that increasing performance on the body schema task (lower efficiency scores) corresponds to better performance on the SPT (greater d-prime scores). Moreover, there was no significant relationship between self-related processing and body schema; ($r(35)=-.225$, $p=.182$) or stranger-related processing and body schema; ($r(35)=-.0678$, $p=.690$). Consequently, the findings in the current study appear to show that body schema ability may correspond to the processing of friend-related information. This may suggest that internal representations of the body are activated in the processing of information of closely related others. This finding partially corresponds to previous research which demonstrated that self- and friend-related stimuli activate an embodied representation of the self that is coded from a first-person perspective (Sun et al., 2016). However, we did not find the same result for self-related information, so the current findings do not wholly align with the results from Sun and colleagues (2016).

Nevertheless, the current findings may provide evidence to suggest that a close friend can be linked to an individual's own representation such that friend-related information is incorporated into an embodied representation of the self. Subsequently enhancing attention to the friend-related stimulus. Indeed, research has demonstrated that friend-related information is typically preferentially processed and remembered compared to stranger-related information (Humphreys & Sui, 2015; Sui et al., 2012; Sui & Humphreys, 2017). Together, these findings may provide a mechanism to explain how socially salient information is attended to. However, as *Study 1* and *2* present different findings, further work may be needed to disentangle the mechanisms of self- and friend-related processing.

Considering the discrepancy in the current findings from *Study 1*, it is important to consider the appropriateness of using mixed linear modelling. Through visual inspection of a quantile-quantile (QQ) plot (Appendix 2.3), the data appears skewed which may reduce the insight that linear modelling can offer. However, additional analysis using robust modelling which is designed to account for skewed data (Lachos et al., 2009) similarly showed that a full model with the significant interactions of *Body Schema* and *Self* trials, *Body Schema* and *Stranger* trials, and *Sensorimotor Integration* accuracy and *Self* trials, was the best fit for the data (see Appendix 2.4). Moreover, from Figure 2.10A it appears as though two participants whose performance on the HLJT was greater than 3.5 are driving the skew in data. However, removing these two participants from the modelling analysis gives the same modelling result and the same pattern of data (see Appendix 2.5). Thus, it does not appear that the skewed pattern of the data and the statistical protocol could account for the current findings.

2.8 General Discussion

We examined the relationship between body schema, sensorimotor integration, and self-related processing in neurotypical adults. Across both studies, we found evidence of a self-bias effect in perceptual processing as has been found previously (Sui et al., 2012; Sui & Gu, 2017; Sui & Humphreys, 2015b, 2017). We found evidence of a relationship between body schema and self-related processing in *Study 1*. In *Study 2*, we found evidence of a predictive relationship between visuo-tactile-motor integration ability and self-related processing.

The discrepancy in results between *Study 1* and *Study 2* regarding the relationship between body schema and self-related performance may be attributable to the different demographics of the participants. For example, in *Study 1* participants were mainly women, whilst in *Study 2* most participants were men. Work has found that men and women may engage different motor processes when completing the hand laterality judgement task (Conson et al., 2020). Indeed, performance was overall better (lower efficiency scores) and less variable in *Study 2* (*M*=2.37, *SD*=0.91) than in *Study 1* (*M*=2.74, *SD*=1.60). Moreover, when judging the backs of hands, women are found to exhibit a biomechanical effect, but men are not (Conson et al., 2020). This suggests that men may not use an embodied motor imagery strategy when evaluating the handedness of back-facing hands. In the current study half of the trials on the hand laterality task were images of the back of hands, therefore, men may have been less likely to engage a motor imagery strategy in 50% of trials. Thus, the task may not be measuring body schema in men. However, a group-level biomechanical effect was observed in *Study 2* despite the majority of participants being men. Consequently, it is unlikely that differences in the results of *Study 1* and *2* can be attributed to gender differences in the samples.

Alternatively, the discrepancy in results between *Study 1* and *2* may be due to language differences between the samples. The majority of participants in *Study 1* were White British whereas in *Study 2* there was a much greater representation of individuals from Eastern Europe, particularly Poland. Therefore, the study instructions being given in a second language in *Study 2* could have affected comprehension of the procedure. For example, participants were instructed to keep their non-dominant hand on their lap or table throughout testing and to keep their dominant hand on the keyboard to respond. However, if this instruction was not followed during the HLJT, participants may have used their hands to evaluate the laterality of the hand stimulus. Therefore, whilst a biomechanical effect may be present in the data, it may reflect the use of self-generated actions of the hands and not motor imagery. As such, future research would benefit from utilising in-person research methods in which task strategy and instruction comprehension could be monitored.

Although this study has made novel findings to improve the understanding of embodied self-related processing, it is not without limitations. As the study was conducted online, it is difficult to ensure that all participants followed instructions correctly and maintained attention. However, all participants included in the analyses in *Study 1* and *Study 2* passed the attention check and all participants completed the study in an appropriate time. Additionally, all tasks were confirmed to have construct validity as the SPT revealed a significant self-bias effect, the body schema task revealed a significant biomechanical effect, and the *Sensorimotor Integration* task showed a significant effect of temporal delay. However, some participants completing the SPT in Study 1 and 2 may have not fully grasped the task as they had d-prime scores close to or less than 0. Thus, indicating that in some conditions, participants may have been randomly responding (d-prime=0) or may have been incorrectly accepting incorrect pairs and rejecting correct pairs (d-prime=negative value). However, any participants with a d-prime score of 0 or less in more than one SPT condition was excluded from the analysis, therefore reducing the impact of participants not understanding the task.

Conclusions

Together, the findings from *Study 1* and *Study 2* suggest that an internal representation of the body, built upon multisensory integration, may be implicated in self-referential perceptual processing. As such, how the brain integrates sensory and motor information to hold a representation of the body may be important for how we understand the thoughts and emotions of others. The current research adds to a growing body of literature revealing the relationship between body schema, sensorimotor integration, and social processing. These findings may serve as a foundation for future research to understand the contribution of sensorimotor processes in how the self is conceptually represented in social interactions.

Chapter Introduction

Findings from Chapter 2 suggest that an internal representation of the body, built upon multisensory integration may be implicated in self-referential perceptual processing. Crucially, results give a theoretical foundation to suggest that processing self-related information could be an embodied process. As research has found autistic individuals may integrate their senses and represent their bodies differently, Chapter 3 will seek to understand if sensorimotor processing explains variability in self-referential effects in autism.

Chapter 3: The Role of Body Schema and Sensorimotor Integration in Self-Related Processing in Autistic Adults

Abstract

Autism is characterised by differences in social processing, and it has been theorised that these differences may be due to a different conceptualisation of the self. Insight into conceptual self-awareness can be gained from research investigating self-referential effects. Research has suggested that self-referential processing might be an embodied process underpinned by an internal representation of the body. Indeed, findings from Chapter 2 of the current thesis suggest that self-related processing could be related to how the body is internally represented and how sensory information is integrated. Early research findings have claimed that self-referential processing might be diminished in autism, however recent research has disputed this. Thus, the current study sought to clarify whether the prioritisation of self-related information is diminished in autistic adults. Moreover, we aimed to investigate whether the body schema and sensorimotor integration are associated with self-related processing in autism. In line with our first hypothesis, we found evidence that autistic adults exhibit self-prioritisation in a perceptual tagging task. This finding counters previous theories which proposed diminished self-referential processing and self-awareness as explanations of social differences in autism. Contrary to our second hypothesis, we found that body schema and

sensorimotor integration ability do not appear to be associated with self-related processing in autistic adults. Whilst this finding may suggest that autistic individuals are less likely to utilise embodied strategies when processing self-related information, we found no difference in body schema or sensorimotor integration performance between autistic and non-autistic participants. Future research is therefore needed to explore whether embodied mechanisms, which rely on sensorimotor integration and the body schema, underly self-related processing and associated social behaviours in autistic and non-autistic populations.

3.1 Introduction

Understanding the intentions, beliefs, and needs of others is a key aspect of socialising. To do this, one must have a stable sense of self to be able to use as a comparison point (Meltzoff, 2007). Moreover, this relates to self-awareness in which one can actively identify, process, and store information that relates to the self (Duval & Wicklund, 1972). It is this awareness of the internal representation of self which allows us to understand that our mental states are distinct from the mental states of others. Indeed, self-awareness is related to Theory of Mind (ToM), the ability to understand the mental states of others (Gallagher & Frith, 2003), and empathy (Dinulescu et al., 2021). As such, self-awareness may be important for wider social cognition (Malle, 2012).

Experimentally, insight into self-awareness can be gained through examination of how humans internally represent the self and how this influences how information is processed, perceived, and remembered. Indeed, self-referential memory is the idea that individuals have a natural propensity to remember information that relates to the self (Rogers et al., 1977). Several studies have demonstrated that recall and recognition of information related to the self are superior compared to other-related information (Rogers et al., 1977; Symons et al., 1997).

Moreover, people are faster to respond to images of their own face compared to others' faces, even when the goal of the task is to make judgements about orientation (Keenan et al., 1999; Keyes & Brady, 2010; Sui, Chechlacz, & Humphreys, 2012; Sui, Liu, & Han, 2009). Such findings extend to basic perceptual processing. In a shape-label matching paradigm, where participants learn pairs of person-related labels (i.e., self, friend, and stranger) and simple geometric shapes (i.e., circle, square, and triangle), participants are faster and more accurate at responding to self-related pairs compared to friend or stranger (Sui et al., 2012, Sui & Humphreys, 2015b). It is thought that this prioritisation of self-related information facilitates social processing by leading to an accurate construct of the self, allowing us to read the emotions and thoughts of others (Decety & Lamm, 2006). Therefore, an investigation into how individuals process self-related information can provide important insight into the links between self-awareness and social processing.

Autism is most commonly characterised by differences in social processing (American Psychological Association, 2013), these differences may be due to a different conceptualisation of the 'self' (Frith & Happe, 1994; Frith, 2003; Lombardo & Baron-Cohen, 2010; Uddin, 2011). It has been argued that autistic individuals may have reduced self-awareness and thus reduced ability to understand the mental states of others (Frith & Happe, 1994; Frith, 2003). To test this theory, self-reference effects have been explored in autism. If autistic individuals exhibit differences in self-related processing, this may explain variability in self-awareness and social processing.

Evidence in favour of an atypical self-awareness in autism has been demonstrated using a self-referential memory paradigm (Lombardo et al., 2007). In this task, participants were required to associate trait adjectives (i.e., kind) with either themselves, a close friend, or a non-close other. Participants were then presented with these trait adjectives in addition to new ones and were asked to decide if the trait adjectives were new or old. Compared to neurotypical individuals, autistic individuals showed a reduced bias for self-attributed traits. Interestingly, individual differences in the size of the self-bias effects were related to mentalizing ability and the number of autistic traits. As such, the authors argued that differences in self-referential cognition in autism are intrinsically linked to core features of autism and social processes such as empathy. However, Lombardo and colleagues did not actually find significant group differences in the size of the self-bias effect, both autistic and non-autistic participants exhibited significant self-referential memory effects. This suggests that whilst self-related processing may relate to mentalising and autistic traits, self-related processing may not be diminished in autistic adults.

Typical self-referential processing has been further evidenced in more recent work, which found no significant difference in the size of self-reference effects between neurotypical and autistic individuals and no relationship between the number of autistic traits and the size of the self-bias (Lind et al., 2019). This discrepancy in results could be attributable to the different tasks used in the studies. In Lombardo and colleagues' (2007) study, participants were required to make explicit self-evaluative judgments about themselves to pair adjective traits with either themselves or another person. It could therefore be argued that autistic individuals only show a diminished self-reference memory when the self must be explicitly thought about and evaluated during the encoding phase of the task. Experimentally, this can be tested using incidental self-processing tasks. Indeed, across three experiments Lind and colleagues (2019) found no evidence of a diminished implicit *or* explicit self-reference effect in autistic individuals. This has been further supported by work utilising the shape-label matching paradigm outlined above (which is similarly thought to tap into an implicit level of self-related processing), which found no difference in the magnitude of self-bias between autistic and non-autistic individuals (Williams et al., 2018). Additional studies using this same shape-label matching task have found no relationship between self-bias processing and autistic traits in a neurotypical population (Dinulescu et al., 2021; Nijhof et al., 2020). Collectively, this more recent work would suggest that autistic individuals prioritise information related to the self similarly to neurotypicals.

Importantly, research has suggested that self-related processing may be an embodied process which relies on an internal representation of the body. Work has found that self- and friend-biases in a perceptual matching task can be boosted when presented on stimuli which align with the participant's body and perspective (Sun et al., 2016). The authors argue it is a bodily representation of self, grounded within a first-person perspective that drives the prioritisation of self- and friend-related information. Further work has found that the processing of conceptual information related to the self is affected by the experience of self-location (Canzoneri et al., 2016), which is a key component of the body schema (Riva, 2018). In turn, multisensory integration (MSI) – the process of combining sensory information to compute a representation of the world is key for establishing a body schema (Blanke, 2012; Riva, 2018; Tsakiris, 2017). Findings from Chapter 2 of the current thesis may suggest that the body schema and visuo-tactile-motor integration are associated with self-referential processing. Therefore, there is evidence to suggest that in non-autistic adults, self-referential processing is linked to internal representations of the body which are formed through MSI. However, it is unknown if similar links between the conceptual self and the bodily self are exhibited in the self-referential processing of autistic adults. This is particularly important to consider as autistic individuals show differences in how they internally represent their bodies and how they integrate sensory information.

Research has demonstrated how autistic individuals may experience differences in how sensory information is integrated (Iarocci & McDonald, 2006). Autistic individuals exhibit differences in visuo-auditory and (Iarocci & McDonald, 2006; Marco et al., 2011) visuo-tactile-proprioceptive integration (Greenfield et al., 2015) as well as differences in integrating sensory inputs with motor system inputs (see Hannant et al., 2016). Such differences in MSI can impact how the body is represented, indeed visual, tactile, and proprioceptive MSI are particularly important as they underly the formation of the body schema (Nava et al., 2014; Schütz-Bosbach et al., 2006). Internal representations of the body are thought to be implicated in embodied social processes such as empathy (Grynberg & Pollatos, 2015) and visual perspective-taking (Kessler & Thomson, 2010; Pearson et al., 2014; Surtees et al., 2013a, 2013b). As such, understanding the links between sensory and motor integration, internal representations of the body and self-referential effects, may provide insight into whether self-related processing is embodied. Importantly, such investigation may also elucidate the role of sensorimotor integration and internal body representations in social differences exhibited in autism. In light of this, the current study will aim to investigate the links between sensorimotor integration, body schema, and self-related processing in autistic adults.

Taken together, the present study aimed to investigate the relationship between sensorimotor integration, body schema and self-related processing in autistic and non-autistic individuals. Using the perceptual shape-label matching task (Sui et al., 2012), the hand laterality judgement task and a novel sensorimotor integration task (as used in Chapter 2), we aimed to determine whether visuo-tactile-motor integration and body schema predict self-related processing. Based on previous research (Lind et al., 2019; Sui & Gu, 2017; Sui & Humphreys, 2015, 2017; Williams et al., 2018), we predicted that both autistic and non-autistic individuals will show a bias in performance for self-related information (Hypothesis 1). Secondly, we predicted that greater sensorimotor integration and body schema performance will positively relate to self-bias in autistic and non-autistic adults (Hypothesis 2). In other words, individuals with poorer visuo-tactile-motor integration and a less optimal body schema will show reduced self-related processing.

3.2 Methods

Participants

Forty-one autistic adults (24 women, 6 men, 9 non-binary, M_{age}=28.68 years, *SD*=9.61, 2 missing demographic data) and thirty-nine non-autistic adults (28 women, 9 men, 1 non-binary, 1 missing demographic data, M_{age}=27.95 years, *SD*=7.21) took part in the study. While simulative a priori power analysis suitable for linear mixed modelling was not conducted, a target sample size of 80 participants was set for recruitment. All participants reported having normal or corrected-to-normal vision. Informed consent was obtained before the experiment according to procedures approved by the University of Nottingham, School of Psychology ethics committee (approval number: S1287R). Six participants (4 autistic, 4 non-autistic) were removed from the sample due to performance errors (see Data Analysis section for further details). Therefore, the final sample consisted of thirty-five autistic adults (20 women, 5 men, 9 non-binary, M_{age}=28.71 years, *SD*=9.0, 1 with missing demographic data) and thirty-seven non-autistic adults (27 women, 8 men, 1 non-binary, missing demographic data, M_{age}=28.12 years, *SD*= 7.40), see Table 3.1 for a summary of demographic information for autistic and non-autistic participants.

Participants were recruited online through social media accounts and local autism support organisations. Two autistic consultants provided guidance on the tasks and procedure of the current study, including task instructions, the choice of questionnaires used, and the procedural flow of the study. Women and non-binary individuals were particularly encouraged to participate in the study to increase their representation in autism research (Lai et al., 2015;

Loomes et al., 2017; Philip et al., 2012), however, autistic men were still accepted to take part. The autistic group was recruited first followed by the non-autistic group. Attempts were made to match groups based on age, gender, and education level. In the autistic group, 12 participants (34.2%) completed higher or secondary education, 14 (40%) completed college or university and 8 (22.9%) completed post-graduate degrees (1 participant with missing data). In the non-autistic group, 22 participants (59.5%) completed college or university, and 14 (37.8%) completed postgraduate degrees (1 participant with missing data).

Table 3.1. Demographic information for autistic and non-autistic participants.

	Autistic (N=35)	**Non-autistic (N=37)**
Age mean (sd)	28.71 (9.0)	28.12 (7.40)
Gender		
Women	20	27
Men	5	8
Non-binary	9	1
***Education** n (%)*		
Higher or secondary	12 (34.2)	0
College of university	14 (40)	22 (59.5)
Postgraduate degree	8 (22.9)	14 (37.8)

Of the autistic group, twenty-seven participants reported having received a clinical diagnosis of autism and seven reported as self-identifying as autistic. Participants completed the Ritvo Autism and Asperger Diagnostic Scale-14 (RAADS-14) (Eriksson et al., 2013), the Autism Quotient-10 (AQ-10) (Allison et al., 2012) and the Camouflaging Autistic Traits Questionnaire (CAT-Q) (Hull et al., 2019). The RAADS-14 and AQ-10 were included to capture clinical levels of autistic traits and the CAT-Q was used to ascertain levels of masking of autistic behaviours. The latter was particularly important to include to provide a measure of masked autistic behaviour as autistic women typically show higher levels of camouflaging behaviour (Beck et al., 2020). Shorter versions of the AQ and RAADS questionnaires were utilised as an autistic consultant indicated that there is a preference for shorter questionnaires amongst autistic individuals and experimentally both the AQ-10 and RAADS-14 have been shown to be internally consistent and robust (Allison et al., 2012; Eriksson et al., 2013). Mean scores for these measures for the self-identified autistic, clinically diagnosed autistic, and non-autistic participants can be seen in Table 3.2. There was no significant difference in score between the self-identified and clinically diagnosed groups for the AQ-10; ($t(33)=-1.39$, $p=.18$), CAT-Q; ($t(33)=-1.06$, $p=.32$), or RAADS-14; ($t(33)=0.84$, $p=0.42$). There was a significant difference between the autistic (self-identified or clinically diagnosed) and non-autistic group for AQ-10; ($t(70)=3.65$, $p<.001$), CAT-Q; ($t(70)=8.74$, $p<.001$) and RAADS-14; ($t(70)=16.6$, $p<.001$), with autistic participants scoring higher in each scale (see Table 3.2).

Table 3.2. Mean AQ-10, RAADS-14 and CAT-Q scores for participants self-identified and clinically diagnosed as autistic. Clinical threshold for each scale shown in parentheses.

	AQ-10 (6)		**RAADS-14 (14)**		**CAT-Q (100)**	
	Mean	SD	Mean	SD	Mean	SD
Self-identified as autistic	4.86	0.690	22.1	2.97	50.1	9.53
Clinical diagnosis of autism	4.37	1.21	23.2	2.76	46.0	7.52
Non-autistic	3.41	1.32	5.57	5.67	27.76	10.37

Materials and Measures

The same stimuli, tasks, and data analysis procedures were utilised in the current study as used in *Study 2*, Chapter 2 of the current thesis, with the following amendments.

Sensorimotor Integration Task

To ensure individual differences in working memory did not account for performance on the sensorimotor integration task, participants also completed a simple working memory task. Participants viewed two geometric shapes that were presented sequentially and were required to judge whether the first or the second shape was the biggest. The same interstimulus intervals were used in this task as in the sensorimotor integration task. Accuracy in the working memory control trials was evaluated and revealed all autistic participants achieved 80% or higher accuracy and all non-autistic participants achieved 70% or higher.

Procedure

Participants were recruited online through social media accounts and local autism support organisations. Participants completed the entire study online on a laptop or desktop computer without the online presence of a researcher. Participants completed the experimental tasks via Pavlovia and the questionnaires were completed via Qualtrics. The task order was randomised for each participant. The questionnaires were always administered last. There were no effects of task order or SPT version (label-shape pairs, e.g., triangle-self or square-self) on SPT, HLJT, or sensorimotor integration task performance (see Appendix 3.1). The total testing time was approximately 40 minutes.

Data Analysis

In the self-prioritisation and body schema tasks, reaction times less than 200ms were filtered to remove anticipatory responses. If a participant had more than half of their experimental trials removed due to anticipatory responses, they were removed from the analysis. Six participants (four autistic, two non-autistic) were subsequently removed from the analysis. Two further autistic participants were removed from the analysis due to having d-prime scores ≤0 in more than one SPT condition.

Manipulation checks for the HLJT and sensorimotor integration task were performed. A paired samples t-test was used to assess the difference in efficiency scores between biomechanically viable and restrictive stimuli. Significantly better performance in the viable condition evidences a biomechanical effect. In the sensorimotor integration task, a repeated measures ANOVA was conducted to check that accuracy increases as the delay between participant keypress and visual stimulus increases. Additionally, group comparisons (autistic and non-autistic) were made as performance in both the HLJT, and sensorimotor integration tasks would be expected to be reduced in the autistic group. Therefore, independent samples t-tests were conducted to evaluate group differences in the HLJT and sensorimotor integration data. Significantly better performance in the non-autistic group may evidence task construct validity.

Linear Mixed Modelling

Mixed-effect models were run using the lme4 package in R (R Core Team, 2022) to understand the predictive relationship of *Body Schema* and *Sensorimotor Integration* on self-prioritisation. A full model was constructed for each group (autistic or non-autistic) that included the predictors of *Label* (*Self*, *Friend*, or *Stranger*), *Sensorimotor Integration* (accuracy), and *Body Schema* (efficiency scores). The full models also included interactions between *Label*, *Body Schema*, and *Sensorimotor Integration*. The full models included random intercepts for participant ID to account for the nested structure of the data. The null models consisted of only the random effect of participant ID. For each group, the model fit of the full and null model was assessed using an analysis of variance (ANOVA). If the full model was a significantly better model fit compared to the null model, then the full model was compared to a simple main effects model (full model without the interactions) to ascertain the contribution of the interaction.

3.3 Results

Manipulation Checks

Hand Laterality Judgement Task

Autistic Group

A paired samples t-test revealed a significant difference between the biomechanical conditions; (*t*(34)=-3.45, *p*=.002), with participants performing better (lower efficiency scores) in the *Viable* condition (0° and 90° rotation) (*M*=2.15, *SD*=0.66) compared to the *Restrictive* condition (180° and 270° rotation) (*M*=3.06, *SD*=1.77). Thus, evidencing a group-level biomechanical effect, indicating an embodied motor strategy was utilised (see Figure 3.1). Through visual inspection of Figure 3.1, an outlier can be identified in the *Restrictive* biomechanical condition. However, removing data for this participant did not alter the t-test result; (*t*(33)=-5.63, *p*<.001), performance remained better (lower efficiency scores) in the *Viable* condition (0° and 90° rotation) (*M*=2.13, *SD*=0.66) compared to the *Restrictive* condition (180° and 270° rotation) (*M*=2.81, *SD*= 0.96). Moreover, this participant's overall efficiency score was not identified as an outlier, therefore they were not excluded from the main analyses.

Non-autistic Group

An independent samples t-test revealed no significant differences in *Body Schema* scores between the autistic (*M*= 2.41, *SD*=0.67) and non-autistic group (*M*=2.21, *SD*=0.51); (*t*(72)=1.46, *p*=.15). Therefore, evaluation of the biomechanical effect was made across both groups together. A paired samples t-test revealed a significant difference between the biomechanical group (*t*(36)=-6.01, *p*<0.001), with participants performing better (lower efficiency scores) in the *Viable* condition (0° and 90° rotation) (*M*=1.98, *SD*=0.50) compared to the *Restrictive* condition (180° and 270° rotation) (*M*=2.59, *SD*=0.76). Thus, evidencing a sample-level biomechanical effect, indicating an embodied motor strategy was utilised (see Figure 3.1).

Group Differences

A mixed ANOVA showed no significant effect of *Group* (autistic or non-autistic) on efficiency scores on the HLJT; ($F(1,70)=2.19$, $p=.14$), and no significant interaction between *Group* and *Biomechanical Condition* (*Viable* or *Restrictive*); ($F(1,70)=1.15$, $p=.29$). Performance in the autistic and non-autistic group on the HLJT therefore appears comparable.

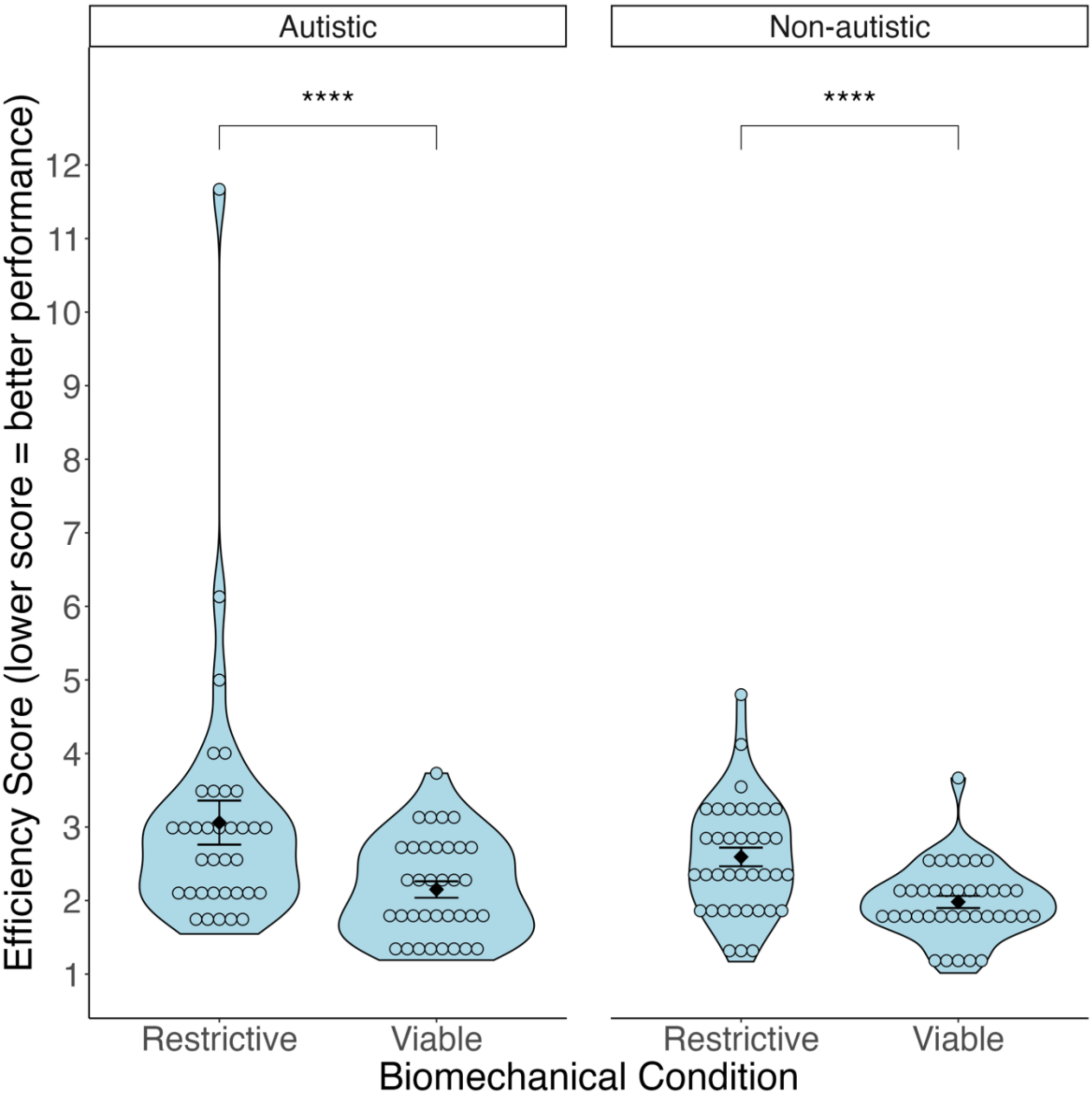

Figure 3.1. Violin plot showing the mean efficiency scores on the Hand Laterality Judgement Task, split by *Biomechanical Condition* for the autistic and non-autistic participants. The *Restrictive* condition consists of rotations at 180° or 270°, the *Viable* condition consists of rotations at 0° or 90°. The lower the score the better the performance. Coloured dots indicate individual data points and diamonds indicate group mean. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ****=$p \leq .0001$, ns= non-significant.

Sensorimotor Integration Task

Autistic Group

A repeated measures ANOVA revealed a significant main effect of delay on Sensorimotor Integration accuracy; (*F*(4,168)=76.64, *p*<.001). Four Bonferroni adjusted paired t-tests (α=0.0125) revealed significant differences between 50 and 100ms; (*t*(34)=-4.42 p<.001), between 100 and 150ms; (*t*(34)=-3.55, *p*=.004) and between 200 and 300ms; (*t*(34)=-2.27, *p*=.043). There was no significant difference between 150 and 200ms; (*t*(34)=-1.49, *p*=.15) (see Figure 3.2).

Non-autistic Group

A repeated measures ANOVA revealed a significant main effect of delay on Sensorimotor Integration accuracy; (*F*(4,183)=51.15, *p*<.001). Four Bonferroni adjusted paired t-tests (α=0.0125) revealed significant differences between 50 and 100ms; (*t*(36)=-4.67, *p*<.001) and between 100 and 150ms; (*t*(36)=-3.87, *p*=.0092). There was no significant difference between 150 and 200ms; (*t*(36)=-2.00, *p*=.12) or 200 and 300ms; (*t*(36)=-.734, *p*=.47) (see Figure 3.2).

Group Differences

A mixed ANOVA showed a significant main effect of delay (ms); (*F*(2.80,193.17)=85.74, *p*<0.001) on accuracy in the *Sensorimotor Integration* task. There was no interaction between group and delay on sensorimotor integration accuracy; (*F*(2.8,193.17)=1.55, *p*=.21). In addition, an independent samples t-test showed no significant difference in overall (across all delays) *Sensorimotor Integration* accuracy scores between the autistic (*M*=0.80, *SD*=0.16) and non-autistic group (*M*=0.82, *SD*=0.11); (*t*(70)=-.64, *p*=.53).

Performance on the *Sensorimotor Integration* task therefore appears comparable in the autistic and non-autistic groups.

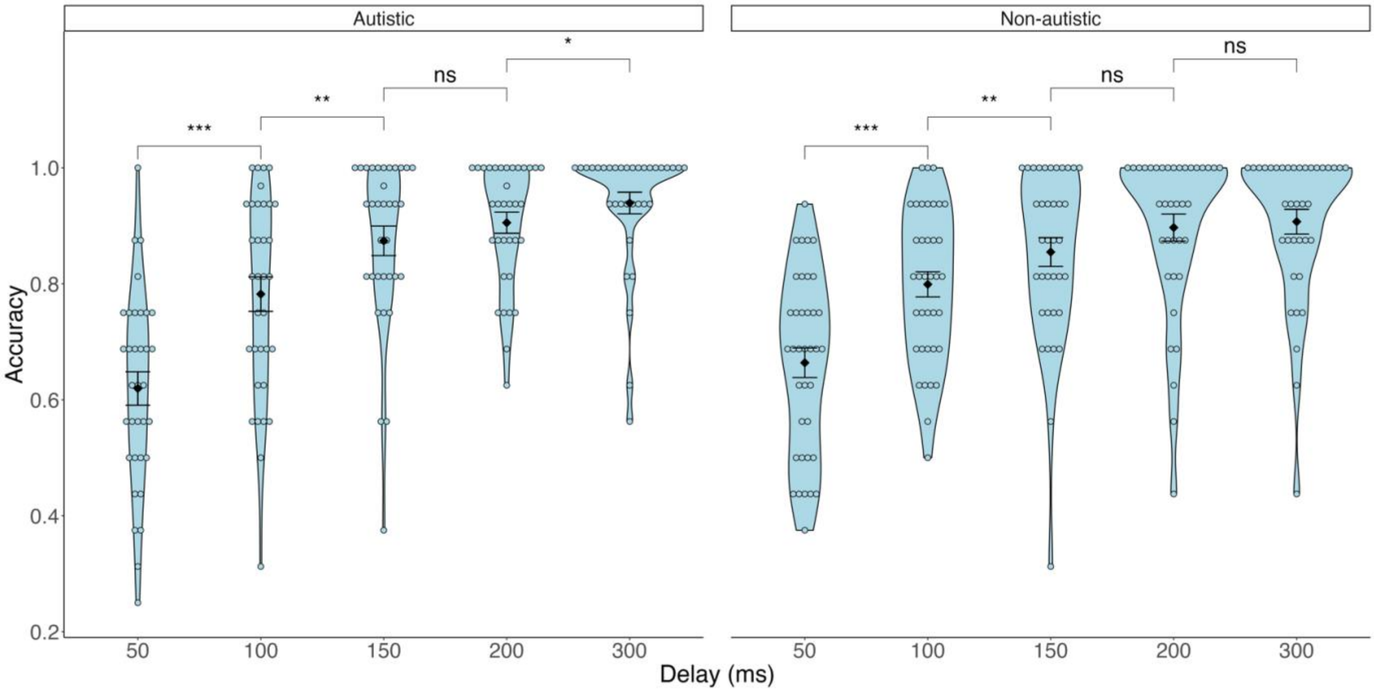

Figure 3.2. Violin plots showing the mean accuracy for each delay on the sensory integration task for autistic and non-autistic participants. Coloured dots indicate individual data points and black diamonds indicate group mean. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ***=$p \leq .001$, **=$p \leq .01$, *=$p < .05$, ns=non-significant.

Hypothesis 1: Self-related performance will be greater than other-related performance

Autistic Group

Two paired samples t-tests showed significant differences in d-prime scores in the autistic group between *Self* and *Friend*; (*t*(34)=-2.58, *p*=.029) and between *Self* and *Stranger*; (*t*(34)=2.78, *p*=.026), with autistic participants performing better in *Self* trials (*M*=2.87, *SD*=0.68) compared to *Friend* (*M*=2.48, *SD*=0.92) and *Stranger* (*M*=2.39, *SD*=1.08) (see Figure 3.3).

Non-autistic group

Two paired samples t-tests showed no significant differences in d-prime scores in the non-autistic group between *Self* and *Friend*; (*t*(36)=.97, *p*=.34) or *Self* and *Stranger*; (*t*(36)=2.08, *p*=.09). Participants performed best in *Friend* trials (*M*=2.80, *SD*=0.70), then *Self* trials (*M*= 2.65, *SD*=0.79), and lastly *Stranger* trials (*M*=2.34, *SD*=0.83) (see Figure 3.3).

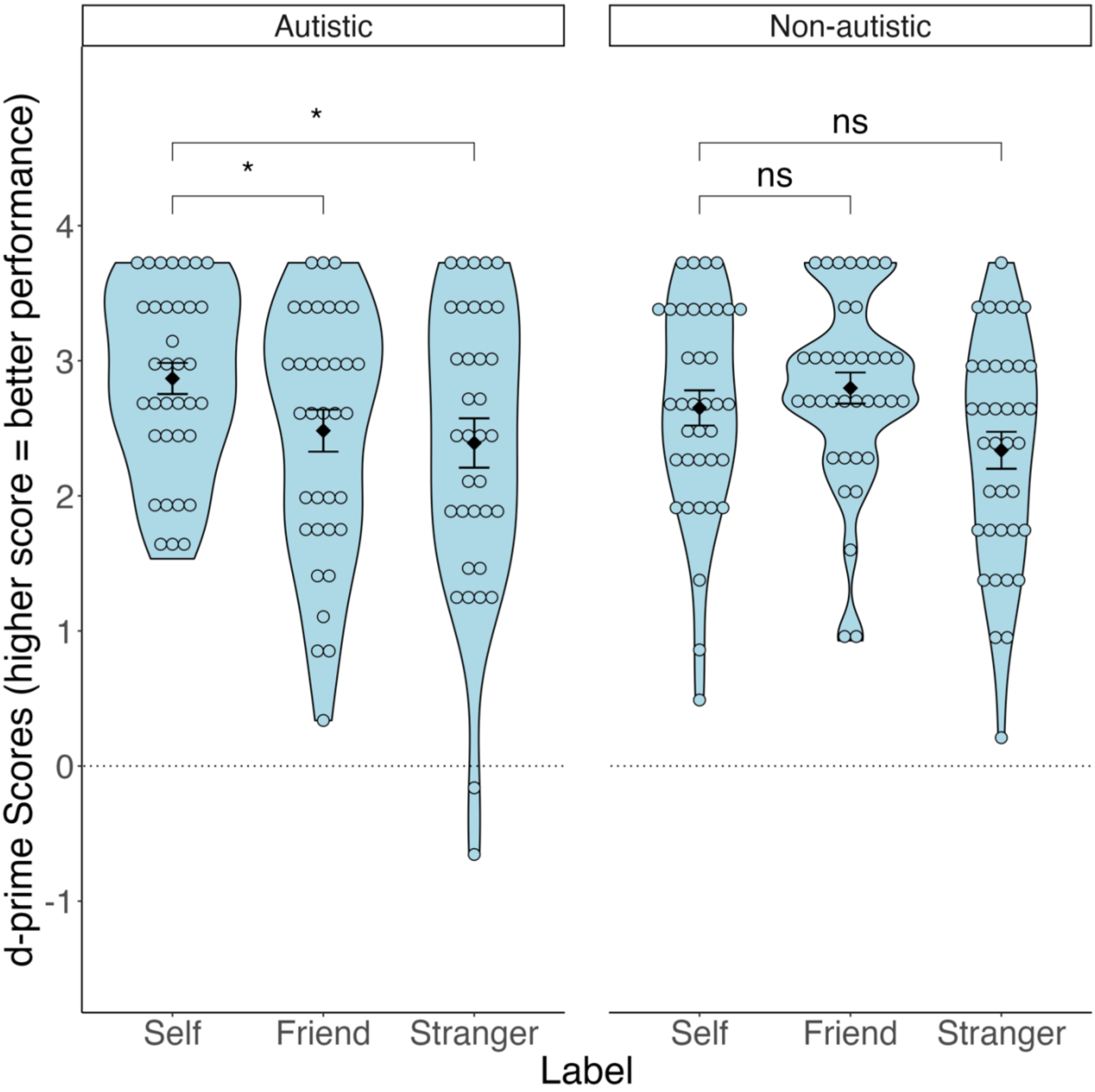

Figure 3.3. Violin plots showing the mean d-prime scores for each *Label* on the self-prioritisation task for the autistic and non-autistic groups.

The diamonds represent the means. The dotted line indicates chance performance on the SPT. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, *=*p*<.05, ns=non-significant.

Hypothesis 2: Body schema and sensorimotor integration performance will predict self-related processing performance

Autistic Group

The full model was a significantly better fit compared to the null but not the simple main effects model, see Table 3.3 for model summaries and comparisons.

Table 3.3: Predictors of d Prime scores on the SPT in the autistic group. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	267.34	275.30	
Simple Main Effects (Null + Label, Body Schema Score, Sensorimotor Integration Accuracy)	259.33	277.91	0.003 vs Null
Full (Simple Main Effects+ Label*Body Schema Score + Label*Sensorimotor Integration Accuracy)	260.67	289.87	0.155 vs Simple Main Effects

In addition, AIC and BIC values for the simple main effects model were lower compared to the full model. Therefore, the simple main effects model was selected as the most appropriate. The simple main effects model explained 13.8% of the fixed effects and 53.6% of the variance including random effects. In the simple main effects model, only the *Self* label was a significant predictor of SPT performance (*p*=0.014, 95% CI [0.08, 0.69]). *Body Schema* (*p*=0.25, 95% [-0.56, 0.15]) and *Sensorimotor Integration* (*p*=0.069, 95% [-0.11, 2.88]) did not significantly predict performance on the SPT, as can be seen in Figure 3.4 and 3.5 respectively.

Non-autistic Group

The full model was not a significantly better fit compared to the null (*p*=0.066) or the simple main effects model (*p*=0.79), see Table 3.4 for model summaries and comparisons. However, the simple main effects model was a significantly better fit compared to the null model (*p*=0.011). Therefore, the main effects model was selected as the most appropriate. The simple main effects model explained 9.7% of the fixed effects and 39.6% of the variance including random effects. In the simple main effects model, only the *Stranger* label was a significant predictor of SPT performance (*p*=0.002, 95% CI [-0.75, -0.17]). *Body Schema* score (*p*=0.55, 95% CI [-0.26, 0.49]) and *Sensorimotor Integration* (*p*=0.10, 95% CI [-0.28, 3.23]) did not significantly predict performance on the SPT, as can be seen in Figures 3.4 and 3.5 respectively.

Table 3.4: Predictors of d Prime scores on the SPT in the non-autistic group. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	260.43	268.56	
Simple Main Effects (Null + Label, Body Schema Score, Sensorimotor Integration Accuracy)	255.47	274.44	0.01 vs Null
Full (Simple Main Effects+ Label*Body Schema Score + Label*Sensorimotor Integration Accuracy)	261.79	291.59	0.80 vs Simple Main Effects

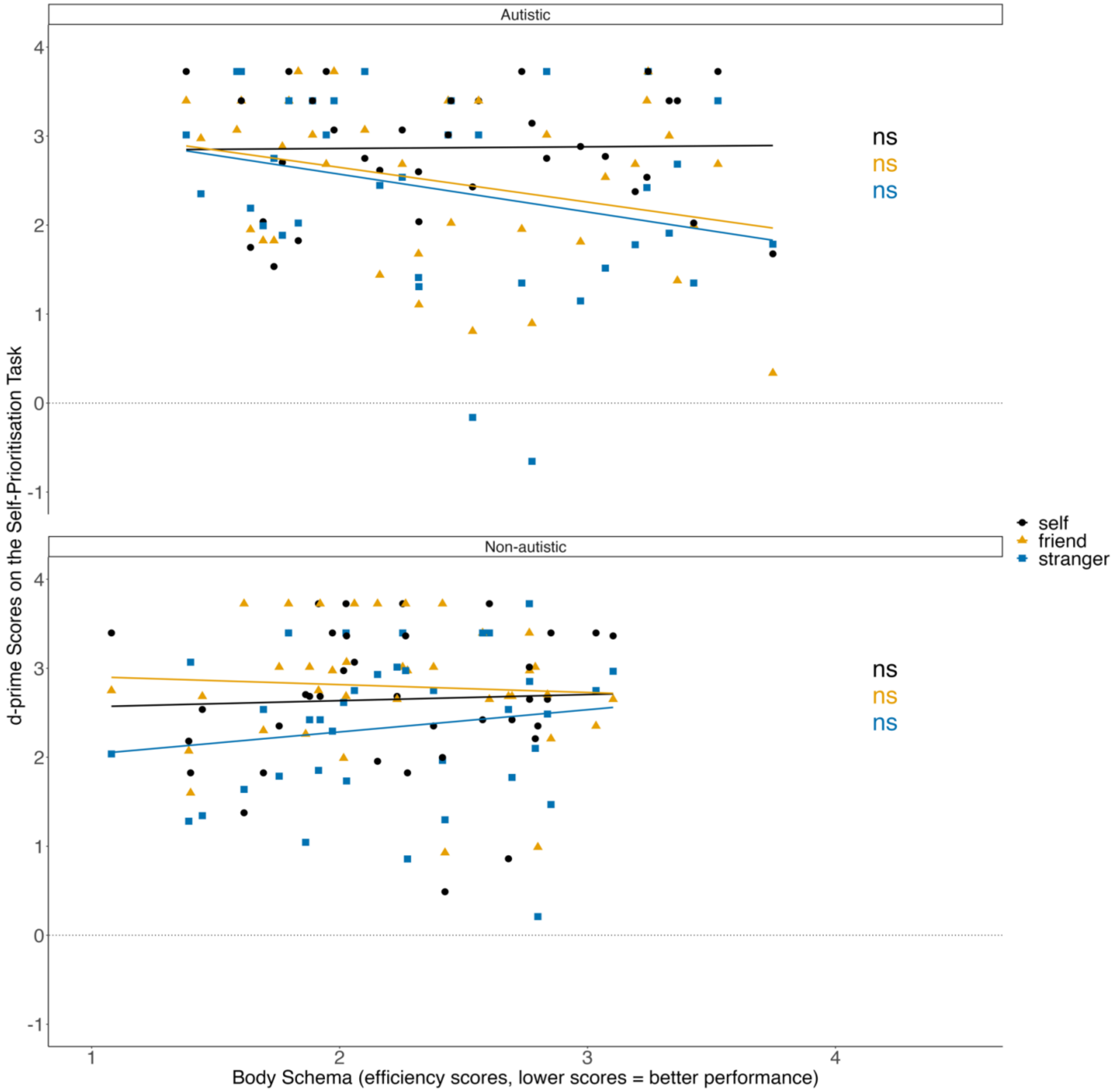

Figure 3.4. Plots showing the relationship between *Body Schema* (efficiency scores) on d-prime scores for *Self*, *Friend*, and *Stranger* trials on the self-prioritisation task for the autistic and non-autistic groups. The dotted line indicates chance performance on the SPT.

P-values are shown for the interactions between *Label* and *Body Schema/Sensory Integration*, ns represents a non-significant result.

Standard error is not displayed graphically here to maintain clarity of results.

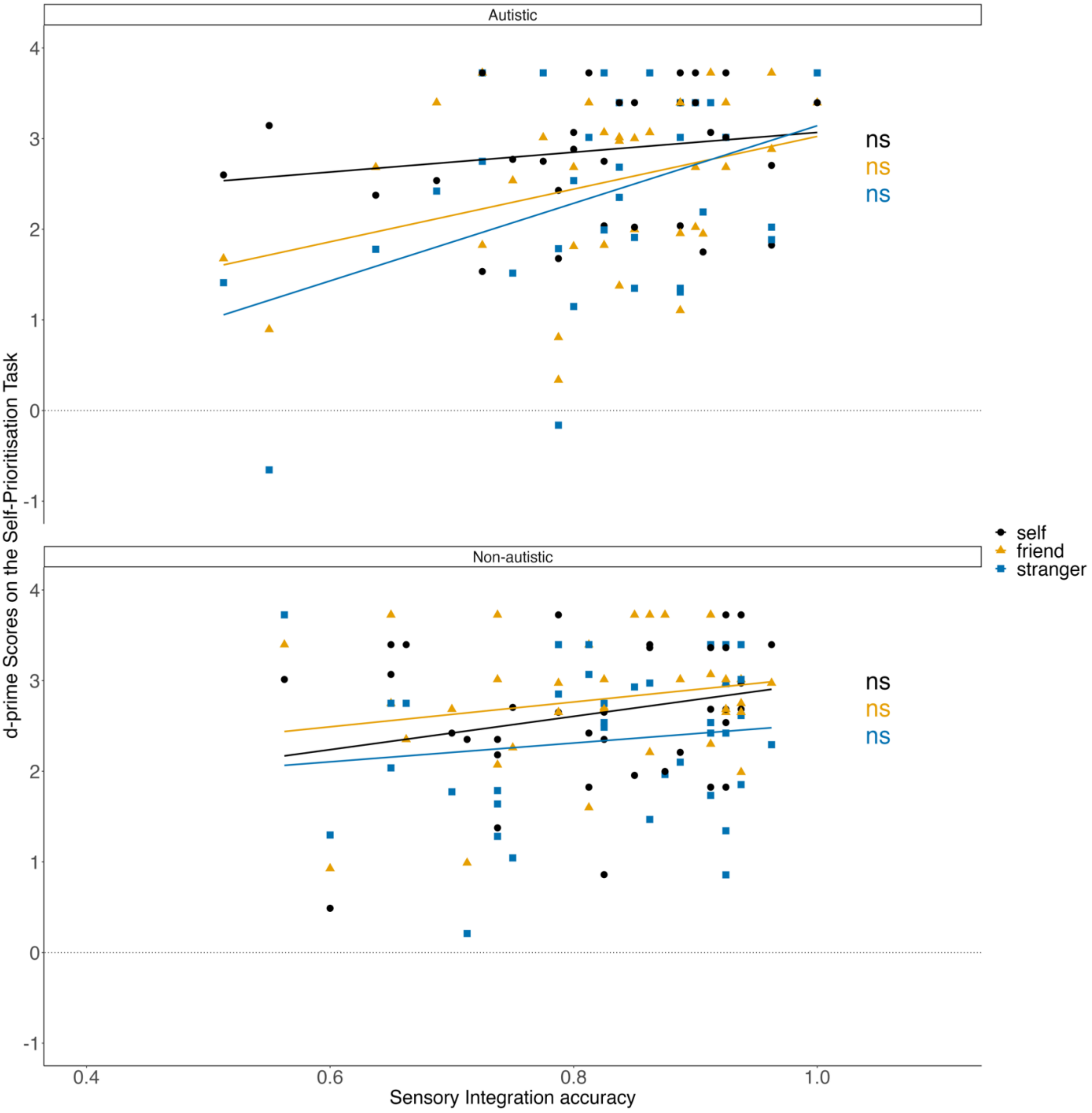

Figure 3.5. Plots showing the relationship between *Sensory Integration* (accuracy) on d-prime scores for *Self*, *Friend*, and *Stranger* trials on the self-prioritisation task for the autistic and non-autistic group. The dotted line indicates chance performance on the SPT. P-values are shown for the interactions between *Label* and *Body Schema/Sensory Integration*, ns represents a non-significant result.

Standard error is not displayed graphically here to maintain clarity of results.

3.4 Discussion

We investigated the relationship between body schema, sensorimotor integration, and self-related processing in autistic and non-autistic adults. In line with Hypothesis 1, we found that autistic individuals show a strong and significant bias in processing self-related information compared to other-related information. Contrary to Hypothesis 1, non-autistic participants did not show a self-bias in performance on the perceptual processing task. Using linear mixed modelling we did not find evidence in support of Hypothesis 2 as the simple main effects model best-explained performance on the SPT for autistic participants. Only the *Self* label significantly predicted performance on the SPT for autistic participants. In a second model, we found that a simple main effects model best explained performance on the SPT for the non-autistic group, with only the *Stranger* label significantly predicting performance on the SPT.

Our first finding corroborates previous work that has demonstrated autistic individuals show a self-bias in perceptual and memory tasks (Lind et al., 2019; Williams et al., 2018). In line with Hypothesis 1, this finding provides further evidence to counter earlier work which suggested autistic individuals have impairments in self-referential cognition (Lombardo et al., 2007). Taking the current findings in combination with previous work that has assessed self-referential memory in autistic individuals (Lind et al., 2019; Williams et al., 2018), there is evidence to suggest that self-bias in memory and perceptual processing is not absent in autistic adults. This finding has important theoretical implications for how we understand the 'self' in autism. It argues against the theoretical idea that autistic individuals have an 'absent self' which inhibits them from understanding their own and others' mental states (Frith, 2003). Instead, these results suggest that implicit levels of self-awareness may be intact in autism, or at least sufficiently intact to allow bias in perceptual processing.

By comparison, and contrary to our prediction (Hypothesis 1), we did not find evidence of a self-prioritisation effect in the d-prime scores of the non-autistic group. Indeed, non-autistic participants showed the best performance in friend-related trials. Moreover, in the subsequent modelling analysis, only the stranger label was a significant predictor of d-prime scores in the SP task. This further suggests that non-autistic participants were not exhibiting a self-bias. Previous work has consistently found that individuals are more accurate at responding to basic perceptual information that has been paired with a self-label (Sui et al., 2012; Sui & Gu, 2017; Sui & Humphreys, 2015b, 2017).

The discrepancy between the current findings and previous works could be due to the online methods employed in the current study. it is possible that if participants were in the same room as a friend, they might prioritise friend-related information. Indeed, previous work has found that friend-biases can be facilitated when perceptual information is presented on avatars in a socio-communicative state (facing each other) (Sun et al., 2016). Thus, if participants were in a socio-communicative state (i.e., sat opposite or near a friend) it is possible their performance for friend-related information would increase. Further work using in-person research methods could control for such social contexts and thus offer more robust methods to investigate self-referential effects. However, due to the global environment caused by the COVID-19 pandemic, such a measure was not possible to control with the same experimental rigour.

Counter to Hypothesis 2, we found that *Body Schema* and *Sensorimotor Integration* performance did not predict self-related processing for either group. This contradicts our expectation that self-bias would be grounded within a bodily self as suggested by previous work (Canzoneri et al., 2016; Sun et al., 2016) and findings from Chapter 2 of the current thesis.

As a self-prioritisation effect was not found in the non-autistic group, any relationship between *Body Schema*, *Sensorimotor Integration*, and performance on the SPT would not be evaluating self-referential processing. As such, we will discuss this finding in relation to the autistic group only. This finding may suggest that an internal representation of the body, formed through MSI is not associated with self-related processing in autistic individuals. This finding corresponds with previous work which suggests that differences in MSI and body schema may explain differences in embodied social processes (Cascio et al., 2012; Greenfield et al., 2015; Pearson et al., 2014). Previous work has found that whilst autistic individuals can perform visual perspective-taking, they do not use an embodied egocentric rotation of the self to complete the task. Instead, it is thought they utilise spatial rotation strategies to understand what someone else can see (Pearson et al., 2013, 2014). Subsequently, although autistic individuals exhibit a self-bias in perceptual processing, they may not be using strategies which rely on an internal representation of the body.

However, there are limitations that need consideration to contextualise the current findings. Visual inspection of a QQ plot (Appendix 3.2) shows that the data is skewed which may have reduced the appropriateness of using linear mixed modelling. However, when robust models were applied that are designed to account for skewed data, the null model was found to be the best fit for the data (see Appendix 3.3 for details). Thus, applying analysis that accounted for the skewness of the data still found that *Body Schema* and *Sensorimotor Integration* performance did not predict self-related processing in the autistic group.

Notably, we found no differences in *Body Schema* or *Sensorimotor Integration* scores between autistic and non-autistic participants. This finding is not in line with previous work that has found autistic individuals show disrupted MSI compared to non-autistic individuals

(Ainsworth et al., 2021; Greenfield et al., 2015; Iarocci & McDonald, 2006; Marco et al., 2011; Pellicano et al., 2005; Ropar et al., 2018) and reduced ability to perform embodied rotations of the self, as required in the HLJT (Conson et al., 2015; Pearson et al., 2014). Instead, autistic participant demonstrated a significant biomechanical effect on their HLJT performance, as has been found previously (Chen et al., 2018; Conson, Hamilton, De Bellis, et al., 2016). The current findings suggest that non-autistic *and* autistic participants were using an embodied motor imagery strategy to evaluate the handedness of the stimuli (Mibu et al., 2020).

In the sensorimotor integration task, we found a significant main effect of delay on sensory integration accuracy with participants' accuracy improving as the delay increased. This seems to indicate that participants were better at detecting longer visuo-tactile-motor delays, which is to be expected when integrating information across senses (Greenfield et al., 2017; Shimada et al., 2010). However, it is possible that participants were utilising a strategy to complete the task that did not rely on visuo-tactile-motor integration. For example, participants may have been using auditory information from their self-generated keypress to detect a visual delay. Subsequently, the task may have been evaluating audio-visual integration. Previous work has shown autistic individuals exhibit similar audio-visual integration in adulthood as non-autistic individuals (Keane et al., 2010; Van Der Smagt et al., 2007) so this may explain the lack of group differences in sensorimotor integration. What these results might suggest is that the tasks utilised in the current study were not sensitive enough to detect group differences in motor imagery and sensorimotor integrations. As such, future research would benefit from employing in-person research methods to more robustly evaluate the relationship between the body schema, sensorimotor integration, and self-related processing in autistic and non-autistic individuals (see General Discussion).

Although conducting research online can allow for a diverse sample of participants it can lead to experimental issues. For example, whilst efforts were made to ensure clarity in experimental instructions, using online research methods means it is not possible to directly evaluate how the participant is performing and whether they have clearly understood all the experimental tasks. Moreover, the diagnosis of autistic participants could not be confirmed with a formal diagnostic protocol due to the utilisation of online methods. The theoretical discourse of this topic would benefit from exploring the role of sensorimotor integration, body schema, and self-related processing utilising in-person research methods. For example, mediated reality techniques could be utilised to manipulate the sensory experience of participants to evaluate sensory integration (e.g., Greenfield et al., 2015; Newport et al., 2010). A temporal delay could be applied to the virtual video image of a participant's own body, such that visuomotor synchrony of a body movement would be manipulated. The length of the temporal delay could be varied to allow for the evaluation of the sensitivity of individuals' visuomotor integration. The greater the participant's accuracy at detecting the synchronous movement at shorter temporal delays, the more sensitive their temporal processing of sensory information. This measure of visuomotor integration could be related to self-referential processing to understand if there is an association between how sensory information is processed and how self-related information is prioritised. Using an in-person self-prioritisation task as has been previously utilised (Sui et al., 2012; Sui & Humphreys, 2015b, 2017), would also allow for a greater number of practice and experimental trials in addition to closer monitoring of how the participant is performing the task. As such, using these methods would allow for more experimentally robust (compared to online methods) measures of self-referential processing and visuomotor integration to evaluate the contribution of sensory integration in self-related processing.

Conclusions

The current study has expanded on previous work demonstrating that autistic individuals do not appear to have diminished self-bias in perceptual processing. Thus, differences in the expression of social behaviours of empathy and Theory of Mind may not simply be explained by absent implicit self-awareness. Furthermore, we found no evidence of differences in body schema or sensorimotor integration ability between autistic and non-autistic participants. Moreover, we found that body schema and sensorimotor integration ability do not appear to be associated with self-related processing in autistic adults. Future research is needed to understand whether this lack of relationship is due to reduced engagement of embodied mechanisms in autism and if these mechanisms differ in autistic and non-autistic populations.

Chapter Introduction

In Chapters 2 and 3 we explored the link between sensorimotor integration and how the self is internally represented. Holding self-awareness is thought to be related to this mentalising ability and is thus a key component of social processing. Beyond understanding what other people might be *thinking*, it is also important to understand what others might be *seeing*, known as visual perspective taking (VPT). To further elucidate the links between sensorimotor integration and social processing, Chapter 4 will utilise mediated reality technology to investigate the role of the body schema and sensorimotor integration in visual perspective-taking.

Chapter 4: Using Mediated-Reality to Explore How Body Schema and Multisensory Integration Contribute to Visual Perspective Taking

Abstract

Being able to understand how people see the world, known as visual perspective taking, is essential for social function. Level-two visual perspective taking (VPT2) is thought to involve egocentric transformations of the body to understand what another person sees. Embodied accounts of VPT2 stipulate that one's own body and how it is internally represented have a causal role in VPT2. The integration of sensory information across modalities provides the basis for how the body is internally represented (i.e., the body schema). Moreover, knowing where the body is, i.e., the experience of self-location, is thought to be an important component of the body schema. Yet it is unknown how these elements might be associated with VPT2. The current study investigated whether the experience of self-location and visuo-proprioceptive integration are implicated in VPT2. Using the Disappearing Hand Trick (DHT) and the MIRAGE mediated reality system we manipulated the perceived self-location of the

right hand. Contrary to our first hypothesis we found that disrupting the experience of self-location of the right hand did not reduce subsequent performance in a VPT2 task. Secondly, we did not find evidence of visuo-proprioceptive integration being related to VPT2 performance. These findings have elucidated the link between sensorimotor integration and social processing by suggesting that holding an accurate spatial representation of a body part, formed through visuo-proprioceptive integration may not be implicated in the ability to take another person's perspective.

4.1 Introduction

Understanding how other people view the world is essential for navigating social interactions (Frith, 2007). It is not only important to understand what other people might be thinking but also what others might be seeing, known as visual perspective taking (VPT). The ability to take another person's perspective allows for the understanding that other people can have different visual experiences and may perceive the world differently. Indeed, brain areas associated with the process of perspective-taking have been shown to overlap with areas related to understanding other's mental states (Gunia et al., 2021; Schurz et al., 2013). Additionally, visual perspective taking is associated with self-other distinctions (Gunia et al., 2021; Quesque & Brass, 2019) which are argued to be fundamental for understanding the thoughts, intentions, and beliefs of others (Meltzoff, 2007). Visual perspective-taking is therefore cemented in social cognition.

There are two dissociable perspective-taking processes, level 1 (VPT1) and level 2 (VPT2). VPT1 can be accomplished through simple line of sight to understand what another person sees (Surtees et al., 2013b). Conversely, VPT2 is thought to involve egocentric transformations of self 'into the shoes' of the other person (Devlin & Wilson, 2010; Kessler &

Thomson, 2010; Surtees et al., 2013b), whereby an individual must imagine the rotation of their own body into the space of an observer. For example, if a person sitting across from you is trying to locate the saltshaker on the table, you might be able to see that it is occluded from their vision by a plant pot. Thus, you can understand *what* they can see using line of sight (i.e., VPT1). But to help the person sitting across from you find the saltshaker, you might describe its location using their spatial reference frame, i.e., "it's to your left behind the plant pot" (i.e., VPT2).

The distinction between VPT1 and VPT2 is reflected in the underpinning neural networks, the former is associated with the mesial cortical areas which are related to visuospatial processing and decision-making (Vogeley et al., 2004) whilst the latter is associated with the temporoparietal junction (TPJ) and medial prefrontal cortex, areas associated with social cognition (David et al., 2006; Mazzarella et al., 2013). VPT1 and VPT2 also exhibit different developmental trajectories (Kessler & Rutherford, 2010). Work has found that very young children hold an awareness of what others can see (VPT1) (Lempers et al., 1977; Sodian et al., 2007) whilst VPT2 develops later in childhood (Flavell et al., 1981; Moll & Meltzoff, 2011; Piaget & Inhelder, 1956). Therefore, VPT1 and VPT2 rely on at least partly distinct neural networks and develop at different points in childhood, thus evidencing the dissociation between these visual perspective-taking skills.

VPT2 is thought to involve egocentric transformations of self into the viewpoint of the other person (Devlin & Wilson, 2010; Kessler & Thomson, 2010; Surtees et al., 2013a), whereby an individual must imagine the transformation of their own body into the space of an observer. This is dissociable from object rotation whereby an individual performs allocentric rotations of the object or visual scene. Whilst object rotation strategies can be employed to understand the perspective of someone else, this involves the rotation of the entire visual scene which can be much less efficient (Zacks & Tversky, 2005).

According to the embodied cognition viewpoint, VPT2 relies on having a representation of one's own body. The body schema is an internal dynamic representation of the body in space and VPT2 is thought to engage mental transformations of the body schema into the location and orientation of another person in space (Kessler & Thomson, 2010). Neuroimaging studies have evidenced this theory by demonstrating that motor regions of the brain are engaged when individuals imagine their own bodily motion (Creem et al., 2001; Wraga et al., 2005). Further neuroimaging work has found evidence that VPT2 engages brain areas associated with the coding of internal representations of the body (Gunia et al., 2021). Thus, the neurocognitive mechanisms of VPT2 appear to combine input from motor simulation processes and body schema representations.

Behavioural studies have further illustrated the embodied nature of VPT2. Motor expertise has been shown to enhance the ability to perform egocentric transformations but not object rotations (Kaltner et al., 2014). This suggests that having a heightened awareness of the body and its movements facilitates egocentric rotations of the body. Thus, the ability to imagine the rotation of one's own body is grounded within motor and body representations. Importantly, this finding shows that motor processes only relate to egocentric transformations and not allocentric rotations, thus evidencing how specifically egocentric transformations are embodied and not object rotation processes in general. Moreover, creating angular disparities between the participant's and the target's bodies increases the time taken to take the visual perspective of the target (Kessler & Rutherford, 2010; Surtees et al., 2013a, 2013b). These findings indicate that participants are mentally imagining rotating their own bodies into the position of the target. Thus, the greater the angular disparity, the longer it takes to complete the mental rotations. Together there is robust behavioural evidence to suggest that VPT2 is an embodied process that is grounded within motor and body representations.

Further evidence of the embodied nature of VPT2 has come from research investigating egocentric transformations in autistic children and adults. Autistic individuals show reduced performance in VPT2 tasks, but not VPT1 tasks (Hamilton et al., 2009; Pearson et al., 2013, 2014; Reilly, 2020). The authors suggest that this finding illuminates a specific difficulty to use the self as a reference frame in autistic individuals. In addition, autistic individuals have been shown to exhibit differences in how they form an internal representation of the body through multisensory integration (MSI) (Cascio et al., 2012; Hense et al., 2019; Ropar et al., 2018). It is thought that these differences may reduce the effectiveness of egocentric transformations, and therefore other strategies are used to complete VPT2 tasks. These works, therefore, evidence the idea that VPT2 is an embodied process which relies on internal representations of the body. Whilst it is theorised that reduced VPT2 performance may be underpinned by differences in how the body is internally represented, no study has investigated the effect of disrupting the body schema on VPT2 in neurotypical individuals. Moreover, although there is evidence to suggest that body schema is implicated in VPT2, it is unknown whether sensorimotor integration is similarly implicated in VPT2.

The body schema is thought to depend on the optimal integration of sensory information (de Vignemont, 2011; Longo et al., 2010; Matsumiya, 2022; Medina & Coslett, 2010; Paillard, 1999), to create a spatial framework of where the body is and an experience of self-location (where one feels in space) (Blanke, 2012; Riva, 2018). This has been demonstrated in previous work through the use of body illusions, which work by utilising synchronous sensory signals to alter the experience of self-location. For instance, the Rubber Hand Illusion (RHI) uses a combination of synchronous tactile and visual input to induce feelings of ownership (Botvinick & Cohen, 1998; Braun et al., 2018) and self-location (Tsakiris & Haggard, 2005) over a rubber hand. These findings illustrate how the integration of visual-tactile information can influence how the body is represented in space as the experience of self-location shifts towards the rubber hand and away from the real hand. However, methods such as the RHI often rely on the top-down representations of the body being overridden for the illusion to work (i.e., having to ignore the knowledge that one's hand is not made of rubber).

Research utilising mediated technology has demonstrated the role of MSI in the body schema whilst reducing the top-down load of the body illusions. Indeed, the mediated reality system MIRAGE can use live video images of the participant's own hand to create the sensation of a missing limb (Newport & Gilpin, 2011), the feeling of an elongated finger (Newport et al., 2015) and even the feeling of owning multiple left hands (Newport et al., 2010). It is thought that individuals with optimised MSI are more likely to experience these body illusions as the brain is more efficiently combining information across multiple modalities (Greenfield et al., 2017; Newport et al., 2010). For example, the Disappearing Hand Trick (DHT) uses a sensorimotor adaptation procedure to create an incongruency between the *real* and *perceived* location of a limb through visual and proprioceptive inputs to induce the sensation of a missing limb (Newport & Gilpin, 2011). Indeed, work has found that participants report feeling as though their hand has disappeared, therefore disrupting their experience of self-location and thus body schema. Susceptibility to the illusion is found to increase through childhood (Ratcliffe et al., 2021), mirroring the developmental optimisation of MSI. This illusion can therefore be utilised to understand how individuals are integrating visual and proprioceptive information in addition to disrupting their experience of self-location.

Whilst the link between body schema and VPT2 has been well established (Kessler & Rutherford, 2010; Surtees et al., 2013a, 2013b), the bodily components of the body schema (i.e., self-location) that are implicated in VPT2 are unknown. Moreover, despite MSI being the basis of the body schema, the link between sensorimotor processes and VPT2 has not been directly explored. In light of this, the current study will utilise the DHT (Newport & Gilpin, 2011) to evaluate whether 1) a temporary disruption to the body schema by manipulating self-location can impact upon VPT2 ability and whether 2) better visuo-proprioceptive integration is associated with better VPT2 performance.

4.2 Methods

Participants

Forty-seven adults (38 women, 8 men, 1 non-binary individual, M_{age} = 20.04 years), undergraduate and postgraduate students, participated in the current study. Undergraduate students volunteered to participate in return for course credit. Data from seven participants were removed due to procedural errors. Therefore, the final sample consisted of forty adults (32 women, 7 men, and one non-binary individual, M_{age} = 20.33 years). A priori power analysis reported a minimum sample of 27 was required to find a significant matched pairs t-test with a medium effect size (d=0.5) and 0.8 power and 39 would be required to find a significant moderate correlation (r=0.3) with 0.8 power. Ethical approval for both was granted by the School of Psychology ethics committee at the University of Nottingham, reference number: S1215R. The experiment was conducted in accordance with ethical standards and GDPR. Informed consent was obtained from all participations before participation.

Design

A repeated measures design was used as all participants were exposed to both the experimental conditions (*Illusion* and *Non-Illusion*). The order of the experimental conditions (*Illusion* and *Non-Illusion*) was fully counterbalanced across participants. The dependent variables were VPT accuracy and reaction times for correct trials. Individual differences in object rotation (OR) were accounted for such that the VPT performance was calculated as the difference from OR performance (i.e., VPT accuracy – OR accuracy). There were no effects of condition order on VPT performance (see Appendix 4.3).

Materials and Measures

MIRAGE

The DHT body illusion was conducted using the mediated reality device called MIRAGE (see Figure 4.1), which presents live video images of the participant's hand in real-time. When participants put their hand into the MIRAGE device, they can no longer see their actual hand; instead, they see live footage (minimal delay of 16ms) of their hand in the same spatial location, depth plane and from the same visual perspective as their veridical (real) hand. Participants had their arms covered with a black curtain to ensure the upper arm was not visible when their hand was within the MIRAGE.

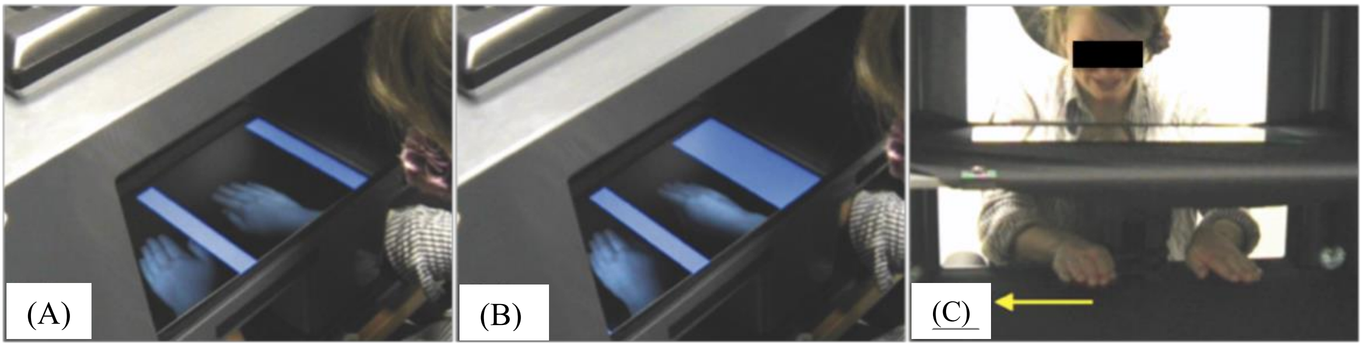

Figure 4.1. From Ratcliffe et al., (2021).

(A) Start of the sensorimotor adaptation procedure, the virtual right hand and veridical right hand are congruent (note alignment of the upper arm position). In the *Congruent* condition of the hand localisation task and the *Non-Illusion* experimental condition, the virtual and veridical right hands remain in this position.

(B) During the sensorimotor adaptation procedure, the blue bars constrict the space surrounding the virtual hands. To keep the virtual right hand in between the blue bars, the participant slowly moves their right hand leftwards without their awareness. Following the sensorimotor adaptation procedure, the location of the virtual right hand and veridical right hand are incongruent (note the misalignment of the upper arm position). In the *Incongruent* condition of the localisation task and the *Illusion* experimental condition, the virtual and veridical hands end in this position.

(C) The participant's hands following the Incongruent condition, viewed from the experimenter's perspective. The arrow indicates the direction the virtual right hand moves during the adaptation procedure.

Hand Localisation Task

This task was used to evaluate participants' integration of visual and proprioceptive information. Participants placed their hands into the MIRAGE and held them approximately 5cm above the worksurface. Blue bars were superimposed on the visual worksurface on either side of the participant's hands and were shown to expand slowly over 25 seconds (see Figure 4.1). Participants were instructed to try to not 'touch' the blue bars as the space around their hands became constricted.

In the *Incongruent* condition, the congruency in spatial location between the virtual hand and the veridical hand was manipulated using a sensorimotor adaptation procedure adapted from Newport & Gilpin (2011). This was achieved by moving the image of the right hand smoothly and incrementally leftwards at a rate of 4.5 mm/s during the blue bar task. Therefore, the participant had to move their hand rightwards at the same rate to keep their seen hand from touching the blue bars. This resulted in the virtual hand being viewed 11.25cm to the left of its true location (see Figure 4.1B). An incongruency between the felt position of the right hand and the last seen position of the right hand is then created. Once the adaptation procedure was completed, the participant's hands were placed on the worksurface (see Figure 4.1C). The vision of the right hand was occluded. Participants then completed the localisation task. Whilst their hands were hidden from view, arrows were superimposed on the MIRAGE window in the same depth plane as the previously seen virtual hand. The arrow was shown to move slowly horizontally across the window and participants were asked to say 'stop' when they felt like the arrow was pointing in line with their right index finger. This would prompt the experimenter to immediately release a button on the computer keyboard stopping the arrow from moving. The position of the arrow was then recorded in pixels along the x-axis of the experimenter's view of the MIRAGE window on the experimenter's laptop. Each measurement was taken twice for each condition, once with the arrow travelling from right to left and once from left to right (order counterbalanced across conditions and participants). The true location of the participant's right hand was not revealed to them in the localisation task. This *Incongruent* condition in this task provides a measure of sensorimotor integration, as efficient integration of proprioceptive and visual information leads to a drift in self-location towards the virtual hand and away from the veridical hand. As such, the greater the localisation error, the more optimal the sensory integration.

In the *Congruent* condition, the participants completed the same blue bar task as described above but did not experience the sensorimotor adaptation procedure. Instead, they viewed the virtual right-hand oscillating leftwards and rightwards, such that it remained in the same position as the veridical hand. This meant that both the virtual and veridical hands were in the same visual and spatial locations. Following the blue bar task, participants had their hands placed down on the worksurface and the right hand was hidden from view. Participants then completed the same localisation task with the superimposed arrows as described above. Again, the true location of the participant's right hand was not revealed to them in the localisation task. This *Congruent* condition provides a control condition to ascertain how well participants can locate their own hand when it is visually occluded. The order of the *Congruent* and *Incongruent* localisation conditions was counterbalanced across participants.

Disappearing Hand Trick: Illusion Condition

This task was used to disrupt the body schema by manipulating the experience of self-location of the right hand. In the *Illusion* condition, participants completed the sensorimotor adaptation task as described above and then placed their hands down on the MIRAGE worksurface. The right hand was occluded from view and the participant's left hand was moved to the last seen location of the virtual right hand. Thus, all that can be seen and felt is the worksurface where the virtual hand had last been seen. Therefore, this creates the sensation that the right hand has ‘disappeared’ and thus self-location of the right hand is disrupted.

Disappearing Hand Trick: Non-Illusion Condition

This condition was used as a control for the *Illusion* condition. In the *Non-Illusion* condition, the participants completed the same blue bar task as described above but did not experience the sensorimotor adaptation procedure. Instead, they viewed the virtual right-hand oscillating leftwards and rightwards, such that it remained in the same position as the veridical hand. This meant that both the virtual and veridical hands were in the same visual and spatial locations. Following the blue bar task, participants had their hands placed down on the worksurface and the right hand was hidden from view. The left hand was moved to the location the virtual right hand was last seen to be, such that the right hand was touched by their left hand (see Newport & Gilpin 2011 and Ratcliffe et al., 2021). Therefore, participants should have a clear idea of where their right hand is located, and this is confirmed when their left hand is moved to touch their right hand.

Visual Perspective Taking Task

Participants completed the VPT task on a laptop and responded with a keypad. The task was programmed using the software Psychopy (Peirce et al., 2019) and presented on a laptop positioned directly above where the participant’s hands were located within MIRAGE. Participants viewed videos of a puppet dragon being covered with a basket and then turned on a rotating platform (see Figure 4.2A). In the VPT trials, a human model was located behind, or to the sides of the puppet (see Figure 4.2B).

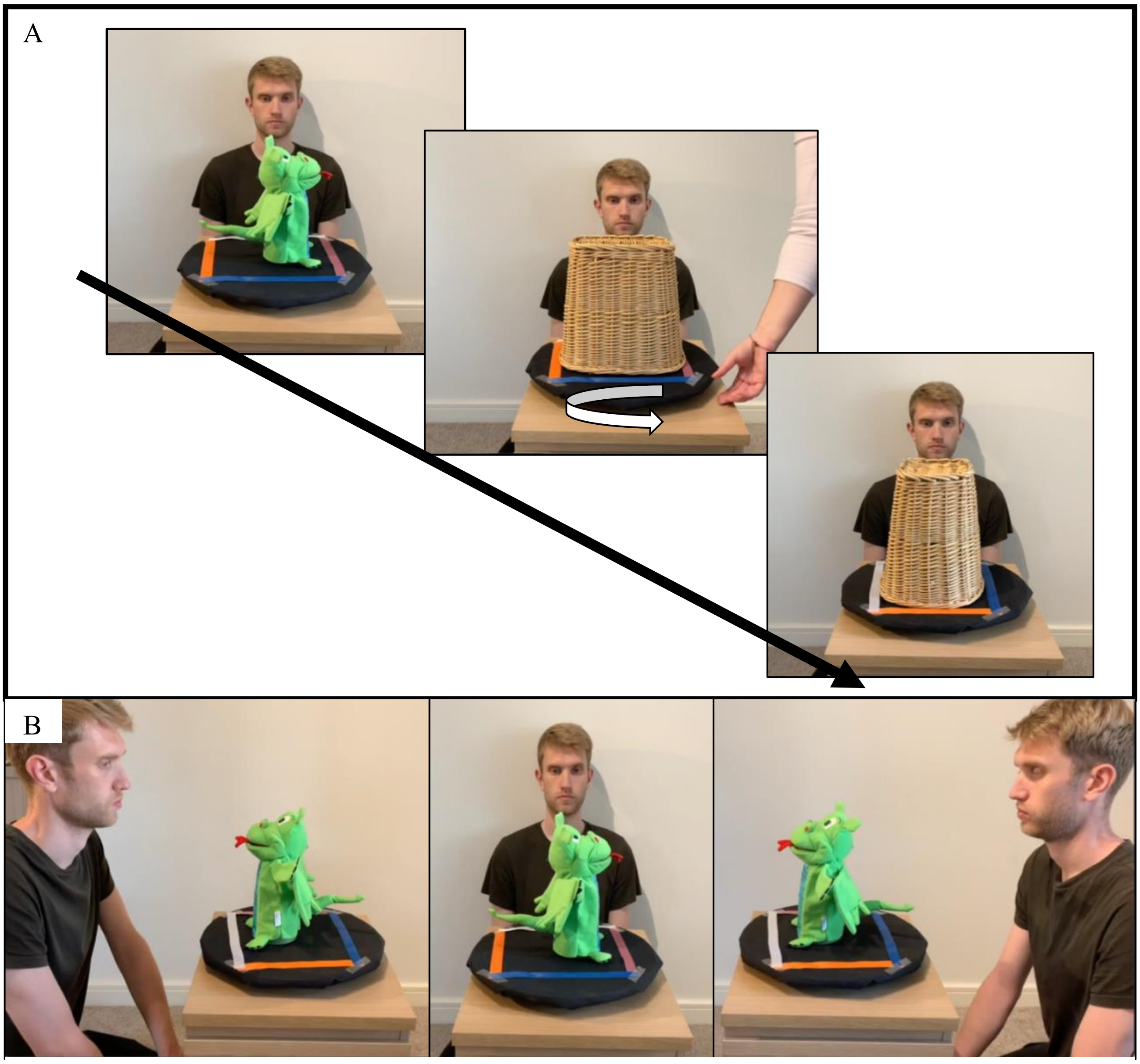

Figure 4.2.

(A) schematic of VPT trial videos viewed by participants showing a puppet dragon covered by a basket and rotated on a platform. Object rotation trials were the same but without the human model. (B) Illustration of how the human model was positioned at 90° left, 180°, and 90° right from the participant viewpoint during the VPT trials. The starting positions of the puppet and the position of the human model were counterbalanced across trials.

The participants were asked to select which view of the puppet they believed the human model would see if the basket was removed. The participants were given reference images of the puppet presented at either 90° left or right°, or 180° degrees front or back to help them answer (see Figure 4.3).

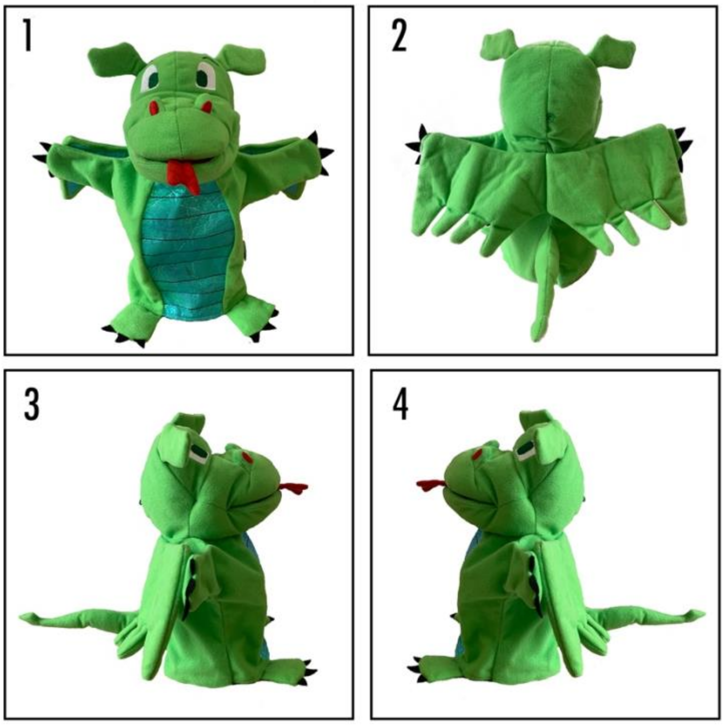

Figure 4.3. Illustration of the response options participants were given to select from. Participants made a number keypress to make their selection. The options display order was counterbalanced across trials.

Object rotation (OR) trials were included to control for spatial rotation ability. In the OR trials, there was no human model, instead, participants selected which view of the puppet they believed *they* would see if the basket was removed. Thus, evaluating allocentric spatial rotations and not VPT ability. Participants were asked to respond as quickly and as accurately as possible. Participants completed a total of three blocks (*Baseline*, *Illusion* and *Non-Illusion*) with 20 trials per block, with an intermix of OR and VPT trials randomly presented in each block. A *Baseline* block was included to ascertain VPT performance prior to any experimental manipulation.

Procedure

All participants were tested in a quiet room at The University of Nottingham, where they were sat across from the experimenter. The experimental procedure took a total of 40 minutes. Firstly, participants completed the hand localisation task for the *Congruent* and *Incongruent* conditions (see Figure 4.4). The order of conditions was counterbalanced across participants. Then participants completed a *Baseline* measure of VPT ability. Following this, participants completed the DHT *Illusion* condition. Next, participants completed a second block of the VPT task (i.e., *Illusion* condition). Participants then completed the *Non-Illusion* condition before completing a final block of the VPT task (i.e., *Non-Illusion* condition). Whether the participants experienced the *Illusion* condition, or the *Non-Illusion* condition first was counterbalanced across participants. The hand localisation task was always conducted first.

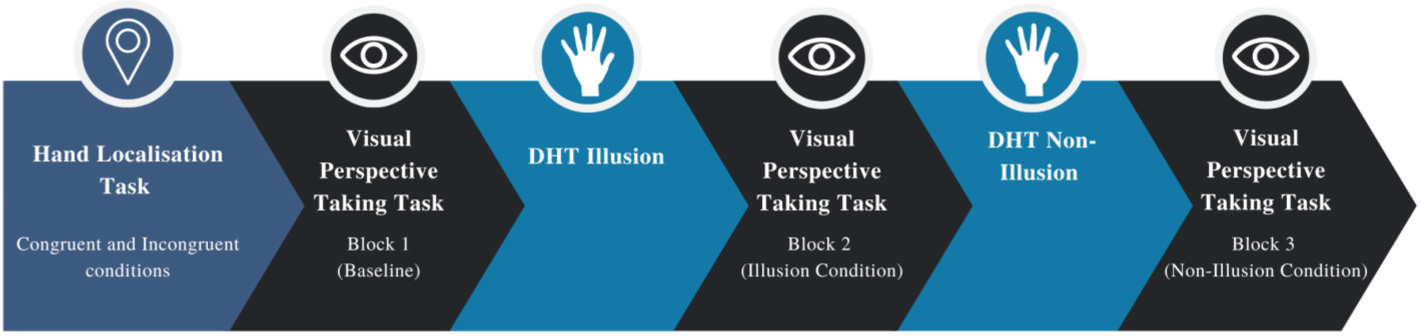

Figure 4.4. Schematic of the task order. The order of the *Congruent* and *Incongruent* conditions in the Hand Localisation Task was counterbalanced across participants. The order the of the DHT *Illusion* and *Non-Illusion* conditions was counterbalanced across participants. The Hand Localisation Task was always administered first.

Data Analysis

All data were processed and analysed in custom-written scripts using R (R Core Team, 2021).

Hand Localisation Error

Localisation error values were calculated for each participant and each of the *Congruent* and *Incongruent* conditions in the following way. For each trial, the experimenter recorded the x-axis coordinate of the position of the tip of the right index finger from the veridical hand in pixels. The position of the right hand was initially recorded in pixels as the x-coordinate was taken from the camera feed of the MIRAGE worksurface which was displayed on the experimenter's computer. This pixel value was then converted into centimetres (100 units equates to 7.5 cm). For each condition, the average of the two hand localisation estimates was calculated and subtracted from the veridical hand position to give an estimate of localization error (in cm). A value of zero represents a completely accurate estimate of hand location. Positive values indicate estimates to the left (i.e., closer to the midline) of the veridical hand location and negative values indicate estimates to the right (i.e., away from the midline). In the *Incongruent* condition, the virtual hand was seen 11.25 cm to the left of the veridical hand; thus, a localisation error value of 11.25 in this condition would represent an estimate which matched the location of the virtual hand, not the veridical hand (see Figure 4.5). Conversely, a value of zero would indicate estimates which matched the veridical hand but not the virtual hand. The greater the localisation error in the *Incongruent* condition, the greater the susceptibility to the illusion and thus the better the MSI.

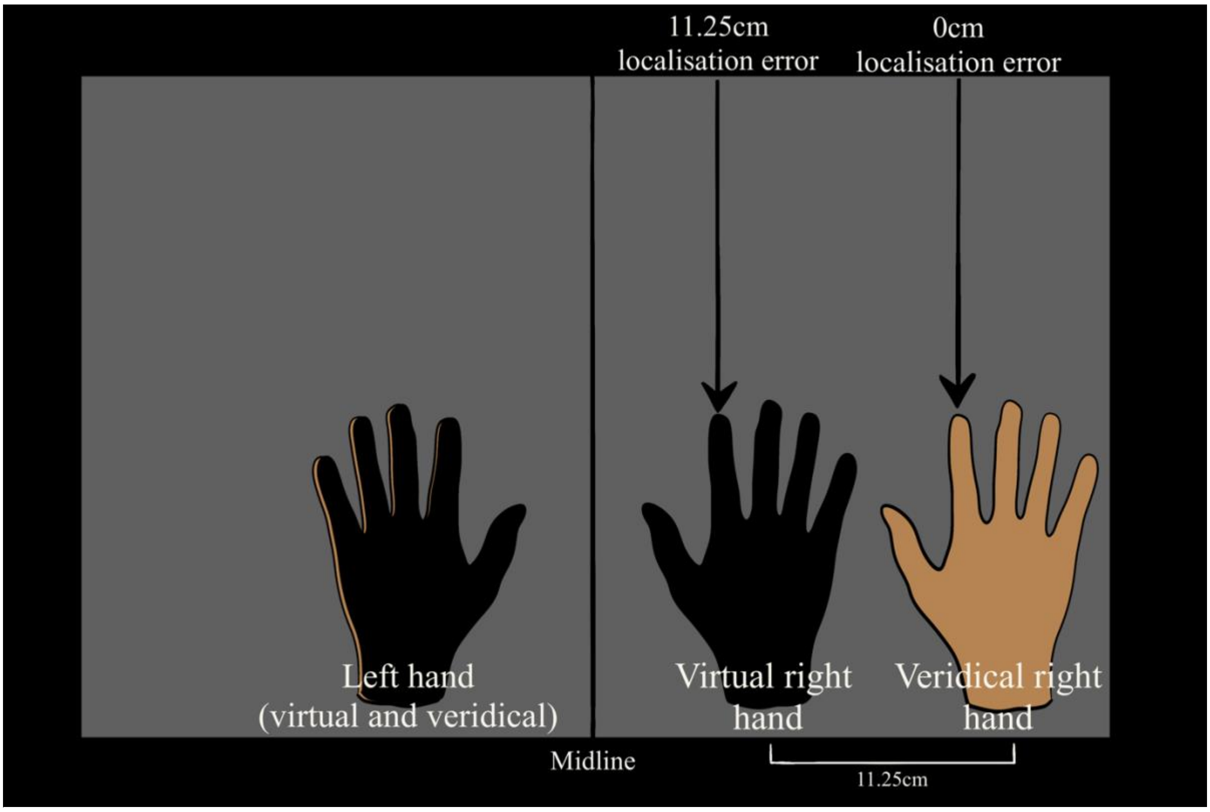

Figure 4.5. Illustration of the virtual and veridical right hand positions in the *Incongruent* condition of the hand localisation task. When participants are making their hand localisation estimates, they cannot see the virtual or veridical hands. In the hand localisation task, the true location of the veridical hand is not revealed to participants.

In the *Congruent* condition, the locations of the virtual and veridical hand are the same, thus, a value of zero in this condition would indicate total accuracy in locating the hand. The *Congruent* condition ensures participants can locate their own hand when the virtual and veridical hands are congruent in space.

As a manipulation check, the difference in localisation error between the *Incongruent* and *Congruent* conditions was evaluated using a paired samples t-test to ensure participants experienced a drift in self-location towards the virtual hand. A significant increase in error in the *Incongruent* compared to the *Congruent* conditions indicates that the sensorimotor adaptation procedure is inducing the sense that the right hand is located much closer to the midline than it actually is. A significant difference between these conditions also indicates that the *Illusion* experimental condition influences the perceived self-location of the right hand.

Visual Perspective Taking Performance

VPT scores were calculated to account for individual object rotation (OR) ability. For each participant, the OR value (accuracy or reaction times for correct trials) was subtracted from the VPT value. For accuracy, the more positive the score, the better the performance compared to OR ability. For reaction times, the smaller or more negative the score, the quicker the performance compared to OR ability. Only reaction times for correct responses were used in the analysis. Reaction times in both the object rotation and VPT trials were calculated as being the time taken to respond from when the platform had finished rotating. For each participant and each condition (*Baseline*, *Illusion*, and *Non-Illusion*) means of these VPT scores were calculated.

To evaluate whether there was a difference in performance in the *Baseline*, *Illusion*, and *Non-Illusion* conditions, a repeated measures ANOVA was used to evaluate the main effect of condition. Bonferroni corrected post-hoc t-tests were then used to evaluate pairwise comparisons.

The relationship between hand localisation error and VPT performance

To answer the second research question, a correlation analysis was conducted to investigate the relationship between hand localisation error and VPT performance. To take into account individual differences in the ability to locate an unseen hand, the localisation error in the *Congruent* condition was subtracted from the *Incongruent* condition. This score of localisation error was used in the correlational analysis in addition to *Baseline* VPT performance. A significant Shapiro-Wilk normality test; W=0.92, *p*=.0097, and visual inspection of QQ plots (Appendix 4.1) for the accuracy and reaction times differences scores suggested the data were not normally distributed. Therefore, Spearman's correlation analyses were conducted between localisation and VPT *Baseline* accuracy and reaction times scores. VPT performance scores accounted for OR ability (i.e., VPT accuracy – OR accuracy), thus negative values for accuracy indicate poorer performance compared to OR ability, and positive values for reaction times indicate slower performance compared to OR ability.

4.3 Results

Manipulation Checks

A mixed ANOVA showed no significant effect of condition order on accuracy (F(2,37)=.14, *p*=.87) or reaction time (F(2,37)=1.85, *p*=.17) scores on the VPT task.

Hand localisation Error

A paired samples t-test was used to compare localisation error in the *Congruent* and *Incongruent* conditions of the hand localisation task. The test revealed a significant difference in localisation error; *t*(39)=-20.1, *p*<0.001. Participants were significantly more likely to mislocalise their right hand in the *Incongruent* condition (*M*=6.62cm, *SD*=2.5) compared to the *Congruent* condition (*M*=-1.69cm, *SD*=1.72), (see Figure 4.6).

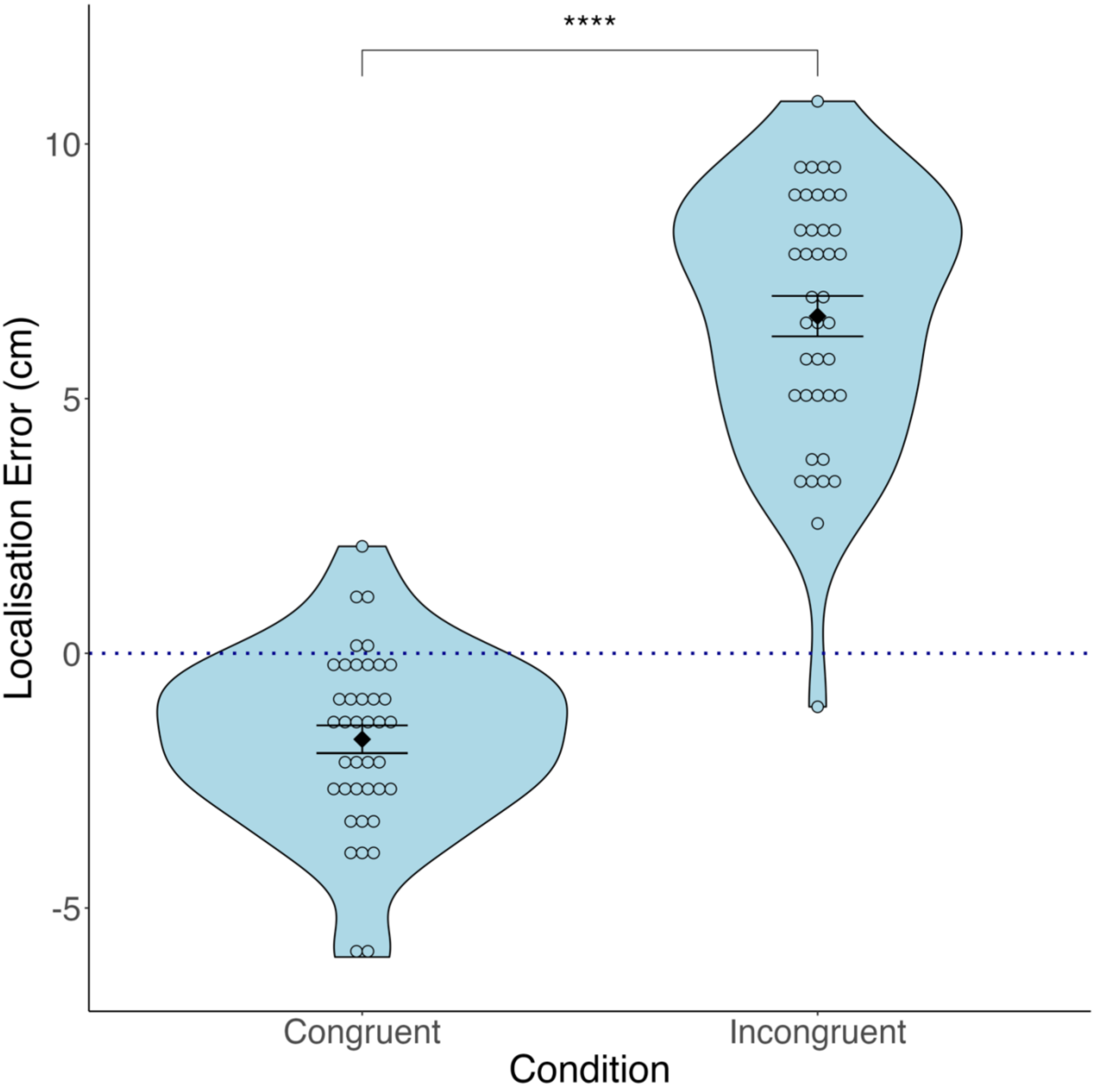

Figure 4.6. Locations error in centimetres for the *Congruent* and *Incongruent* conditions. Circles represent individual data points and the diamonds represent the means. Positive values indicate estimates to the left (i.e., closer to the midline) of the veridical finger location and negative values indicate estimates to the right (i.e., away from the midline). The dotted line indicates 100% accuracy (no error). Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons ****= $p \leq .0001$.

Hypothesis 1: VPT2 performance will be significantly lower following the Illusion condition compared to the Non-Illusion condition

Two repeated measures analysis of variance (ANOVA) tests were used to investigate the effect of condition (*Baseline*, *Illusion*, *Non-Illusion*) on the VPT performance accuracy and reaction times. The first test revealed a significant main effect of condition on VPT accuracy $F(2,78)=11.01$, $p<.001$. Two Bonferroni corrected paired sample t-tests ($\alpha=0.025$) revealed a significant difference between *Baseline* and *Non-Illusion* VPT accuracy; $t(39)=-4.15$, $p<0.001$ and *Baseline* and *Illusion* VPT accuracy; $t(39)=-3.11$, $p=0.007$, such that participants performed best (highest value) in the *Non-Illusion* condition ($M=-0.12$, $SD=0.16$), then the *Illusion* condition ($M=-0.15$, $SD=0.15$) and lastly the *Baseline* condition ($M=-0.24$, $SD=0.18$), (see Figure 4.7).

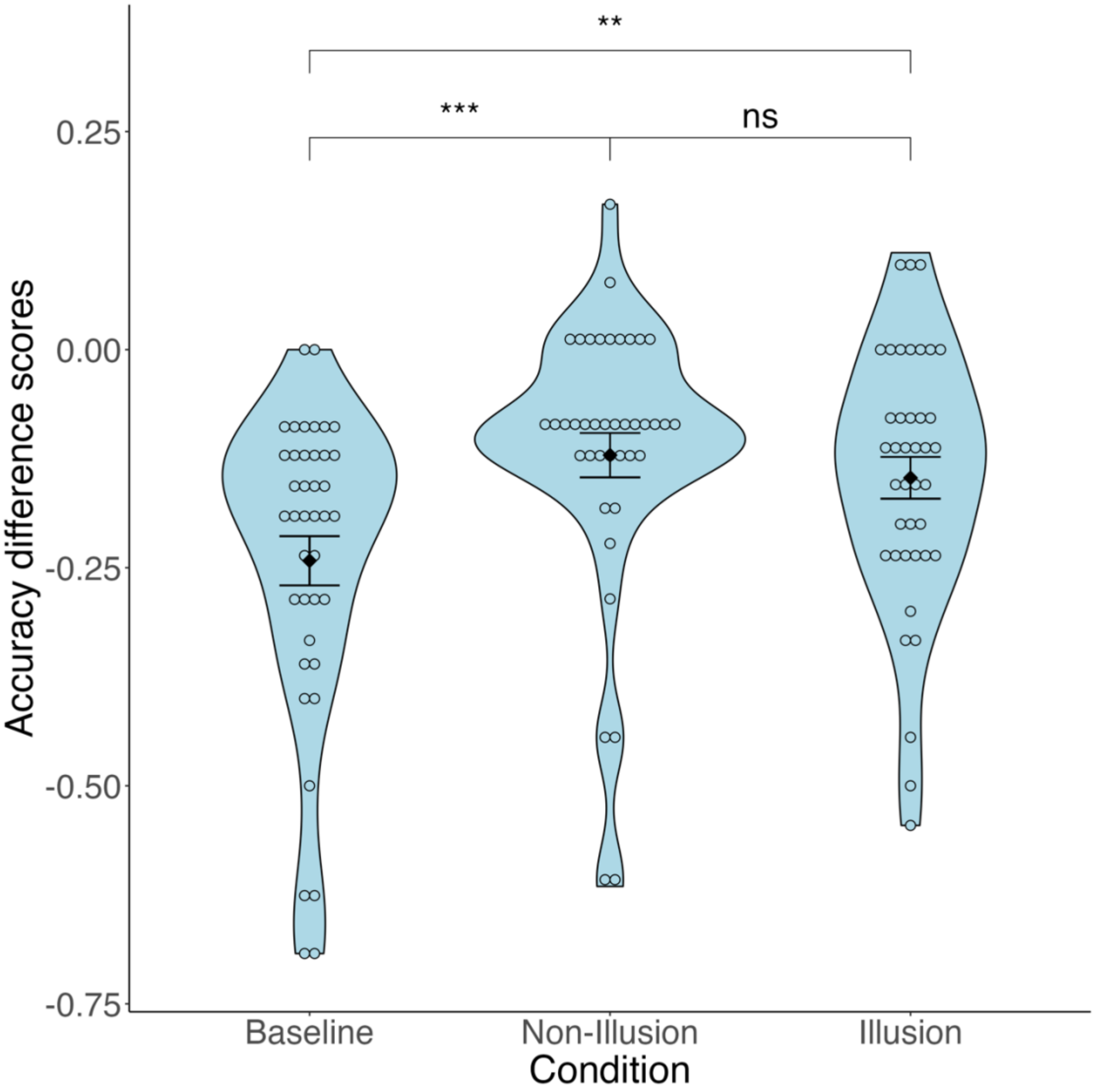

Figure 4.7. Violin plot of the mean accuracy OR adjusted difference scores in the VPT task for the Baseline, Illusion and Non-Illusion conditions. The black diamonds represent the means, the circles represent individual datapoints. Whiskers indicate standard error of the mean.
Brackets show the pairwise comparisons **= *p*≤.01, ***=*p*≤.001, ns=non-significant.

The second test revealed no significant main effect of condition on the reaction time scores in the VPT task; F(1.4,54.55)=.33, *p*=.64. The assumption of sphericity was violated for this effect, as specified by Mauchly's test, $X^2(2)$=.57, *p*<.001, thus, degrees of freedom are reported using the Greenhouse-Geisser estimates of sphericity. Participants were fastest (lower scores) at responding with correct answers in the *Non-Illusion* condition (*M*=0.30, *SD*=0.59) then the *Illusion* condition (*M*=0.41, *SD*=0.62) and lastly, the *Baseline* condition (*M*=0.42, *SD*=0.88), (see Figure 4.8).

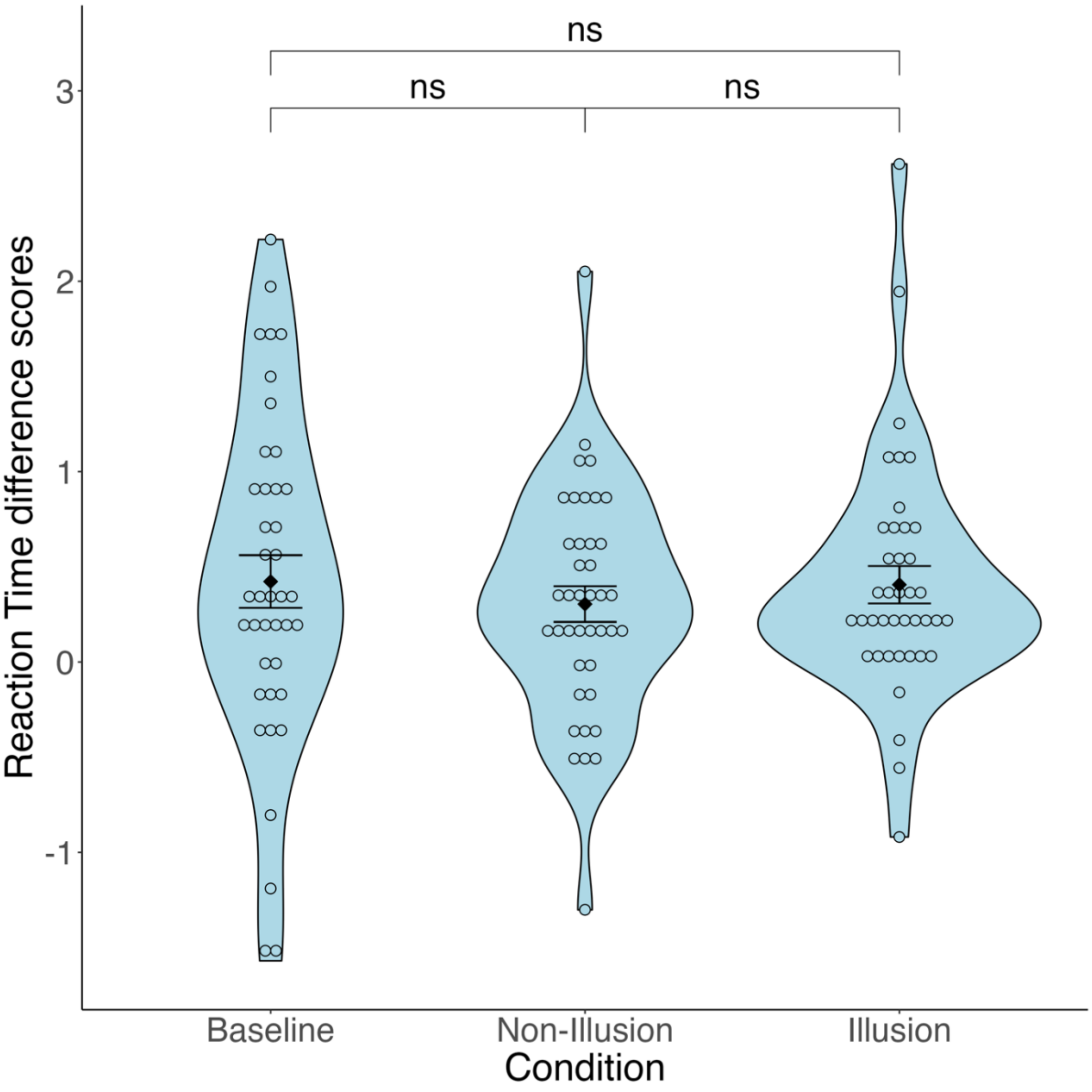

Figure 4.8. Violin plot of the mean OR adjusted reaction time difference scores in the VPT task for the Baseline, Illusion and Non-Illusion conditions. The black diamonds represent the means, the circles represent individual datapoints. Whiskers indicate standard error of the mean.

Brackets show the pairwise comparisons, ns= non-significant.

Hypothesis 2: Greater localisation error will relate to better VPT2 performance

Spearman's correlation analyses were conducted between localisation and VPT *Baseline* accuracy and reaction times scores (see Appendix 4.2 for parametric test results). As there was no significant effect of the Illusion condition on VPT2 accuracy or reaction times, VPT performance was collapsed across conditions to enter into the correlation analysis.

We found there was no significant relationship between localisation error score and VPT accuracy; (*r(*38)=-0.027, *p*=.87), as can be seen in Figure 4.9A. In addition, we found no significant correlation between localisation error and VPT reaction times; (*r*(38)=-.077, *p*=.64), as can be seen in Figure 4.9B.

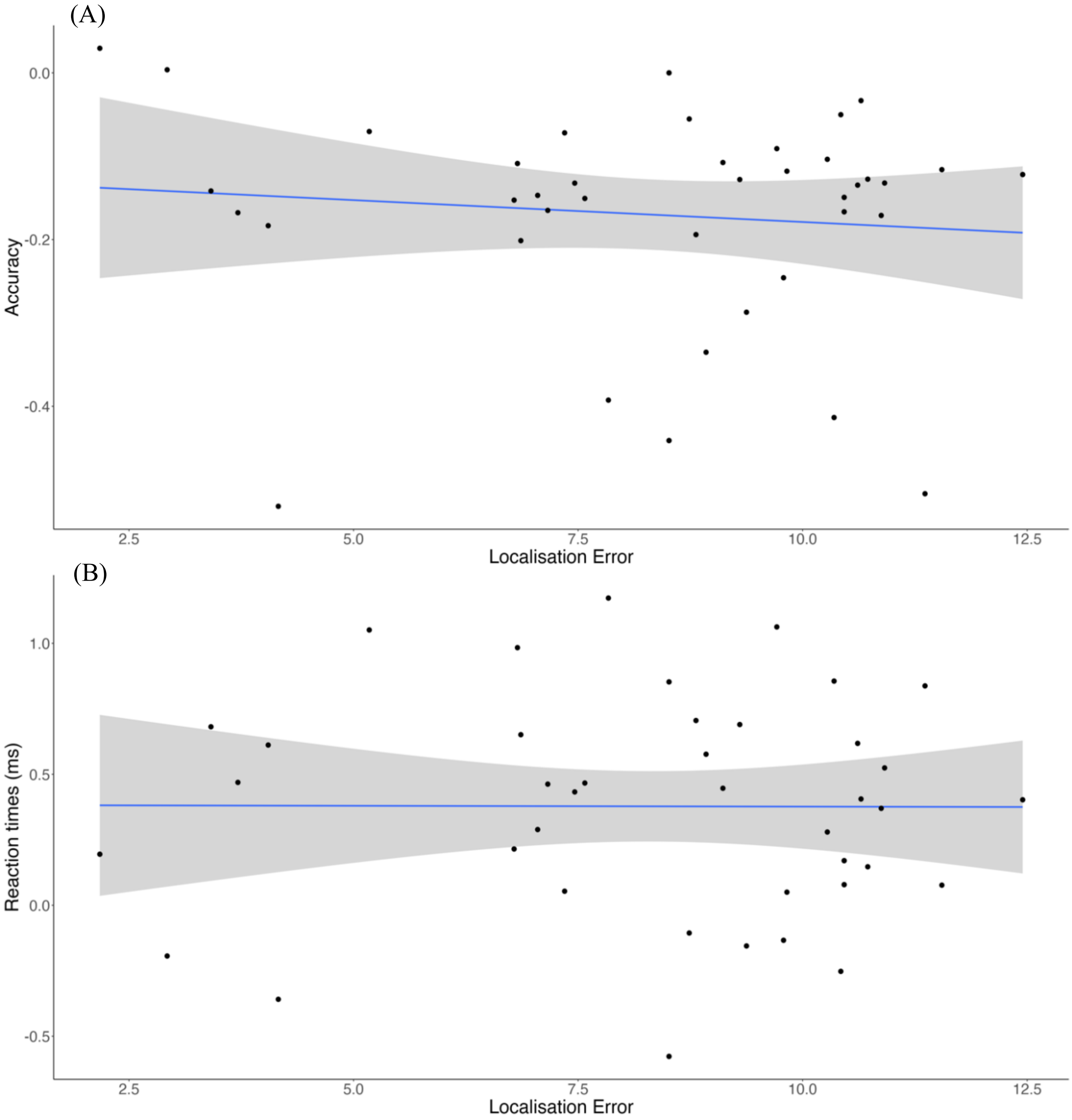

Figure 4.9. Localisation error (cm) and (A) mean accuracy in the VPT trials (OR adjusted) (B) mean reaction times (s) in the VPT trials (OR adjusted). Linear regression lines are represented by the blue lines and standard error is represented by the grey bars.

4.4 Discussion

The current study aimed to investigate whether the experience of self-location and visuo-proprioceptive integration are implicated in VPT2. Using the Disappearing Hand Trick (DHT) and the MIRAGE mediated reality system we induced a drift in self-location towards a virtual hand which was spatially incongruent with the participant's real hand. We investigated whether disruption to the experience of self-location would negatively impact VPT2 performance. In addition, we investigated whether better integration of visuo-proprioceptive inputs was associated with faster and more accurate VPT2 performance. Contrary to Hypothesis 1, we found that disrupting the experience of self-location using the DHT did not impact upon participants' accuracy or reaction times in the VPT2 task. Furthermore, we did not find evidence of visuo-proprioceptive integration being related to VPT2 performance (Hypothesis 2).

Research has found that to take the perspective of another person, one must hold an internal representation of the body (i.e., body schema) to perform egocentric rotations of the body (Gunia et al., 2021; Kessler & Rutherford, 2010; Surtees et al., 2013a, 2013b). Importantly, the experience of self-location is thought to be a crucial component of the body schema (Riva, 2018; Serino et al., 2013). In the current study, whilst the sensorimotor adaptation procedure in the DHT caused participants to shift their perceived self-location towards the virtual hand, we found no evidence that this impacted VPT2 performance (Hypothesis 1). Indeed, we found that the disruption to the experience of self-location caused by the *Illusion* condition did not reduce accuracy or processing times on the VPT2 task compared to the *Non-Illusion* or *Baseline* conditions. This may suggest that the experience of self-location is not implicated in the ability to take another person's visual perspective. This finding is contrary to our first hypothesis, in addition to what previous findings have indicated (Gunia et al., 2021; Kessler & Rutherford, 2010; Surtees et al., 2013a, 2013b).

One explanation for this finding is that participants were not using an embodied transformation strategy to take the perspective of the human avatar. Previous work has found that as the angular disparity between the participant and the avatar increases, VPT2 reaction times similarly increase (Surtees et al., 2013b). This shows that the larger the rotation, the more time required to mentally transform the self into that position, which thus evidences the use of an embodied egocentric strategy (Kessler & Rutherford, 2010). In the current study, the angular disparity in the VPT trials can be considered as the degree of rotation of the human avatar away from the participant (90º left, 90º right or 180º). Additional analyses revealed a significant main effect of angular disparity in the VPT trials (across all conditions; *Illusion*, *Non-Illusion* and *Baseline*) for accuracy ($F(2,120)=3.58$, $p<.001$) but not reaction times ($F(2,120)=0.44$, $p=0.65$). The lack of angular disparity in the reaction times for the VPT trials contradicts previous work which has found that greater egocentric transformation angles result in slower performance (Kessler & Rutherford, 2010; Surtees et al., 2013b). This is likely due to the VPT task utilised in the current study. Participants viewed videos of the puppet being rotated, and thus it is possible that participants mentally made their response selection before the end of the trial (i.e., when the puppet had stopped rotating), thus reducing variability in reaction times. Nevertheless, strong orientation effects for accuracy were observed, in line with previous work (Pearson et al., 2014; Voyer et al., 2017), suggesting that participants were using a simulative rotation of their own body to evaluate the visual perspective of the human avatar. Future research may benefit from utilising a cognitive debriefing procedure to allow participants to verbalise what strategies they used to complete the VPT.

An alternative explanation is that the *Illusion* condition did not successfully disrupt participant's experience of self-location and thus body schema. If participants had an accurate idea of where their body was located, then we would expect no difference in localisation error in the *Congruent* and *Incongruent* condition of the hand localisation task. However, we found that participants were significantly more likely to mislocalise their right hand in the *Incongruent* condition, as has been found previously (Newport & Gilpin, 2011; Ratcliffe et al., 2021). This demonstrates that the sensorimotor adaption procedure used in the *Illusion* condition significantly impacted where participants experienced their right hand to be located. Importantly, this suggests that participants did not have an accurate idea of where their right hand was located, such that when their left hand was moved to the perceived location of their right hand and it was not felt to be there, their experience of self-location should have been disrupted. However, it is possible that once participants felt that their right hand wasn't where they thought, tactile input may have updated their body schema (Blanke, 2012), thus not sufficiently disrupting the body schema whilst participants were completing the VPT2 task. Additionally, it is unknown whether participants subjectively experienced a 'loss of limb' sensation. As such, future research utilising a cognitive debrief procedure may provide insight into the subjective experience of participants during a body illusion task.

Alternatively, it is possible that manipulation of self-location of the right hand was not sufficient to impact upon full-body egocentric transformations. Indeed, the body schema is thought to be formed from sensory modalities from multiple parts of the body (de Vignemont, 2011; Longo et al., 2010; Medina & Coslett, 2010). As such, the shift in self-location away from the right hand may not have impacted upon the whole-body experience of self-location. Future work could adopt a full-body illusion paradigm as has been used previously (Aspell et al., 2009) to manipulate whole-body self-location to investigate whether this component of bodily self-consciousness is implicated in VPT2 (see Chapter 7, Section 7.3.1).

Research has evidenced that VPT relies on embodied transformations of the body which in turn relies upon holding an internal representation of the body, formed through multisensory integration (Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Pearson et al., 2014; Surtees et al., 2013a, 2013b). Indeed, optimal MSI is key to holding a body schema and individuals with more optimised MSI are thought to be more susceptible to body illusions (Blanke, 2012; Blanke & Metzinger, 2009; Greenfield et al., 2017; Ratcliffe et al., 2021). Thus, we would expect that individuals with greater MSI would exhibit a greater localisation error and better VPT2 performance. However, contrary to Hypothesis 2, we found no evidence of a relationship between visuo-proprioceptive integration (as measured by hand localisation error) and VPT performance. This may suggest that the process of effectively integrating visual and proprioceptive signals is not associated with the ability to take another person's perspective.

This finding might be explained by a trade-off between optimal MSI and body schema disturbance. It is possible, that individuals with heightened MSI would exhibit a greater localisation error and would in turn be more impacted by the effects of the illusion, thus reducing VPT2 performance. Conversely, individuals with less efficient MSI might exhibit reduced localisation error, be less impacted by the illusion and thus show no reduction in VPT2 performance. As a result, this could plateau the correlation between localisation error and VPT2 performance. If this is the case, we would expect that those with greater localisation errors would show a greater drop in VPT performance between the *Baseline* and *Illusion* conditions. However, in additional analysis we found no significant correlation between localisation error and difference in performance between the *Illusion* and *Baseline* performance (baseline VPT accuracy – illusion VPT accuracy); *r*(38)=-0.130, *p*=.43. Moreover, when a median split of the sample based on localisation error was performed (high and low localisation error), a mixed ANOVA revealed no significant main effect of error (high or low) on VPT accuracy across conditions; *F(*1,38)=.08, *p*=.78. Additionally, there was no significant interaction between condition (*Baseline*, *Non-Illusion*, and *Illusion*) and error group (high or low localisation error); *F*(1.62, 61.59)=2.04, *p*=.71. Subsequently, it is unlikely that an interaction between localisation error and effect of illusion could explain the lack of relationship between localisation error and VPT performance.

Alternatively, it is possible that the VPT task was not challenging enough for participants for true variability to be exhibited in the data. Indeed, 14 participants (35%) exhibited 100% accuracy in at least one condition of the VPT task. Future work should seek to utilise a more challenging VPT task for adults. For example, instead of using video stimuli, adult participants could be shown visual scenes in which they have to quickly identify the orientation of an object from another person's perspective. The task could be made more challenging by presenting the stimuli for a short amount of time and by giving a narrow response window. This would require participants to process and respond more quickly, making the task more difficult and therefore reducing the chance of ceiling effects.

Conclusions

The current study investigated whether the experience of self-location and visuo-proprioceptive integration are implicated in VPT2. Using the Disappearing Hand Trick and the MIRAGE mediated reality system we manipulated the perceived self-location of the right hand. Contrary to our first hypothesis we found that disrupting the experience of self-location of the right hand did not reduce subsequent performance in a VPT2 task. Secondly, we did not find evidence of visuo-proprioceptive integration being related to VPT2 performance. These findings have elucidated the link between sensorimotor integration and social processing by suggesting that holding an accurate spatial representation of a limb, formed through visuo-proprioceptive integration may not be implicated in the ability to take another person's perspective. Future work should aim to adopt full-body illusions to ascertain whether self-location of the whole body is associated with VPT2, to further understand the relationship between sensorimotor processing and social interactions.

Chapter Introduction

In Chapter 4 we explored the contribution of self-location and visuo-proprioceptive integration in visual perspective taking. Visual perspective taking is thought to be a key component of social processing as it allows us to understand how others view the world. Beyond how people *see* the world, being able to understand how people *move* in the world is also thought to be socially advantageous. Understanding other people's actions allows for imitation, mimicry, and interpersonal synchrony, which are key elements of social interaction. Chapter 5 will seek to understand the contribution of sensorimotor processes in interpersonal synchrony. This will be explored through investigation of how sensorimotor processes relate to visuomotor synchrony in children and adults. Exploring interpersonal synchrony from a developmental perspective has the potential to offer insight into 1) the directionality of the relationship between sensorimotor integration and social processing and 2) the mechanisms underpinning interpersonal synchrony and its social bonding outcomes.

Chapter 5: The Contribution of Sensorimotor Processes in Interpersonal Synchrony and Social Bonding

The empirical work presented in this chapter is published in the Scientific Reports journal: Howard, E. M., Ropar, D., Newport, R., & Tunçgenç, B. (2021). Social context facilitates visuomotor synchrony and bonding in children and adults. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-02372-2 [2]

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[2] The author, Ellen M. Howard, contributed to the design of the experiment, collected that data, analysed the results, and wrote the manuscript under the supervision of Dr. Danielle Ropar, Dr Roger Newport, and Dr Bahar Tunçgenç. We would like to thank Lauren Fingret and Lucy Drage who contributed to the data collection in Study 1.

Abstract

Interpersonal synchrony is a fundamental part of human social interaction, with known effects on facilitating social bonding. Moving in time with another person facilitates prosocial behaviour, however, it is unknown if the degree of synchronisation predicts the degree of social bonding. Similarly, while people readily fall in synchrony even without being instructed to do so, we do not know whether such spontaneous synchronisation elicits similar prosocial effects as instructed synchronisation.

Across two studies, we investigated how context (social vs non-social stimulus) and instruction (instructed vs uninstructed) influenced synchronisation accuracy and bonding with the interaction partner in adults and children. The results revealed improved visuomotor synchrony within a social, compared to non-social, context in adults and children. Children, but not adults, synchronised more accurately when instructed to synchronise than when uninstructed. For both children and adults, synchronisation in a social context elicited stronger social bonding towards an interaction partner as compared to synchronisation in a non-social context. Finally, children's, but not adults', degree of synchrony with the partner was significantly associated with their feelings of social closeness. These findings illuminate the interaction of sensorimotor coupling and joint action in social contexts and how these mechanisms facilitate synchronisation ability and social bonding.

5.1 Introduction

Interpersonal synchrony, whereby two or more people move in temporal and spatial coordination with each other, is observed frequently and cross-culturally in group dance, marching bands, and children's clapping games (Ehrenreich, 2006; McNeill, 1995). Research investigating embodied cognition has shown that synchronous interpersonal movement plays a crucial role in social bonding starting from early infancy (Cirelli at al., 2014; Trainor & Cirelli, 2015; Tunçgenç, et al., 2015; Tunçgenç & Cohen, 2016a). Interpersonal synchrony may serve important cultural-evolutionary functions by helping establish and communicate positive affect, group identity, and bonding with others (Mogan, et al., 2017). Distinctly from other forms of social coordination (e.g., mimicry and imitation), in interpersonal synchrony, individuals become temporally and spatially aligned in their movements rather than after a short delay. It has been shown that interpersonal synchrony is a self-organising system which can be mathematically modelled (see Coey et al., 2012). Such modelling specifies that oscillations of synchronised individuals settle either within in-phase synchrony (i.e., individuals move in the same way at the same point in the cycle) or anti-phase synchrony (i.e., individuals move with opposite movement at the same point in the cycle) – similar to the oscillations of physical metronomes. There is growing evidence to suggest that interpersonal synchrony is driven by the same coordination principles of the physical world across different contexts, underpinned by the same self-organising physical principles (Kelso 2013; Schmidt et al. 2011; Schmidt & Richardson, 2008). However, relatively little is known about how social versus non-social contexts impact synchronisation ability and its subsequent social bonding outcomes in children and adults. Building upon bottom-up sensory and top-down joint action accounts of interpersonal synchrony, we examined the conditions that facilitate synchronisation and its social bonding outcomes in adults (*Study 1*) and in children (*Study 2*).

Individuals can synchronise their movement with a non-social object (i.e., a metronome) or with another person (interpersonal synchrony). When moving together with another person, different degrees of shared intentionality may exist among the interacting partners. For instance, two individuals may be instructed to synchronise with each other ('instructed synchrony'), they may be instructed to synchronise with an external metronome beat and may thus end up moving synchronously with each other ('incidental synchrony') or they may spontaneously synchronise their movements in the absence of any instruction on how to move ('uninstructed synchrony'). Research investigating interpersonal incidental synchrony has found that individuals feel more bonded to others after performing a task with them that involves synchronous, as compared to asynchronous interpersonal movement. For instance, adults exhibit increased feelings of bonding, trust, empathy, and pro-social behaviours following interpersonal synchrony (Anshel & Kippler, 1988; Hove & Risen, 2009; Launay et al., 2014; Valdesolo et al., 2010; Wiltermuth & Heath, 2009). Adults are also more likely to imitate a partner after engaging in a synchronous movement task with them as compared to after performing those movements asynchronously with their partner (Cross et al., 2021). Similarly, in children, interpersonal synchrony has been shown to facilitate pro-social sharing (Rabinowitch & Knafo-Noam, 2015; Rabinowitch & Meltzoff, 2017) and helping behaviour (Tunçgenç & Cohen, 2016a). Therefore, moving in coordination with other people seems to incur social interaction benefits. Synchrony and social bonding outcomes can in turn be influenced by more complex social structures such as identity, intergroup dynamics and representations of self and other (Hove, 2008; Miles et al., 2011; Tunçgenç & Cohen, 2016b). Since movement synchrony helps forge and signal shared goals/intentions, group alliance and similarity, it has been proposed to play a prominent role in social interactions. What, then, are the mechanisms that link movement alignment in the form of visuomotor synchrony to positive social bonding outcomes? Two prominent accounts have been put forth in the literature to explain the synchrony – social bonding link: a bottom-up sensorimotor coupling account and a top-down joint action account.

Sensorimotor coupling defines the process whereby an external rhythm is identified (e.g., through visual observation) and integrated into one's own movements (Phillips-Silver et al., 2010). Previous research has shown that interpersonal synchrony is improved when information about an external rhythm is available through multiple modalities, for example visual and auditory (Gipson et al., 2016). Further, some stimuli may be easier to couple with than others. For instance, viewing a biologically similar stimulus (i.e., hand), compared to a non-social, mechanical stimulus, can facilitate synchronisation (Kirschner & Tomasello, 2009), arguably due to the ease of creating motor representations of the other person's actions (Calvo-Merino et al., 2005; Iacoboni et al., 1999, Brass & Heyes, 2005; Rizzolatti, 2005; Casile et al., 2011). In turn, perceptual representation of synchronised movement may result in a less effortful and more rewarding experience through minimising neural processing costs (Koban et al., 2019), thereby creating a cycle encouraging interpersonal synchrony. Indeed, an fMRI study has shown the brain's reward system to be activated following synchronous, as compared to asynchronous, interpersonal movement (Kokal et al., 2011). Moreover, previous work has investigated whether the exact degree of synchrony predicts social bonding, as this would suggest that sensorimotor coupling between individuals is a key driver of interpersonal synchrony and its subsequent social bonding outcomes. The evidence has been mixed. While one study found that the degree of synchrony between individuals predicted subsequent feelings of affiliation (Hove & Risen, 2009), more recent work has found that degree of coordination did not predict cooperation between individuals (Cross et al., 2016). Thus, more research is needed to understand under which conditions the degree of synchrony is related to positive social interactional outcomes. Given that adults and children show greater social bonding to a partner following incidental synchrony, (e.g., Hove & Risen, 2009; Tunçgenç &

Cohen, 2016a) a social context that encourages sensorimotor coupling may facilitate synchronisation accuracy and feelings of social closeness.

Top-down joint action processes can also facilitate interpersonal synchrony, and indeed modulate how quickly sensorimotor coupling takes place. Joint action can be defined as the coordination or complementarity of two or more individuals' actions "to bring about a change in the environment" within a social interaction (Sebanz et al., 2006). According to this framework, the shared goal and mutual knowledge that the goal is shared, unites the interaction partners' intentions, attention, and representation of the task in hand (Tomasello et al., 2005). These shared representations enable easier prediction of the other's behaviour and coordination of movements (Sebanz et al., 2006; Ramenozi et al., 2015). Note that all instructed, uninstructed and incidental types of synchrony can occur within joint action contexts, depending on what the objects of people's shared intentions are.

Prior research has indeed found that joint action contexts facilitate synchronisation, even when individuals share a goal or intention that is not related to synchronisation. For example, individuals who shared a mutual goal to empty a box of 100 plastic balls coordinated movements more than those without a shared goal (Allsop et al., 2016). Moreover, research has shown that sharing visual attention during a joint task alone can be sufficient to promote feelings of social closeness with a partner (Wolf et al., 2016). Other work has found that individuals with a shared intentionality to move in time with each other reported feeling closer to each other than those with a shared intentionality to synchronise with an auditory beat, i.e., when emergence of interpersonal synchrony was incidental (Reddish et al., 2013). The authors conclude that a combination of synchrony and shared intentionality to synchronise gives rise to the greatest social bonding outcomes. Additionally, when participants shared the intention to synchronise with each other, and the salience of a social context (i.e., synchronisation with visible actors vs point-light displays) was enhanced, even less precise forms of synchronisation elicited similar levels of cooperation (Cross et al., 2016). Furthermore, recent work has found that when adults intentionally moved in time with a partner, they were more likely to imitate their partner's actions, compared to a partner they had not moved in time with (Cross et al., 2021). This work also found that when individuals incidentally moved in time with each other (i.e., were not instructed to synchronise) they were no more likely to imitate each other than those who did not incidentally synchronise. This suggests that a shared intention to synchronise may be fundamental for promoting imitation. Thus, beyond precise sensorimotor coupling, the social bonding outcomes of synchrony seem to depend on whether synchronisation occurs within a salient social context in which joint action can arise. Based on this research, we might expect that instructing a participant to synchronise with a partner would facilitate synchrony and social bonding outcomes. In light of this, the current study aims to investigate the impact of instruction on synchronisation accuracy within social and non-social contexts.

The facilitatory effect of a joint action context on synchronisation has been shown even in the absence of any explicit instruction to synchronise with the other person. In adults, studies have robustly shown that people tend to spontaneously entrain to others' movements when walking (Nessler et al., 2011), swinging their legs (Schmidt et al., 1990), clapping (Nèda et al., 2000) and rocking in chairs (Richardson et al., 2007). One study found that children as young as 2.5-year-olds spontaneously synchronise their drumming and do so better when performing drumming with another person as opposed to with a robot (Kirschner & Tomasello, 2009). These findings suggest humans have a natural propensity to synchronise with others, with synchronisation improving when both sensorimotor coupling and joint action are facilitated simultaneously. Still, we do not know whether social bonding outcomes would follow from uninstructed synchronisation in children and adults.

Across two studies, we investigated how adults (*Study 1*) and children (*Study 2)* synchronise their movements and subsequently bond with their interaction partner. Synchronisation was assessed with a finger-tapping task, with participants being randomly assigned to either the instructed or uninstructed condition. Combining the bottom-up and top-down accounts of interpersonal synchrony, we created a social context that included joint action (i.e., participant tapping together with the partner) and better opportunities for sensorimotor coupling (i.e., participant viewing the partner's hand). This social context was contrasted to a non-social context that included neither joint action (i.e., participant tapping on their own while the partner is doing another task) nor enhanced sensorimotor coupling (i.e., participant viewing a moving ball). The adult study aimed to establish the effects of instruction within a social context on synchrony and social bonding, before investigating if similar results would also be found in children.

We made four predictions: (1) during a finger-tapping activity, children and adults will synchronise with the stimulus better in the social than in the non-social context, (2) children and adults will feel more bonded to their partner after completing the finger tapping task in a social as compared to a non-social context, (3) synchronisation accuracy and social bonding will be greater in the instructed compared to uninstructed condition, and (4) the degree of interpersonal synchrony in the social context will positively predict social bonding. The latter hypothesis would reveal the relative contributions of the top-down versus bottom-up processes – beyond performing a task in a joint action context, the precise degree of sensorimotor coupling would be associated with the social bonding effects observed after interpersonal synchrony. Given that children as young as 2.5 years of age are able to synchronise with external stimuli and show improvement in synchronisation within a social context (Kirschner & Tomasello, 2009), we would not anticipate a different pattern of results for children compared to adults, however the children may be more variable (Kurganksy & Shupikova, 2011).

Study 1: Adults

5.2 Methods

Participants

Forty-three adults (37 women, 6 men, M_{age} = 20.44 years), predominantly White, undergraduate students, participated in the current study. Students volunteered to participate in return for course credit. Data from three participants were removed due to experimenter error. Therefore, the final sample consisted of forty adults (34 women, 6 men, M_{age} = 20.38 years) evenly split into the instructed and uninstructed conditions. Ethical approval for both *Study 1* and *Study 2* were granted by the School of Psychology ethics committee at the University of Nottingham, reference number: F1075R. The experiment was conducted in accordance with the key ethical standards of the Declaration of Helsinki and GDPR. Informed consent was obtained from all participations prior to participation.

Design

A 2 (context: social vs non-social) x 2 (instruction type: instructed vs uninstructed) x 2 (stimulus tempo: 750ms vs 1000ms tempo) mixed design was used. All participants were presented with two social and two non-social trials, with the visual stimulus being presented at 750ms and 1000ms tempo within each condition. The two speeds (750ms and 1000ms) were used in order to maintain engagement with this repetitive task, and to prevent tempo practice effects, particularly as the same task was used with both children and adults. No specific hypotheses were made about the effects of the speed conditions, though they were nevertheless included in the analysis to control for any potential confounding effects speed might have on synchronisation ability. The between-group factor was type of instruction, in which half of the participants were explicitly instructed to synchronise with the visual stimulus whilst the remaining half were told to tap as they wish, without any emphasis on synchronising with the stimulus. Participants were randomly assigned to the instructed or the uninstructed condition. Order of the social and non-social trials as well as the stimulus tempi was fully counterbalanced. The dependent variables were synchronisation accuracy (i.e., difference from the stimulus in ms) and social bonding as measured by subjective assessment of proximity with the partner.

Materials and Measures

Synchronisation accuracy.

The tapping tasks were conducted using a mediated reality device called MIRAGE (see Figure 5.1A; Newport et al., 2010;2011), which presents live video images of the participant's hand in real time. When participants put their hand into the MIRAGE device, they can no longer see their actual hand; instead, they see a live footage (minimal delay of 16ms) of their hand in the same spatial location, depth plane and from the same visual perspective as their 'real' hand. Each participant had their arm covered with a black curtain to prevent them from viewing their 'real' hand within the MIRAGE device. This device has been successfully used with adults and children in previous research (e.g. Greenfield et al., 2017; Newport & Gilpin, 2011; Newport et al., 2015; Ratcliffe et al., 2021; Ropar et al., 2018).

In our study, the social (hand) and non-social (moving circle) stimuli were presented in the MIRAGE window opposite the live image of the participant's hand, as can be seen in Figure 5.1A. Finger taps were registered using a button placed under the participant's index finger. The MIRAGE device was connected to a computer that controlled the tempo of the visual stimulus and recorded the timestamps of the participants' taps at millisecond precision. Each participant completed four trials in total: two trials in the social context (at 750ms and 1000ms tempo) and two trials in the non-social context (at 750ms and 1000ms tempo). Each trial consisted of 70 cycles of visual stimulus. Therefore, for each participant, approximately 140 responses were recorded for the social context and 140 for the non-social context.

Synchronisation error was calculated as the Root Mean Square (RMS) of the difference between the participant's and the stimulus' inter-tap intervals. The stimulus inter-tap intervals were constant over time within a trial (i.e., either 750 or 1000, depending on the stimulus tempo). To calculate the participants' inter-tap intervals, we subtracted the timestamp of one tap from the timestamp of the subsequent tap in a sliding window fashion (window size = 2 taps). Next, the difference between the participants' inter-tap intervals and that of the stimulus was taken. Finally, the RMS of this difference was calculated, yielding one synchronisation error score per participant per trial. To obtain single synchronisation accuracy scores for the social and non-social conditions each, we took the mean of the two trials comprising these conditions, respectively. Synchronisation error scores closer to zero indicate less difference between the participant and the stimulus, and thus better synchronisation accuracy.

Social closeness

Social closeness was measured using the 7-point Inclusion of Other in Self scale (Aron et al., 1992). In this scale, two circles labelled "you" and "[partner's name]" were shown in differing proximities to each other across the 7 points, starting with very distant at 1 and gradually getting closer, with a near-merging image at 7. To calculate the change in feelings of closeness, a baseline measure was taken once at the start of the study and four more times at the end of each tapping trial. Change in social closeness was calculated separately for each experimental trial by deducting the participants' baseline score from their score following that trial. Then, the mean of the two difference scores obtained from the social and the non-social trials were taken to construct one social and one non-social score per participant, respectively. The more positive the social bonding difference values are, the closer the participant felt towards the experimenter after the tapping task as compared to baseline.

Procedure

All participants were tested in a quiet room at The University of Nottingham, where they were sat across from the experimenter and the partner in both social and non-social context conditions (see Figure 5.1B for a schematic of the set-up). The experimental procedure took a total of 30 minutes.

Firstly, participants completed a baseline measure of the *Inclusion of Other in Self* scale. Then, participants placed their dominant hand into the MIRAGE to start the finger tapping task. The participants were instructed to place the tip of their index finger on a button that was used to register taps. The button made a dull click when tapped. The participants were instructed to keep their hand in this location throughout all trials. All participants completed a practice trial to ensure they were comfortable with MIRAGE and that they understood the task. Once five consecutive taps had been successfully registered, the practice trial was terminated, and the participant proceeded to the experimental trials.

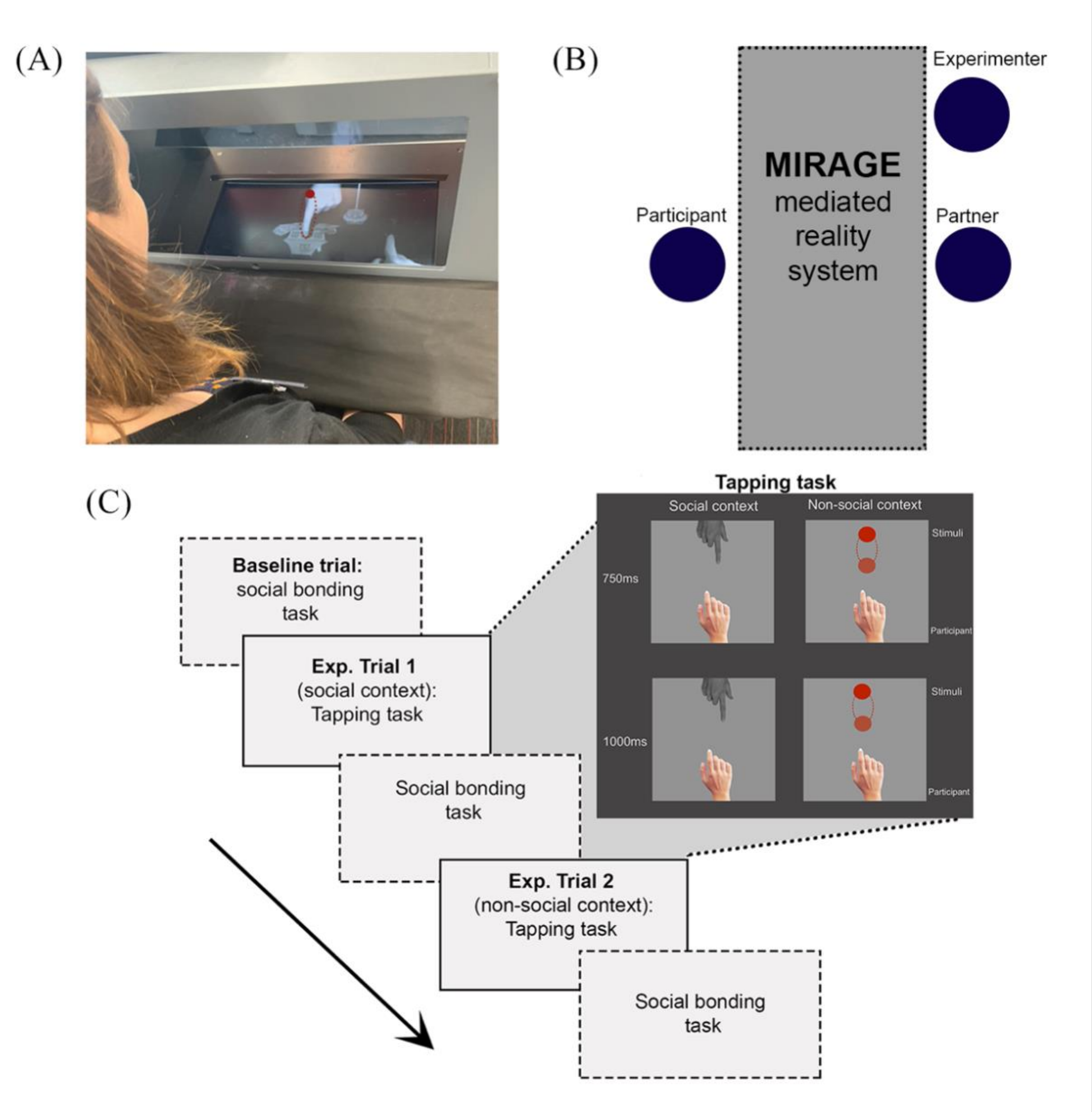

Figure 5.1. Schematic of the study procedure.

(A) Participant view of the MIRAGE window, with their hand on the bottom right of the window and the social stimulus (partner's hand) and non-social stimulus (red ball) opposite. The cartoon house and animal were used in the child-friendly dummy task.

(B) Study set-up. The partner sat in the same position in both the social and the non-social context conditions.

(C) Procedure of Study 1 and Study 2 (order of context and stimulus tempo counterbalanced across participants). In Study 1, participants completed two social context trials at each tempi and two non-social context trials at each tempo, therefore a total of four tapping trials. In Study 2, participants only completed one social trial and one non-social trial, with the tempo varied between trials (e.g. social at 750ms and non-social at 1000ms) for a total of two tapping trials.

In the experimental trials, participants completed two social and two non-social context trials, each followed by the social closeness measure (see Figure 5.1C). Regardless of the instruction condition, all participants were first given the following instructions: “If you look through the MIRAGE window, you will see a ball (non-social context) moving elliptically up and down or [the partner’s name]’s finger (social context) tapping. Please start tapping as soon as you see the ball/finger start and keep tapping until it stops”. At this point, the instructions diverged depending on the instruction condition. While participants in the instructed condition were told to “try to tap in time with the ball/finger as best as you can”, participants in the uninstructed condition were told “to keep looking at the ball/finger while tapping as slowly or as fast as you wish”. Participants were randomly assigned to either the instructed or uninstructed condition.

In the non-social context, a red ball moved up and down in an elliptical movement for the duration of the trial. In the social context, participants viewed a pre-recorded video of a hand tapping although they were told that the partner was tapping in real time. The size of the area in which the visual stimulus moved was kept constant across the social and non-social stimuli to ensure that the amount of visual information was similar between conditions. In both social and non-social context, the partner sat opposite the participant, without explicitly interacting with the participant (e.g., by making eye contact or smiling). The only differences between contexts were that in the social context: (a) the participants were told that the partner was also finger-tapping, and (b) the participants viewed a hand, rather than a ball, as they tapped. The partner was alternated between two researchers across participants.

To ensure that all participants attended to the stimuli similarly in all conditions, we also introduced a dummy task. A child friendly dummy task was used so it could also be introduced in *Study 2*. Participants were told the visual stimulus was knocking on the door of the house (see Figure 5.1A) and waking up the animals inside. Pictures of animals would then appear next to the visual stimulus 2-3 times per trial. Since the animal pictures appeared next to the target stimulus, participants were required to look towards the stimulus at all times and then tell the names of the animals whose pictures popped up.

5.3 Results

Data Analysis

For both *Study 1* and *Study 2*, the timestamp data was processed using a custom-written script on MATLAB R2018b and the statistical analyses (including the power analysis using package "pwr"; Champely et al., 2020) were conducted using R (R Core Team, 2014). To examine Hypotheses 1 – 3, mixed 2 (context: social vs non-social – within variable) x 2 (instruction: instructed vs uninstructed – between groups variable) x 2 (stimulus tempo: 750ms vs 1000ms – within variable) separate ANOVA tests were conducted with synchronisation accuracy and social bonding measures as the dependent variables. Stimulus tempo was included in the analyses as an independent variable despite not being part of a specific hypothesis to control for its potential effects on our outcome measures. To examine Hypothesis 4, linear regression was conducted within the social context, with synchronisation accuracy as the predictor and social bonding measure(s) as the outcome variable(s).

Hypotheses 1 and 3: Adults will synchronise with the stimulus better in the social than in the non-social context and when instructed compared to uninstructed.

A mixed 2x2x2 analysis of variance (ANOVA) was used to investigate the effects of context (social vs non-social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on synchronisation accuracy (i.e., RMS of inter-tap intervals). The results revealed main effects of context ($F(1,112) = 31.71$, $p < .0001$, partial η^2=.46), and tempo

($F(1,112) = 85.83$, $p < .0001$, partial $\eta^2=.70$) on synchronisation accuracy. There was no significant main effect of instruction or any significant interactions (all *p*s > .05; see. Appendix 5.1 for details). Participants synchronised better (i.e., lower error) in the social context (*M* = 343.66, *SD* = 103.04) than in the non-social context (*M* = 408.67, *SD* = 97.38; see Figure 5.2A) and better when the visual stimuli moved at 750ms tempo (*M* = 319.81, *SD* = 93.52) as compared to at 1000ms tempo (*M* = 431.70, *SD* = 84.68). These findings show that irrespective of whether explicitly instructed to do so, participants were better able to synchronise with the partner's hand in the social context compared to the moving ball stimulus in the non-social context. To account for the possibility of more errors in cases when inter-tap intervals are larger (i.e., stimulus tempo at 1000ms vs 750ms), we also calculated a normalised synchronisation accuracy metric by dividing the RMS inter-tap intervals by the stimulus tempo. Analyses using this normalised metric similarly showed significantly better synchrony performance in the social than in the non-social context (see Appendix *5.2*).

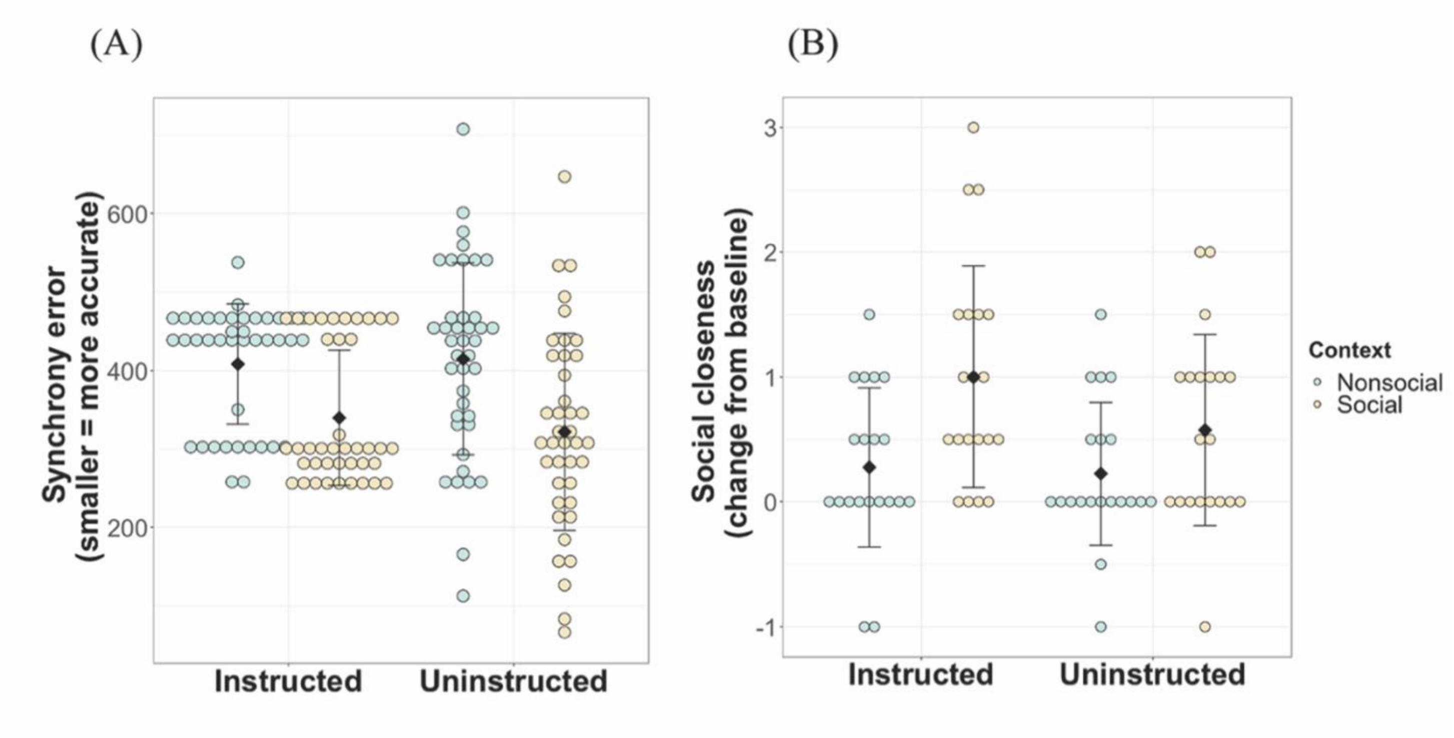

Figure 5.2. Synchronisation accuracy and social closeness by context and instruction conditions in adults.

(A) Synchronisation accuracy per context and instruction condition. The y-axis shows mean RMS of the difference in inter-tap intervals between the participant and the stimulus, with higher scores indicating more errors and worse synchrony accuracy.

(B) Social closeness per context and instruction condition. Mean change in closeness score (test – baseline), with higher scores indicating an increase in closeness as compared to baseline.

Coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.

Hypotheses 2 and 3: Adults will feel more bonded to their partner after completing the finger tapping task in a social as compared to a non-social context and when instructed compared to when uninstructed

To assess the impact of context (social vs non-social), stimulus tempo (750ms vs 1000ms), and instruction condition (instructed vs uninstructed) on change in social closeness from baseline, a mixed 2x2x2 ANOVA was employed. This analysis revealed a significant main effect of context ($F(1,114) = 58.11$, $p < .0001$, partial $\eta^2 = .34$), on social closeness. No other main effects or interactions were statistically significant ($p > .05$). While participants' social closeness towards the partner increased from baseline levels ($M = 5.90$, $SD = 0.98$) in both the social ($M = 5.08$, $SD = 1.20$) and non-social ($M = 5.68$, $SD = 1.05$) contexts, as can be seen in Figure 5.2B the increase was significantly higher in the social context ($M = 0.82$, $SD = 0.87$) as compared to the non-social context ($M = 0.23$, $SD = 0.66$). This suggests that social context, but not explicit instructions to synchronise, affected the participants' feelings of social closeness.

Hypothesis 4: The degree of interpersonal synchrony in the social context will positively predict social bonding

Finally, using linear regression analysis, we explored whether synchrony accuracy is associated with change in social closeness within the social context condition. The results were not significant ($F(1,38) = 0.92$, $\beta = .003$, $SE = .003$, $p = .34$, $R^2 = .001$), indicating that the degree of synchronisation with the partner was not related to the observed increase in feelings of social closeness.

5.4 Discussion

As predicted, we found that a social context facilitated synchronisation accuracy and social bonding with an interaction partner in adults. This novel finding in adults corresponds to previous work that has demonstrated social facilitation of synchronisation accuracy in children (Kirschner & Tomasello, 2009). Contrary to our predictions, synchronisation accuracy was not enhanced when the participants were explicitly instructed to tap in time with the stimulus, and the degree of interpersonal synchrony within the social context did not predict subsequent social bonding.

Despite the partner being present in both the social and non-social contexts, the social context enhanced synchronisation accuracy and social bonding significantly more than the non-social context did. This finding suggests that both synchronisation accuracy and social bonding can be facilitated (a) in a context in which the partner is perceived to be engaging in the task, and (b) when the participant views a biologically more similar stimulus that facilitates sensorimotor coupling. Given that our social context combined these two elements, we cannot identify specifically which aspect of the social context led to the observed effects. Nevertheless, these findings extend previous work that has found increased social bonding following instructed interpersonal synchrony (e.g., Hove & Risen, 2009; Marsh et al., 2009; Launay et al., 2014) by showing that the same effects are observed following uninstructed synchrony as well.

The hypothesised effect of instruction on synchronisation accuracy was not observed; participants were similarly accurate at synchronising with the visual stimulus in the instructed and uninstructed conditions. Yet, visual inspection of the data shows that participant responses were less variable in the instructed condition than in the uninstructed condition, with the responses in the instructed condition displaying a bipolar distribution, suggesting a clustering of the errors based on the stimulus tempo. The absence of an effect of instruction seems to contradict previous work demonstrating that intentionality facilitates synchronisation (van Ulzen et al., 2008; Leow et al., 2018). However, in the current study, the intention was not explicitly shared between the participant and the partner, whilst in previous work the intention was shared between individuals (van Ulzen et al., 2008). This may suggest that shared intentionality between individuals, rather than individual intention, is key to facilitating coordination, rather than merely the instruction to synchronise.

Additionally, we found no relationship between the degree of synchronisation accuracy and the strength of feelings of social closeness. This may suggest that sensorimotor coupling of visual information did not drive the bonding effects; instead, joint action factors within the social context may have been sufficient to boost social closeness. These contradictory results are likely to be explained due to the differences in the social bonding outcome measures that were utilised. Feelings of affiliation or social closeness may therefore be driven by sensorimotor coupling, whilst cooperation may not. Alternatively, it is possible that the low sensitivity of the social closeness scale to detect change in social bonding could explain why no relationship with synchrony was found (see Cross et al., 2019 for review). For instance, the Inclusion of Other in Self (IOS) Scale used may not capture affective, expressive or implicit aspects of social bonding. Instead, it is argued the IoS measures explicit perceptions of shared similarity and closeness (Aron et al., 1992; Cross et al., 2019). Within the current study, this may suggest that sensorimotor coupling does not drive explicit reports of affiliation, but future work is needed to understand if the same is true for other aspects of prosocial behaviour.

Finally, despite not having any specific hypothesis based on stimulus tempo, we also found that visuomotor synchronisation accuracy was higher with stimuli moving at a faster tempo. This effect is most likely attributable to the Spontaneous Motor Tempo of individuals being faster than the tempo at which the stimuli was presented. Previously work has found that adults aged 18-38 years-old have a mean spontaneous motor tempo of 630ms (McAuley et al., 2006). It is therefore likely that participants were more comfortable tapping at the faster rate of 750ms than they were at 1000ms, therefore synchronisation accuracy was greater when the tempo of the stimuli was faster. Moreover, previous work has found that uninstructed synchrony with non-social visual stimuli becomes more likely to occur as the difference between individual preferred tempo and stimulus tempo decreases (Lopresti-Goodman et al., 2008). With regards to the current study, this may provide further explanation as to why tempo significantly impacted both uninstructed and instructed synchrony.

Social skills and sensorimotor ability develop significantly throughout childhood and adolescence (Cowie et al., 2016, 2018; Greenfield et al., 2017; Hart, 2007; Kurgansky & Shupikova, 2011). As demonstrated in previous work and in the results of *Study 1,* interpersonal synchrony plays a significant role in social interactions. We conducted *Study 2* to explore whether children show similar facilitation of synchrony and social bonding within a social context. We also sought to investigate whether synchrony performance predicts social bonding effects.

Study 2: Children

5.5 Methods

Participants

Sixty-one children (30 girls, 31 boys) aged 4.53 to 14.32 years old (M_{age} = 8.79 years, *SD* = 2.18) from predominantly White, middle-class families took part in the present study. The participants were recruited through a public event held at The University of Nottingham in July 2019, in which children participate in short research studies over the course of a week. As we were running the study at a public event, we aimed to recruit a minimum of 20 participants per condition, and as many as possible thereafter. All children were screened for developmental difficulties via a parental background questionnaire. Verbal mental age was assessed using the British Picture Vocabulary Scale III (BPVS III; Dunn & Dunn, 2009) to ensure participants did not have a delay in their cognitive development. Three participants with a confirmed clinical diagnosis of autism spectrum disorder were removed from analysis as previous work has found this population to exhibit atypical synchrony behaviour (Marsh et al., 2013; Fitzpatrick et al., 2016; Kaur et al., 2018). Four participants were removed from analysis for being extreme outliers (±2 SDs from the mean)[1]. Therefore, the final sample consisted of 54 neurotypical children (27 girls, 26 boys) aged 4.53 to 14.32 years old (M_{age} = 8.80 years, *SD* = 2.16). There were 26 participants in the instructed condition and 28 participants in the uninstructed condition. The guardians of all children gave informed written consent for their child to participate, and the children provided verbal assent at time of the study.

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[1] This method for identifying outliers was utilised for the purpose of publication but was not chosen for other chapters of the present thesis.

Design

The design of *Study 2* differed slightly from *Study 1* due to adjustments made for a child sample. Participants completed two, rather than four, tapping trials in total: one in the social context and one in the non-social context. This meant that stimulus tempo and the order of context conditions were counterbalanced across, not within, participants, such that half of the participants were presented with the social stimulus at 750ms and the non-social at 1000ms, while the remaining half were presented with the social stimulus at 1000ms and the non-social at 750ms. The independent variables of this study were identical to *Study 2*: context (social vs non-social), instruction type (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms). The dependent variables were synchronisation accuracy (i.e., difference from the stimulus in ms) and social bonding. Social bonding was measured in two ways: change in social closeness towards the partner, measured by subjective assessment of proximity with the partner and change in spontaneous behavioural mimicry, measured by frequency of mimicked behaviours. The mimicry task was added as a child-friendly way of assessing social bonding. The nature of the testing event in which *Study 2* was conducted allowed for the addition of the spontaneous behavioural mimicry.

Materials and Measures

Synchronisation accuracy

To measure synchronisation accuracy, the same MIRAGE virtual reality device and the same measure of RMS of inter-tap intervals was used as in *Study 1.*

Social closeness

A child-friendly version of the social closeness task was used here as compared to *Study 1* to ensure participants could understand and relate to the task. To assess social closeness towards the partner, the participants were asked to imagine a hypothetical scenario (e.g., waiting for a train at the station) and indicate first where they would like to sit, and then where they would like the partner to sit in this scenario by placing stickers that represented the child and the partner. The scenarios were accompanied by matching pictures that had 7 seats on them. Building upon similar measures that used physical closeness as a proxy for social closeness (Ijzerman & Semin, 2010; Over & Carpenter, 2015; Tunçgenç & Cohen, 2016b), participants placing themselves closer to the partner was considered indicative of higher social closeness. Since the children were first asked to place themselves and then the partner, the distance between the two people was calculated as a proportion of the number of available seats once the children had placed themselves. To examine change in social closeness, the baseline distance score was subtracted from the distance scores following the tapping trials. Therefore, positive values indicated increased closeness from baseline, while negative values indicated decreased closeness.

Mimicry

Based on research showing positive affiliative effects of mimicking and being mimicked (for reviews, see: Lakin et al., 2003; Stel & Vonk, 2010), spontaneous behavioural mimicry was assessed as an indicator of social bonding. Mimicry was assessed three times with a two-minute-long, semi-structured picture-guessing game played between the participant and the partner: first at baseline, and twice more thereafter each tapping trial. In the game, the partner viewed three pictures in sequence and described each to the participant. The participant, who had not seen the pictures, then guessed which picture (out of three options per picture) they thought the partner had been describing. Whilst describing the pictures, the partner made upper body touches on three areas (i.e., rubbing or scratching her head, shoulder, or upper arm), amounting to a total of nine touches per block. The same picture descriptions were used across participants with the touches occurring at the same timepoints.

The frequency of spontaneous behavioural mimicry was post-hoc coded from the video recordings of the mimicry sessions using the open-source E-LAN software (version 5.8). An action was considered an instance of mimicry if the children touched, rubbed, or scratched their head, shoulders or upper arms following the partner performing one of these actions within the same block. Two raters, one blind to the hypotheses and both blind to the actions of the partner, coded the videos. The primary rater coded 100% of the videos and the secondary rater, who was blind to the hypotheses of the study, coded 40% of the videos. A Pearson's correlation test on the frequency values per participant revealed excellent inter-rater reliability ($r(25) = .89$, $p<.0001$), and the primary rater's codes were used for the few cases where there was disagreement between the raters. To examine change in mimicry, difference scores were obtained by deducting the frequency of mimicry at baseline from the frequency of mimicry following each tapping trial.

Procedure

The procedure was identical to *Study 1* with the addition of the spontaneous behavioural mimicry measure completed at baseline and following each tapping trial.

5.6 Results

Hypotheses 1 and 3: Children will synchronise with the stimulus better in the social than in the non-social context and when instructed compared to uninstructed

A mixed 2x2x2 ANOVA was used to investigate the effects of context (social vs non-social – within variable), instruction (instructed vs uninstructed – between groups variable) and stimulus tempo (750ms vs 1000ms - within variable) on synchronisation accuracy (i.e., RMS of inter-tap intervals). The results revealed significant main effects of context ($F(1,45) = 9.00$, $p = .004$, partial $\eta^2=.17$), instruction ($F(1,47) = 84.15$, $p < .0001$, partial $\eta^2=.64$) and tempo ($F(1,45) = 41.98$, $p < .0001$, partial $\eta^2=.48$). As can be seen in Figure 5.3A, participants' synchronisation accuracy was higher (i.e., lower error) in the social context (*M* = 289.54, *SD* = 202.77) than in the non-social context (*M* = 330.02, *SD* = 217.60). Participants also synchronised better in the instructed condition (*M* = 154.22, *SD* = 87.27) than in the uninstructed condition (*M* = 452.06, *SD* = 188.07) and when the stimulus moved at 750ms (*M* = 256.25, *SD* = 170.72) than at 1000ms (*M* = 365.55, *SD* = 233.45), (see Figure 5.3B). There was a significant interaction between instruction condition and tempo $F(1,45) = 16.56$, $p = .0002$, partial $\eta^2=.27$), such that within the uninstructed condition, synchronisation accuracy was better when the stimulus tempo was 750ms (*M* = 268.59, *SD* = 188.41) than when it was 1000ms (*M* = 443.99, *SD* = 254.76; $F(1,25) = 31.75$, $p < .0001$), while no such difference was observed within the instructed condition ($F(1,22) = 1.94$, $p = .018$). No other interaction effect was significant (all *p*s > .05; see. Appendix 5.3 for details).

Similar to the approach followed in *Study 1*, we also assessed the normalised synchronisation accuracy metric, which was calculated by dividing the RMS of inter-tap intervals by the stimulus tempo for that trial. These results confirmed that even when accounting for the possibility of increased errors in larger inter-tap intervals, the effect of context remained significant such that children synchronised with the stimulus better in the social than in the non-social context (see Appendix 5.4).

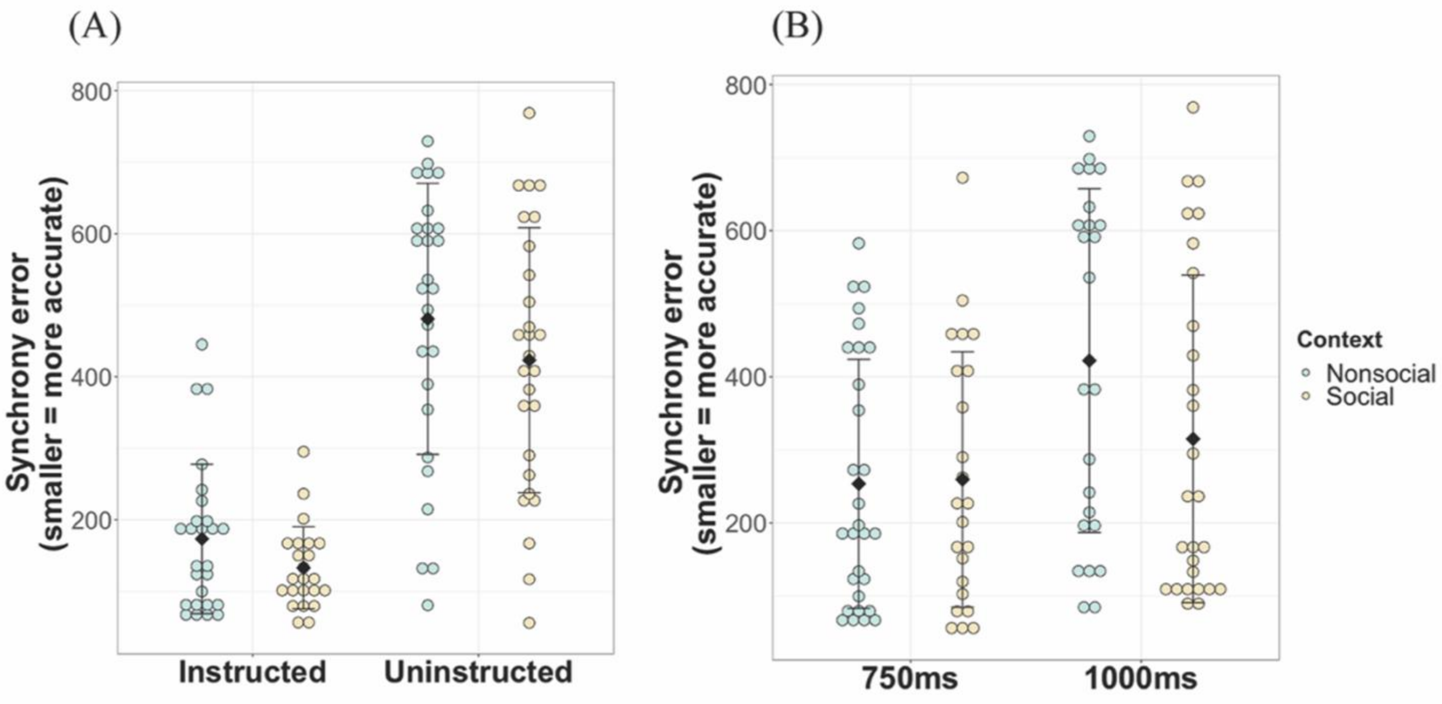


Figure 5.3. Synchrony accuracy by context, stimulus tempo and instruction conditions in children. Lower scores on the y axis indicate less synchrony errors and better accuracy. Coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.

(A) Synchronisation accuracy per context and instruction condition.

(B) Synchronisation accuracy per context and stimulus tempo conditions.

Hypotheses 2 and 3: Children will feel more bonded to their partner after completing the finger tapping task in a social as compared to a non-social context and when instructed compared to when uninstructed

At baseline, the children preferred, on average, to put 52.02% distance (*SD* = 27.78) between themselves and their partner. This distance decreased to 50.74% on average (*SD* = 30.74) in the social context and increased to 60.93% on average (*SD* = 30.26) in the non-social context. A mixed 2x2x2 ANOVA was used to examine the effects of context (social vs non-social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on change in social closeness (i.e., difference from baseline). This analysis revealed a significant main effect of context on social closeness ($F(1,50) = 11.46$, $p = .002$, partial η^2=.19). There was no significant main effect of instruction or stimulus tempo and no interaction effects (all *p's* > .05). As can be seen in Figure 5.4A, while social closeness towards the partner increased following tapping in the social context (*M* = 2.13, *SD* = 37.41), a decrease was observed in feelings of closeness following tapping in the non-social context (*M* = -14.85, *SD* = 37.69).

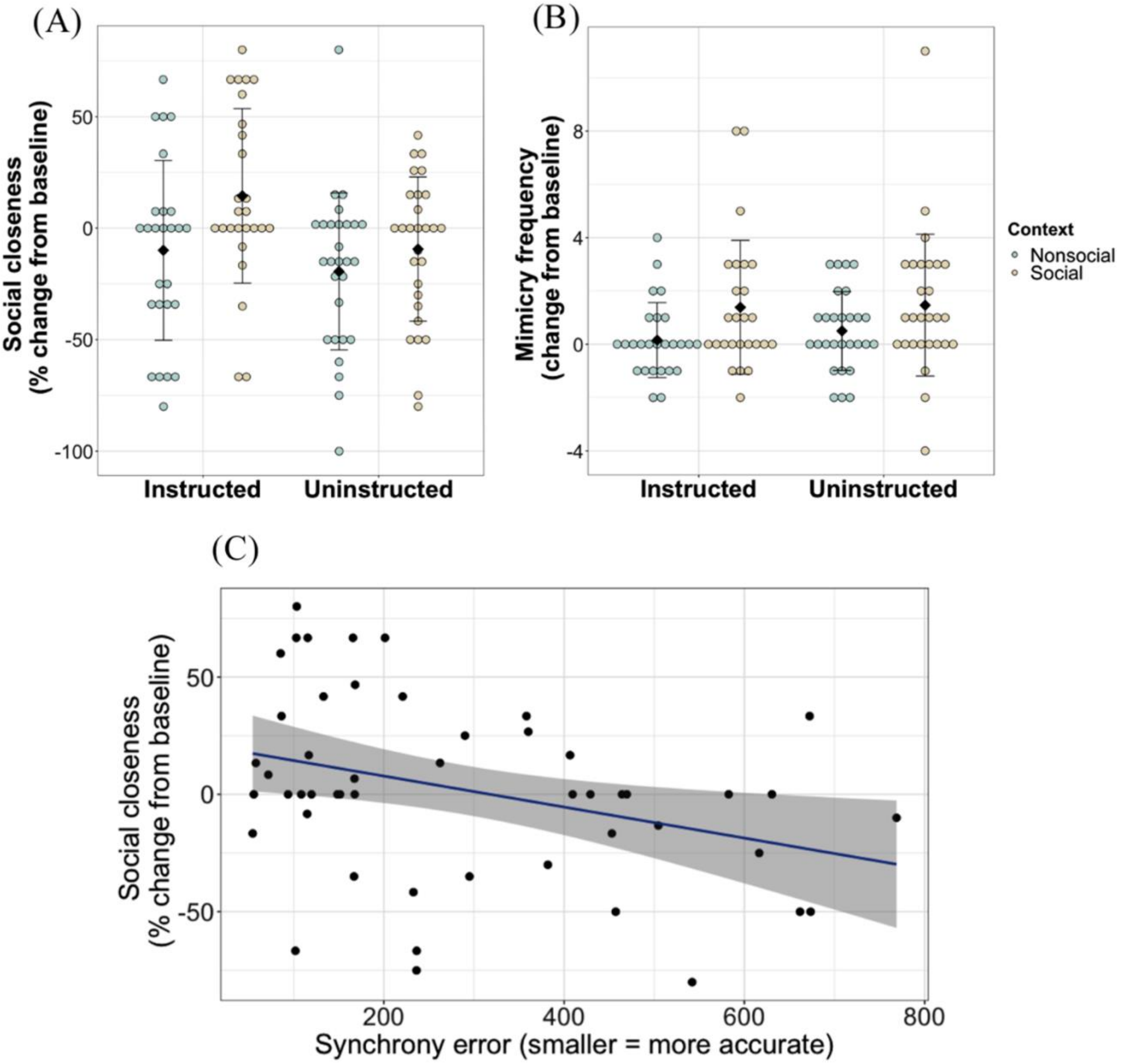


Figure 5.4. Social bonding by context, instruction and synchronisation accuracy in children.

In (A) and (B), coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.

(A) Change in social closeness (test – baseline) per context and instruction condition, with positive scores indicating an increase and negative scores indicating a decrease in closeness as compared to baseline.

(B) Change in mimicry frequency (test – baseline) per social context and instruction condition, with positive scores indicating an increase and negative scores indicating a decrease in mimicry as compared to baseline.

(C) Relationship between synchrony error and change in social closeness within the social context. Shading indicates 95 confidence intervals.

On average, the children mimicked their partner's mannerisms 0.89 times (*SD* = 1.08) at baseline, 2.45 times (*SD* = 2.58) after performing the finger-tapping task in the social context and 1.19 times (*SD* = 1.50) after performing the finger-tapping task the non-social context. The percentage of children who mimicked their partner at least once was, 52% (n = 28) at baseline, 78% (n = 42) in the social context condition, and 61% (n = 33) in the non-social context condition.

A mixed 2x2x2 ANOVA was used to investigate the effects of context (social vs non-social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on change in mimicry frequency (i.e., difference from baseline). The results revealed a main effect of context on mimicry frequency ($F(1,50) = 14.90$, $p = .0003$, partial η^2=.23). There was no significant main effect of instruction, stimulus tempo or any interaction effects (all *p's* > .05). As can be seen in Figure 5.4B, while mimicry frequency showed an increase from baseline in both social and non-social context conditions, this increase was significantly greater in the social context ($M = 1.72$, $SD = 2.69$) as compared to the non-social context ($M = 0.34$, SD =1.47).

Hypothesis 4: The degree of interpersonal synchrony in the social context will positively predict social bonding

Two separate linear regression tests were used to investigate whether synchronisation accuracy within the social context condition predicted change in spontaneous behavioural mimicry and social closeness. While synchronisation accuracy did not predict change in mimicry frequency ($F(1,45) = 0.29$, $\beta = .001$, $SE = .002$, $p = .59$, $R^2 = .005$), it significantly predicted change in social closeness ($F(1,48) = 20.47$, $\beta = .08$, $SE = .02$, $p < .0001$, $R^2 = .28$), (see Figure 5.4C).

5.7 Discussion

As predicted, and in line with previous works (Kirschner & Tomasello, 2009; Tunçgenç et al., 2015), we found that both visuomotor synchrony and social bonding were facilitated in a social as compared to a non-social context. Extending previously used measures of social bonding, we showed that children spontaneously mimicked their partner more following interpersonal synchrony compared to synchronisation in the non-social context.

In line with Hypothesis 3, children synchronised with significantly greater accuracy when explicitly instructed to synchronise with the stimulus compared to when they were left free to tap as they wished. Unlike the adults in *Study 1*, children spent longer participating in the study, participated in more tasks and had more opportunities to socially engage with the experimenter. Children may have had a heightened sense of commitment when instructed, and hence increased effort to synchronise (Michael & Szekely, 2018). In addition, prior work has demonstrated children are less consistent in how they tap as compared to adults (Geuze & Kalverboer, 1994; Greene & Williams, 1993), so it is possible that an explicit instruction therefore increased effort and improved synchronisation accuracy in the instructed condition.

Additionally, despite lower synchronisation in the uninstructed condition, social bonding for both measures remained similar across uninstructed and instructed conditions. This may suggest that merely completing the task together with the partner allowed for social bonding to occur. Yet, in line with Hypothesis 4, the degree of interpersonal synchrony still mattered: the more synchronous the children were with the partner, the greater was their feelings of social closeness. In comparison to adults, this may suggest that children are more likely to base social bonding on unconscious precise sensorimotor coupling between themselves and a partner.

Similar to the adult data, we found an unexpected effect of stimulus tempo on synchronisation accuracy. It is likely that a faster spontaneous motor tempo of children led to greater synchronisation accuracy in the 750ms tempo compared to the 1000ms tempo (McAuley et al., 2006; Lopresti-Goodman et al., 2008).

5.8 General Discussion

Across two studies, we found support for our hypotheses that a social context, as compared to a non-social context, facilitated interpersonal synchrony (Hypothesis 1) and social bonding (Hypothesis 2) in both adults (*Study 1*) and children (*Study 2*). Contrary to our hypothesis (Hypothesis 3), being instructed did not facilitate synchronisation accuracy in the adult sample, but instruction did facilitate synchrony in children. Instruction did not facilitate social bonding in either sample. Uniquely in children, we found that the magnitude of social closeness was positively linked to the degree of synchronisation accuracy (Hypothesis 4).

We found evidence of social context facilitating interpersonal synchrony in adults and children. Previous paradigms have been criticised for their use of social and non-social contexts as often the social condition holds more sensory information, therefore allowing for more accurate synchronisation (see Kirschner & Tomasello, 2009). For instance, the available sensory information is much richer viewing the movement of a whole body as compared to a flashing dot or metronome. However, in the current study only the image of a hand was used as the social context, therefore the area covered by the moving visual stimuli was the same between conditions. Subsequently, this social facilitation effect is unlikely to be attributable to the amount of visual information. Instead, viewing a finger tapping may have enhanced neural representation of the external stimulus (i.e., hand movement), therefore increasing predictability and coordination with the stimulus, (Brass & Heyes, 2005; Calvo-Merino et al., 2005; Iacoboni et al., 1999) making it easier to synchronise with. According to predictive coding principles, synchronisation with the social stimulus may have been less cognitively demanding and effortful, therefore producing fewer errors (Koban et al., 2019). Furthermore, this current finding corresponds to previous works that have suggested the presence of a social agent can induce perceptions of a joint action (Kirschner & Tomasello, 2009; Tunçgenç et al., 2015). Such joint action formation is argued to allow for better anticipation of movement of the external stimulus (Sebanz et al., 2006) and therefore give rise to a coupling of self and other movement (Hove, 2008).

Our social context differed from the non-social context both in terms of providing better opportunities for participants to couple with the visual stimulus (i.e., with a hand as opposed to a ball), and in terms of the partner engaging in joint action with the participants. Both of these factors may facilitate social bonding through promoting participants' perception of the partner as *moving* like them and *being* like them (Meltzoff, 2007). We found that only in children, the degree of synchronisation accuracy was positively associated with feelings of social closeness. This indicates that precise sensorimotor coupling provided an additional cue for children's feelings of bonding, whereas for adults, this was irrelevant and/or insufficient. For instance, as the accuracy of synchronisation was not consequential to task success, for adults, it may have reduced the extent that accuracy impacted upon feelings of social closeness. Alternatively, children may have perceived being in time as more rewarding which may have enhanced synchrony and subsequent social bonding. However, as the children were much more variable in their synchronisation errors compared to the adults, it is harder to draw comparisons between the samples. Future research could seek to contrast joint-action and sensorimotor coupling contexts, for instance, by telling the participants that the non-social stimulus that they are synchronised with is a reflection of a partner's movement, thus retaining a joint action context but removing sensorimotor coupling opportunities of a corporeal stimulus to disentangle the relative roles of bottom-up and top-down factors in facilitating social bonding following synchrony.

In addition, children mimicked the partner more following interpersonal synchronisation. Whilst this corresponds to previous research that has shown mimicry can facilitate social bonding (Lakin et al., 2003; Stel & Vonk, 2010), the present finding corresponds with previous work that has found interpersonal coordination can increase imitation (Cross et al., 2021). This expands possible measures of social bonding to include mimicry. Although interpersonal synchrony enhanced both social closeness and mimicry, the two aspects are distinguishable as synchronisation accuracy did not predict a change in mimicry. One reason for this may be the relatively reduced variability in the mimicry frequencies compared to the social closeness scores, yielding a correlational approach less powerful. Still, the absence of a link between mimicry and interpersonal synchrony suggests that while social closeness may be more selectively boosted by interpersonal synchrony, merely completing the tapping task with the partner appears to be sufficient for perceived coordination and increased mimicry to occur.

This study has emphasised the importance of interpersonal synchrony for social bonding, which opens up further questions as to whether an impaired ability to synchronise, especially in social contexts, may be related with social-communicative impairments. For instance, individuals with Autism Spectrum Conditions, Schizophrenia, social anxiety disorders and Attention Deficit and Hyperactivity Disorder have been found to exhibit differences in interpersonal synchrony (Asher et al., 2020; Fitzpatrick et al., 2016; Georgescu et al., 2020; Problovski et al., 2021; Kaur et al., 2018; Marsh et al., 2013; Varlet et al., 2012). Future work could therefore explore the relationship between sensorimotor processing and joint action mechanisms to further understand the observed differences in interpersonal synchrony in individuals with these disorders.

Whilst the present study provides key insights into the roles of instruction, context, and tempo on visuomotor synchronisation and social bonding, certain limitations should be noted. Firstly, in *Study 2* not all participants experienced both contexts at both tempi due to time constraints of the event at which the experiment was conducted. While it is unlikely that groups of children would be distinguished by their ability to synchronise better at social-fast vs social-slow stimuli, thereby affecting the results in a systematic way, future research can implement full counterbalancing to eliminate this possibility. Finally, the social vs non-social contrast in the current study was created by combining insights from the bottom-up sensorimotor accounts with the top-down joint action accounts. Future research can tease apart how either factor affects synchrony accuracy and its subsequent bonding effects.

Conclusions

The current research adds to a growing body of literature by revealing the importance of social context for interpersonal synchronisation and social bonding in children and adults. Interestingly, we show how social bonding can be elicited following spontaneous (uninstructed) interpersonal synchronisation. These findings provide an evidence-base that social contexts with increased opportunities for sensorimotor coupling and joint action improve synchronisation and bonding between partners.

Chapter Introduction

The theory and empirical findings presented thus far in the current thesis have sought to demonstrate the links between sensorimotor integration and social processing. Autism is associated with differences in both sensory and social processing. Theoretically it has been proposed that differences in how sensory information is integrated could account for differences in social expression. ~~Yet,~~ to what extent is this theoretical bridge between sensory and social represented in the real-life experiences of autistic adults? Chapter 6 utilised quantitative and qualitative research methods to explore the sensory experiences of autistic adults from a multisensory perspective. Insight into the viewpoints of autistic adults can allow for the empirical findings presented thus far to be contextualised by the voices of autistic individuals.

Chapter 6: The Sensory Experiences of Autistic Adults from a Multisensory Perspective.

Abstract

Autism is a neurodevelopmental condition characterised by differences in social interaction and communication as well as sensory processing. Research has demonstrated that sensory differences are a central component of autism and can have a significant impact on the mental and physical well-being of autistic individuals. Furthermore, individuals can experience fluctuations in sensory reactivity (i.e., shifting form under to over aware). Sensory differences are reported to occur cross-modally, yet, no study has investigated how sensory fluctuations are experienced from a multisensory perspective. Using a mixed methods approach (quantitative and qualitative) we aimed to explore the frequency and experience of sensory fluctuations across internal (e.g., proprioception, vestibular and interoception) and external (e.g., vision, tactile, audition, olfaction, and gustation) senses. Our quantitative results show

that sensory reactivity differences and sensory fluctuations are prominent in autistic adults. Moreover, findings suggest that hyporeactivity is more likely to be experienced in internal senses whilst hyperreactivity is more likely to be experienced in external senses. From our qualitative findings we show the impact of sensory differences is wide and complex, affecting physical, mental, and social well-being. Notably, the unpredictability of sensory fluctuations can significantly impact upon social interactions and access to social environments. Interestingly, we found reduced awareness of internal sensory inputs can have a significant impact on the subjective experience of the body and on self-concept. Our findings have important implications for our understanding of autistic sensory experience. Crucially, the findings highlight the need for theoretical frameworks and quantitative measures to take a multisensory perspective of sensory experience in autism.

6.1 Introduction

Autism is a neurodevelopmental condition notably characterised by differences in social interaction and communication (DSM-5 American Psychiatric Association, 2013). Since the Diagnostic Manual added sensory processing difficulties to the symptomatology of autism, there has been increasing research aiming to understanding sensory experience in autism. Previous work found 94% of autistic adults report experiencing ‘abnormal’ levels of reactivity to sensory stimuli (Crane et al., 2009). These sensory differences can be experienced cross modally, with autistic adults reporting sensitivity to visual, auditory, olfactory, gustatory, and proprioceptive inputs (Tavassoli et al., 2014). Importantly, these differences not only impact sensory experience but also affect the development of social behaviours (Hannant et al., 2016), mental well-being (Rossow et al., 2021), and physical health (MacLennan et al., 2021). Therefore, it is important to understand the sensory experiences of autistic people as sensory differences are widely experienced and have a significant impact on their experience of the world.

Research has typically focused on sensory hyperreactivity and sensory hyporeactivity (Baranek et al., 2006; Jones & O'Neill, 1997; Posar & Visconti, 2018) to understand sensory differences in autism. Sensory reactivity is dissociable from sensory sensitivity as it is thought to pertain to self-reported sensory experience, whilst sensory sensitivity is thought to be the ability to detect sensory input (Schulz & Stevenson, 2020). Hyperreactivity is thought to occur due to an increase in sensory sensitivity, leading to the experience of overstimulation and exhibition of increased response to sensory input. Conversely, hyporeactivity is the reduction in response to sensory input due to reduced sensitivity.

Quantitative research has commonly utilised self-report questionnaires to explore the sensory experiences of autistic individuals. For example, the Glasgow Sensory Questionnaire (GSQ) (Robertson & Simmons, 2013) and the Sensory Processing (SP) Scale (Miller & Schoen, 2012) are self-report questionnaires which ask about the frequency of sensory behaviours across vision, audition, gustation, olfaction, touch, proprioception, and vestibular processing. The GSQ produces an overall score indicating sensory differences and subscales of hyperreactivity and hyporeactivity. Similarly, the SP scale produces an overall score and subscales of sensory under responsivity, sensory over responsivity, and sensory craving. Such scales have been used in a research context to investigate sensory differences in autistic individuals (Horder et al., 2014; Robertson & Simmons, 2013) and have also been proposed as being a clinical indicator of autism (Tavassoli et al., 2016). Thus, it is crucial that such measures are able to fully capture the sensory experiences of autistic adults as they have impact in research and clinical contexts.

Whilst previous literature has largely emphasised the experience of sensory hyperreactivity in autistic individuals, evidence suggests that children (Ben-Sasson et al., 2007) and adults can experience *both* hyper- and hypo-responsivity to sensory input (Jones & O'Neill, 1997; Greenspan & Wieder, 1997; MacLennan et al., 2021). In their quantitative analysis, MacLennan and colleagues (2021) found that participants reported experiencing a combination of hypo- and hyperreactivity. Indeed, only 20.5% of participants reported experiencing only sensory hyperreactivity and no participants reported experiencing only hyporeactivity. Thus, research which considers that individuals can experience *both* hyperreactivity and hyporeactivity may be much more representative of actual autistic experience. In terms of sensory domains, interoception has been found to be most commonly reported for sensory hyporeactivity whereas visual, auditory, tactile, and olfactory inputs were more likely to be attributed to hyperreactivity (MacLennan et al., 2021). Therefore, measures used to evaluate sensory experience, such as the GSQ and SP scale also need to capture that most autistic individuals experience a combination of reactivity types, within and across sensory domains. Notably, neither the GSQ or the SP scale evaluate interoceptive sensory experience. Thus, these scales may be omitting insight into the experience of hyporeactivity in autistic individuals. Consequently, it is important that research and the measures used in research, take into account the experience of both hyperreactivity and hyporeactivity across all sensory modalities when understanding autistic sensory experience.

Qualitative research methods have been used by previous work to gain deeper insight into the sensory experiences of autistic individuals. Indeed, work has sought to understand the impact that sensory differences have on the lives of autistic individuals. Autistic adults have reported experiencing hyperreactivity across multiple modalities, including vision, audition, touch, olfaction, and gustation (Chamak et al., 2008; Jones et al., 2003). This can transpire as extreme discomfort or even pain to sensory input, thus having significant physical impact on autistic individuals. Recent work has found that autistic adults most commonly report experiencing hyperreactivity to loud noises, multiple conversations, high-pitched noises, bright lights, clothing, and music (MacLennan et al., 2021). These sensory experiences can have emotional impact, whereby sensory hyperreactivity can induce overwhelming emotions (Chamak et al., 2008). The experience of sensory hyporeactivity has been found to have similar impact. A recent study found that both hyper- and hypo- sensory reactivity can impact upon mental, physical, and social well-being (MacLennan et al., 2021). Moreover, autistic adults have reported that a poorer mental state can lead to increased sensory difficulties (MacLennan et al., 2021). Crucially, this can cause a cycle of cause and effect where sensory hyperreactivity leads to stress which in turn leads to further sensory reactivity (MacLennan et al., 2021; Smith & Sharp, 2013). This highlights the inseparability between an autistic individual's sensory experience and their mental state, such that there is a dynamic bidirectional interaction between the individual and their sensory experience (Sibeoni et al., 2022). Sensory hyperreactivity can therefore have a significant impact on mental well-being. Yet, research has paid comparatively little attention to how changes in hyporeactivity might be experienced by autistic individuals. Moreover, whilst quantitative research has demonstrated that sensory differences can be experienced across external *and* internal senses (MacLennan et al., 2021; Tavassoli et al., 2014), qualitative research has not focussed on understanding how changes in reactivity across internal senses (i.e., interoception, proprioception and vestibular) might be experienced by autistic individuals.

Social interactions also play an important role in sensory experience. From qualitative reports, autistic individuals have described using other people as a source of self-understanding and making sense of their own experience through comparison with others (MacLennan et al., 2021). For example, noting how other people appear unbothered by sensory input compared to their own experience of discomfort. Additionally, others can provide support in managing sensory experiences, particularly through close relationships (MacLennan et al., 2021; Smith & Sharp, 2013). Other people can serve as prompts to increase awareness of sensory input, for example drawing attention to physical responses to hyporeactivity such as shivering (MacLennan et al., 2021). Conversely, other people can negatively impact sensory experience, often making it more challenging (MacLennan et al., 2021; Smith & Sharp, 2013). Notably, difficulty with sensory reactivity can lead to avoidance of environments that would typically offer social interaction, therefore leading to feelings of social isolation (MacLennan et al., 2021; Smith & Sharp, 2013). These findings exemplify the bidirectional relationship between sensory and social experience and emphasise how it is important to consider the social implications of sensory differences in autism.

To understand the sensory experiences of autistic adults, qualitative research has shed light on how individuals cope with sensory differences. Common coping strategies include avoidance, making adaptations, and sensory soothing behaviour (MacLennan et al., 2021; Parmar et al., 2021; Robertson & Simmons, 2015; Smith & Sharp, 2013). Interestingly, sensory soothing was only reported for hyperreactivity not hyporeactivity, suggesting that sensory seeking may only be used as a strategy to regulate hyperreactivity (MacLennan et al., 2021). Crucially, coping strategies are not reported to pertain to a single sensory domain, as reactivity occurs as part of a multisensory experience (Parmar et al., 2021). Thus, it is vital that research considers how autistic individuals manage sensory reactivity from a multisensory perspective. Moreover, it is essential to understand how individuals use strategies to cope with sensory difficulties such that research can identify possible ways in which clinical support can be targeted.

Importantly, previous research has noted that autistic individuals can experience hyperreactivity and hyporeactivity *within* a sensory domain (Elwin et al., 2012). However, comparatively little qualitative research has been conducted investigating sensory fluctuations - whereby individuals experience a change in reactivity to sensory input. In early work, autistic adults reported experiencing unpredictable fluctuations between hyperreactivity and hyporeactivity (Jones & O'Neill, 1997). For example, some individuals reported experiencing sensory blank outs where their vision would black out but then return (Jones & O'Neill, 1997). Further work found individuals can experience fluctuating reactivity to sensory input, in which participants described experiencing a temporary shift in reactivity within a sensory domain (Elwin et al., 2012). However, neither of these studies (Elwin et al., 2012; Jones & O'Neill, 1997) explored in detail about the experience of sensory fluctuations. As sensory experiences have such a wide impact on the lives of autistic people, it is key that research understands the nuances of the sensory experience – including sensory fluctuations.

Whilst previous studies have investigated sensory experiences across a wide range of domains, to our knowledge, no qualitative study has asked participants to report on vision, audition, olfaction, gustation, tactile, interoception, vestibular, *and* proprioception. Moreover, it is unknown how individuals experience fluctuations in reactivity across these sensory modalities. Are autistic adults affected by a particular sensory input on some occasions and not others? If they are, what is this experience like? The current study will use a mixed methods approach (quantitative and qualitative) to explore three key questions 1) what is the frequency of hyperreactivity and hyporeactivity across all major senses 2) what is the frequency of sensory fluctuations across all major senses 3) how do autistic adults experience sensory fluctuations across all major senses?

6.2 Methods

Participants

Thirty-eight autistic adults took part in the study (24 women, 5 men, 9 non-binary, M_{age}=29.29 years, *SD*=9.28). Twenty-eight participants reported having received a clinical diagnosis of autism and ten reported as self-identifying as autistic, see Table 6.1 for full demographic details for each diagnosis group. Informed consent was obtained prior to the experiment according to procedures approved by the University of Nottingham, School of Psychology ethics committee (approval number: S1287R). Participants were recruited online through social media accounts and local autism support organisations. Women and non-binary individuals were particularly encouraged to participate in the study to increase the representation of their voices in autism research (see Theoretical Framework section for details), however autistic men were still accepted to participate. This was achieved through targeted study advertisements and targeted recruitment through local autism support organisations.

Table 6.1. Demographic information for self-identified and clinically diagnosed autistic participants.

Age *mean (sd)*	31.10 (10.61)	28.64 (8.88)
Gender		
Women	8	15
Men	1	6
Non-binary	1	7
Education *n (%)*		
Higher or secondary	3 (7.9)	10 (26.3)
College of university	6 (15.8)	11 (28.9)
Postgraduate degree	1 (2.6)	7 (18.4)
Occupation *n (%)*		
Full time employment	5	6
Part time employment	1	6
Student	2	12
Unemployed	2	4

Participants completed the Ritvo Autism and Asperger Diagnostic Scale-14 (RAADS-14), the Autism Quotient-10 (AQ-10), and the Camouflaging Autistic Traits Questionnaire (CAT-Q). Mean scores and clinical thresholds for these measures for the self-identified and clinically diagnosed participants can be seen in Table 6.2. The RAADS-14 and AQ-10 were included to capture clinical levels of autistic traits and the CAT-Q was used to ascertain levels of masking of autistic behaviours. The latter was particularly important to include to provide a measure of masked autistic behaviour as autistic women typically show higher levels of camouflaging behaviour (Beck et al., 2020). Shorter versions of the AQ and RAADS questionnaires were utilised as an autistic consultant indicated that there is a preference for shorter questionnaires amongst autistic individuals and experimentally both the AQ-10 and RAADS-14 have been shown to be internally consistent and robust (Allison et al., 2012; Eriksson et al., 2013). There was no significant difference between the self-identified or clinically diagnosed group for AQ scores; $t(36)=-1.1$, $p=0.28$, CAT-Q scores; $t(36)=-1.32$, $p=.21$, or RAADS-14 scores; $t(38)=0.045$, $p=.97$. Group means suggest that participants were above the clinical threshold for the RAADS-14 scale, but not AQ-10 or CAT-Q. However, the RAADS-14 has been found to have a sensitivity of 97% and a specificity of up to 64%, therefore a reliable screening measure for autism in adults (Eriksson et al., 2013). Thus, we can be confident that individuals who took part were autistic. Eleven participants reported cooccurrences with other disorders, a breakdown of which can be seen in Table 6.3. Most participants described their ethnicity as white European (92.1 %), with one person describing themselves as white-Asian and two participants not reporting their ethnicity.

Table 6.2. Mean AQ-10, RAADS-14 and CAT-Q scores for participants self-identified and clinically diagnosed as autistic. Clinical threshold for each scale shown in parentheses.

	AQ-10 (6)		**RAADS-14 (14)**		**CAT-Q (100)**	
	M	SD	M	SD	M	SD
Self-identified as autistic	4.70	0.68	23.2	3.16	50.70	9.39
Clinical diagnosis of autism	4.36	1.19	23.2	2.73	46.40	7.57

Table 6.3. Number of participants reporting co-occurring conditions in addition to autism.

Disorder	**Number of participants**
ADHD	3
ADHD and Dyslexia	1
ADHD and Dyspraxia	1
Dyslexia	1
Dyslexia and Dyspraxia	4
Learning Disability	1

Materials and Measures

We developed an online questionnaire consisting of 48 questions to capture the experience of sensory sensitivities and fluctuations across vision, audition, olfaction, tactile, interoception, vestibular sense, and proprioception. We define sensory fluctuation as responding differently to the same sensory input (i.e., the same smell) on different occasions. Definitions and examples of sensory sensitivity and fluctuation were provided at the beginning of the questionnaire for each sensory modality. Participants were asked six questions per sense, three of which were multiple-choice and three were open ended (see Figure 6.1 for flow diagram of the questionnaire). The multiple-choice questions provided a quantitative measure and were designed to capture the frequency of sensory sensitivities and sensory fluctuations across sensory domains. The open-ended questions provided qualitative insight and were designed to provide understanding into the experience of sensory reactions and fluctuations. Participants were given a definition and example of more obscure senses (e.g., proprioception, interoception, tactile, and vestibular sense) before being asked about them (see Appendix 6.1). Participants were also given examples of how each sense might be sensitive and how it might fluctuate.

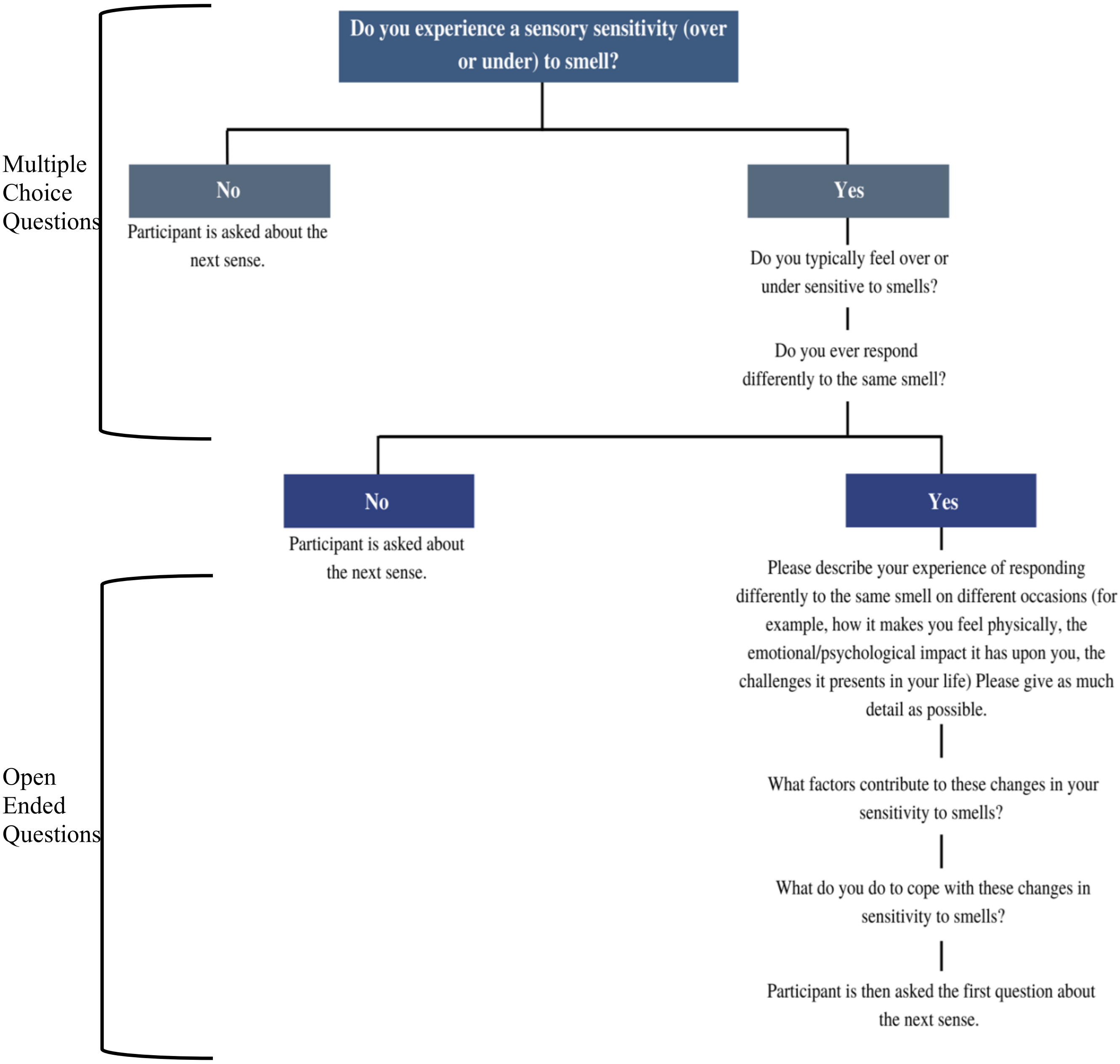


Figure 6.1. Flow diagram of the questions in the online survey using smell as an example.

Procedure

Participants completed the entire study online on a laptop or desktop computer. The questionnaires were hosted on Qualtrics and completed in the following order, demographic questions, AQ-10, RAADS-14, and then the CAT-Q. Participants then answered questions asking them about their sensory experiences including their sensory fluctuations. Total testing time was approximately 30 minutes, although this varied between participants.

Theoretical framework

The current study did not seek to test an explicit hypothesis or theory. Instead, we adopted a phenomenological approach to our study, to understand how autistic people experience and manage sensory fluctuations and to identify areas of investigation. Our underlying epistemology is constructivist, rejecting objectivist approaches which assume an external objective reality that can be discovered and adopting the assumption that knowledge is socially constructed and generated between the researcher and participants (Gergen, 1999). We used a mixed methods approach (quantitative and qualitative), utilising inductive thematic analysis to generate themes and content analysis to provide a rich picture of the sensory experience of autistic individuals. We also adopted a critical theory lens to inform the research methods and goals. A core component of critical theory is to promote equal opportunities for individuals who may be under-represented due to race, socioeconomic status, or gender (Daly, 2007). Historically, women and non-binary individuals have been unrepresented in research (Beery & Zucker, 2011; Kim et al., 2010), and specifically in autism research (Lai et al., 2015; Loomes et al., 2017; Philip et al., 2012). In light of this, women and non-binary autistic individuals were particularly encouraged to take part in this research. Autistic men were not, however, excluded from taking part. As women and non-binary individuals are often diagnosed later in life or struggle to receive a diagnosis (Zener, 2019), participants who self-identified as autistic were accepted to take part.

6.3 Quantitative Analysis

Analysis

To provide insight into the frequency of sensory reactivity differences across sensory domains, we calculated the percentage of participants reporting hyper-, hypo- or mixed reactivity for each sense and the percentage of participants reporting sensory fluctuations in each sense.

6.4 Results

Data from the multiple-choice questions found that all participants reported experiencing a sensory difference in at least one sensory domain. 100% of participants reported experiencing a sensory difference for touch, 92.1% for interoception, 89.5% for sound, 84.2% for smell, 65.8% for taste, 65.7% for visual, 63.2% for vestibular and 60.5% for proprioception. With regards to type of reactivity, participants reported experiencing hyperreactivity or mixed reactivity across all senses. Only one participant per sense reported being hyporeactive to smell, sound, and visual information and no participants reported being hyporeactive to touch information, see Figure 6.2 for reactivity type across each sensory domain.

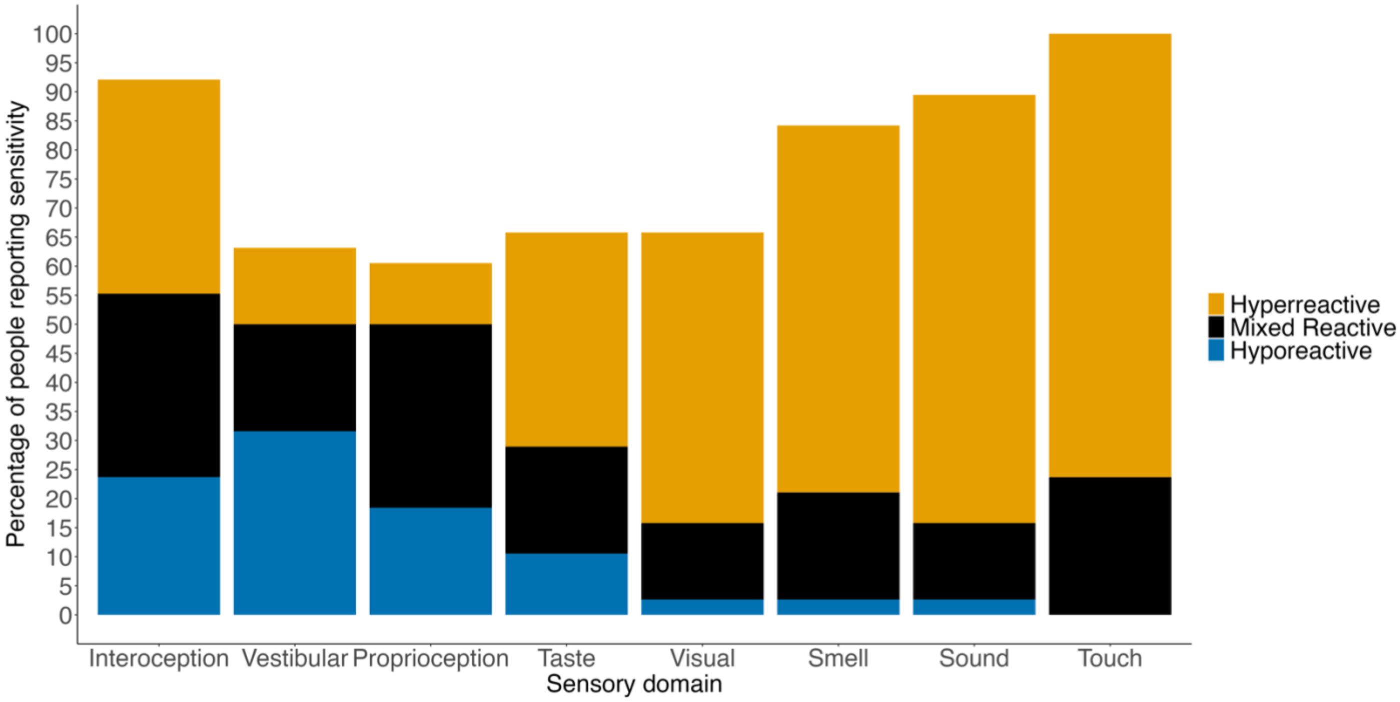


Figure 6.2. Percentage of participants reporting a Hyperreactive (yellow), Mixed Reactive (black) or Hyporeactive (blue) response to each sensory modality.

Experiencing hyporeactivity or mixed reactivity was most commonly reported for vestibular, interoception and proprioception. Conversely, experiencing mainly hyperreactivity was most reported for smell, sound, taste, touch, and visual information. Looking at the participant level, five participants (13.2%) reported experiencing only hyperreactivity to sensory input, 10 (26.4%) participants reported either being hyperreactive or mixed reactive to different sensory inputs, five (13.2%) reported being either hyperreactive or hyporeactive, and 18 (47.4%) participants reported experiencing either hyper-, hypo- or mixed reactivity across sensory input (see Figure 6.3).

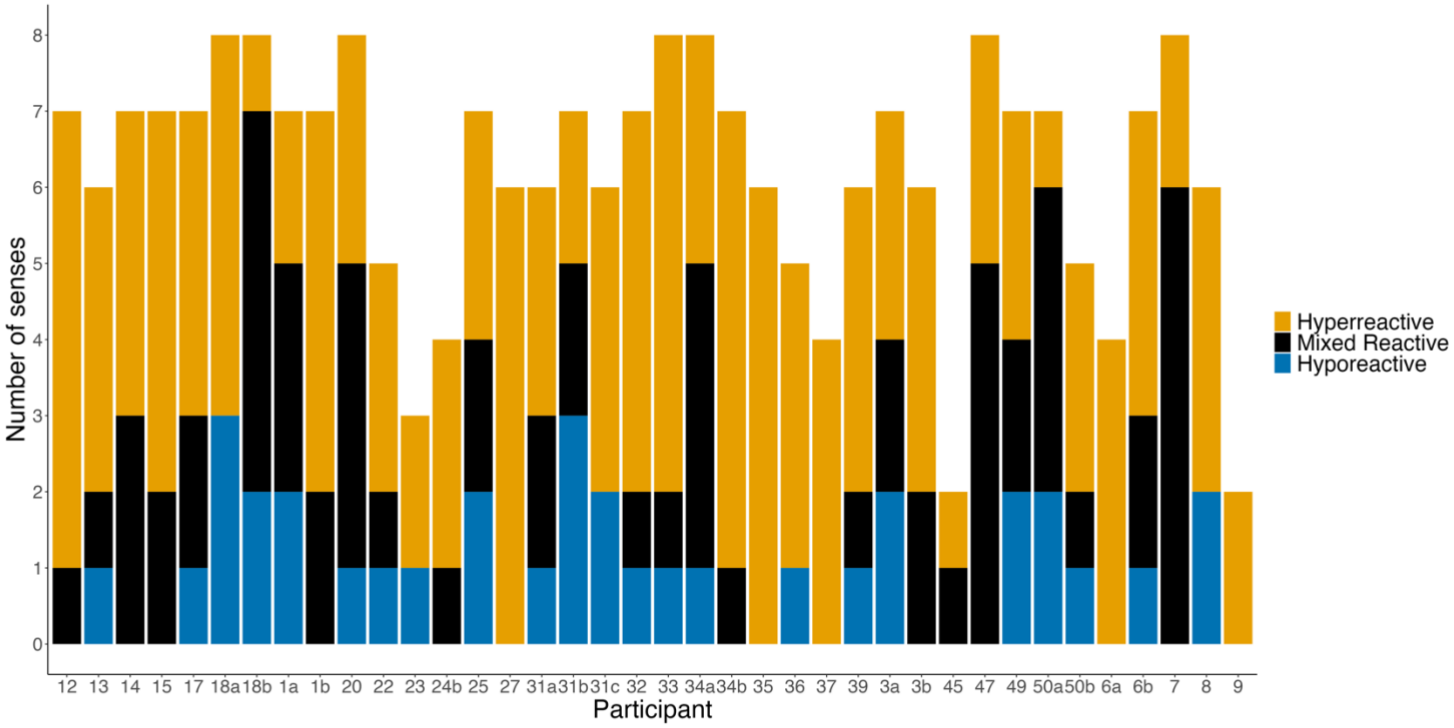


Figure 6.3. Number of senses that participants report experiencing Hyperreactive (yellow), Mixed Reactive (Black) or Hyporeactive (blue) responses.

In addition, participants were asked if they ever experienced fluctuations in reactivity for each sense. Overall, all but one participant reported experiencing fluctuations in at least one sensory domain. Across senses, participants reported experiencing the most fluctuations to interoception (65.8%) and the least for taste (18.4%), see Figure 6.4 for fluctuations across all domains.

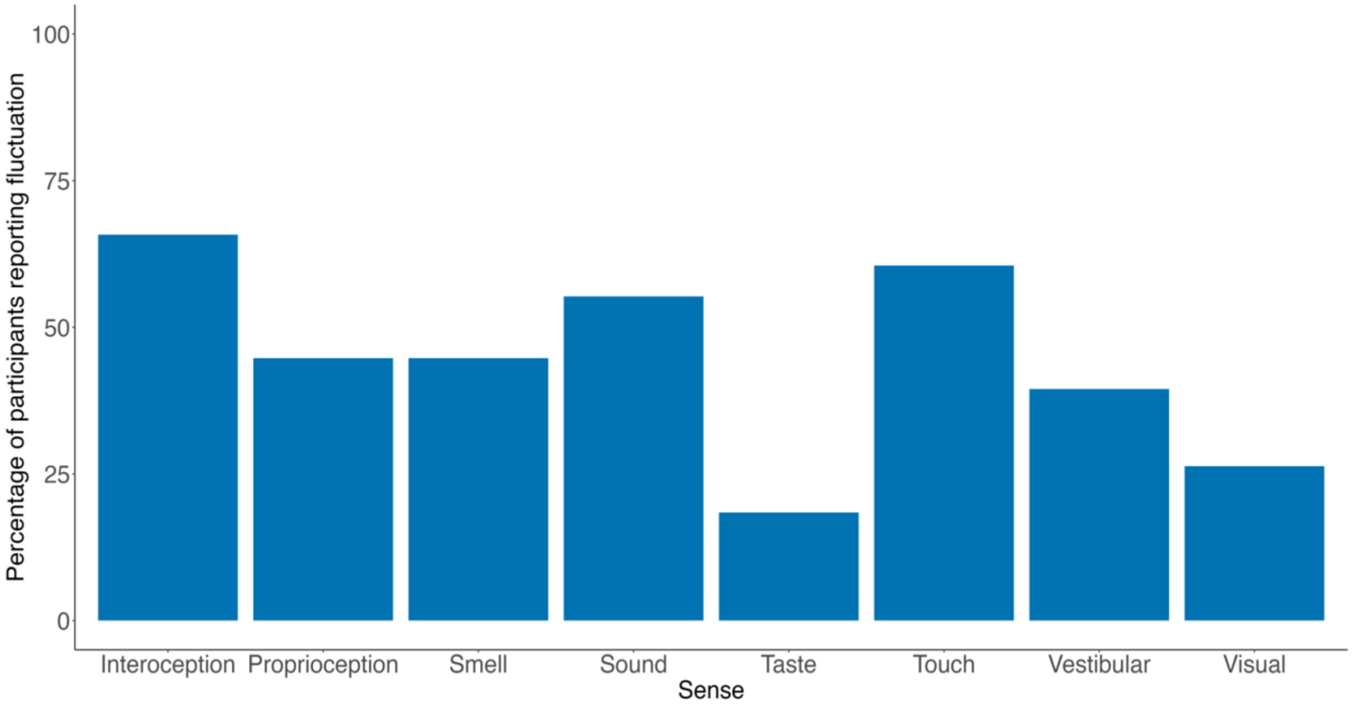


Figure 6.4. Percentage of participants reporting that they experience sensory fluctuations in each sensory modality.

6.5 Qualitative Analysis

Analysis

Written responses were analysed using inductive thematic analysis, following guidelines outlined by Braun & Clarke (2006). Firstly, data were re-read to familiarise the researcher with the data, the order of responses was randomised across participants before each read. Secondly, data units describing similar content were grouped together into categories. At this stage, text units could appear in multiple categories. Thirdly, the categories were reviewed such that a name was attributed to each category. Fourthly, these categories were reviewed and refined. Lastly, these themes were meaningfully defined. The analysis revealed 53 categories, which were grouped into three key themes and nine sub themes, see Table 6.3 for example results from each theme. The coherence and suitability of the themes was established with a second researcher who confirmed that themes were logical and intuitive. Due to an error, participants were not shown the first two open-ended questions relating to vestibular sensory experience. Many participants talked about vestibular when asked about proprioception, so responses from the proprioception and vestibular questions were collapsed together under 'body awareness'.

6.6 Results

From the survey data, three main themes with nine subthemes were identified and presented in Table 6.4. These themes encapsulate the experience of sensory differences and fluctuations across all major senses.

Table 6.4. Summary of themes and subthemes developed from the thematic analysis. Example quotes are given for each subtheme.

Theme	Sub theme	Example
Well-being	Mental	"stress/tiredness/agitation level can combine with a smell to make me feel slightly

		nauseous. under these circumstances, a 'nice' smell can trigger this negative feeling" *P27*
	Physical	"that i'm really sensitive to some touch... that feels genuinely painful when it isn't. i've broken my toe and managed fine, had insect bites/stings that are apparently very painful and been fine, i've cut my fingers and not reacted, just gone and cleaned up, i've burn myself on hot things and not really reacted but then i cannot cope with someone patting my hand too lightly, or brushing against the leaves on a hedge or the tiniest stone in my shoe...which is somehow more painful than everything else and makes me cry." *P31c*
Cognitive aspects	Representation of self	"Just try to give my body things it might like (tea, snacks, etc) until it stops whining" *P49*
	Mental Stimulation	"Smells can be extremely distracting at times and hard to place, I cannot focus until I have figured out what they are." *P50b*
	Preparation/Routine	"Set predictable routines for eating and sleeping and self-soothe or medicate when things go bad."
	Level of Awareness	When asked about what causes fluctuations in touch sensitivity: "I really don't know, sometimes I just feel completely differently about being close to people and interacting with them. It's not always when I'm upset, sometimes I can feel really happy and in control but I still want to be left alone." *P35*
External aspects	Characteristics of sensory input	"Being outside in a t-shirt in the rain and/or wind massively increases my awareness and I absolutely love the feeling." *P50a*
	Social	"This is obviously not ideal from the perspective of a romantic relationship, especially as it can be very unpredictable, meaning my partner has become increasingly anxious about spontaneously showing affection" *P8*
	Daily activities	"It can also make me feel more hesitant to do certain physical activity as I don't want to injure myself." *P17*

Theme 1: Well-being

Subtheme 1.1 Mental

This theme encapsulates the mental experience of sensory fluctuations, the mental impact of sensory fluctuations and mental-based strategies that are used to overcome the impact of sensory fluctuations.

The majority of participants referred to their mental well-being when describing their experience of sensory differences. We define "mental well-being" as emotional and psychological mental health.

Participants often described experiencing stress and anxiety in relation to their sensory fluctuations.

> *"Certain sounds can make me feel like my ears are ringing and make me feel stressed and angry" P37*

Participants also expressed that a sensory fluctuation could cause anxiety.

> *"Some times I will find a smell really lovely but then the next day it makes me feel like I want to vomit. It produces this...visceral reaction where I just can't stand the smell. It ranks my anxiety up through the roof." P1b*

This quote shows how the sensory experience of smell can drastically change, from being a positive experience to causing anxiety. A poignant quote from a participant shows the volatility of these sensory fluctuations, and the impact this can have.

> *"It can change, sometimes very suddenly, between a sound making me feel relaxed and very very stressed." P3a*

This quote also highlights what most participants described that their sensory sensitivities were not consistent. They described experiencing variations in hyperreactivity and hyporeactivity to the same sensory input.

Many participants also highlighted the impact that stress and anxiety can have on the experience of sensory input itself. With stress and anxiety leading to poorer experience of sensory input and fluctuations.

> *"When I am in a calm mood it is fairly pleasant and I enjoy pretending I am lying on crisp, clean sheets. When I am anxious however, it feels like the same sheets have decided to wrap themselves around my neck and are beginning to squeeze" P6a*

This quote highlights an important element of this theme, that stress and anxiety can be experienced as a result of a sensory reactivity, but they can be the cause of fluctuations in sensory reactivities.

Participants also mentioned that sensory sensitivities can impact their mood, sometimes with a positive impact.

> *"the smell of food when ive been craving it makes me happy, excited" P24b*

However, the majority of participants who discussed emotions mentioned the negative impact that sensory fluctuations can have on their mood. When talking about the impact of fluctuations in interoception, a participant said:

> *"I won't eat or go to the toilet for 10+ hours. And then I get really miserable and grouchy and shaky and I don't understand what it is until I break out from that and realise I am amazingly hungry/need to go the toilet" P3a*

Most participants who talked about emotions mentioned that mood mediates their experience of sensory fluctuations. If they are feeling happy, their experience of sensory sensitivities is usually better but made worse if they are in a bad mood. When talking about reactivity to body awareness someone stated:

> *"Also think it makes me less resilient than other people because even if its just like a grazed knee it's all I can think about and I can't just get on with my day. But if I'm in a pretty good mood it's not as bad." P39*

An interesting quote from another individual further highlights the bi-directional relationship of emotions and sensory experience. Emphasising how an individual's emotional state impact sensory experience, which can then lead to further changes in mood.

> *"my emotional state is the biggest contributor to my changes in tactile over stimulation. Often when I feel like i am not in control of my emotions is when the stimulation becomes negative, often resulting my emotional state worsening." P20*

With regards to coping mechanisms, some participants mentioned using strategies that aim to reduce stress and anxiety as a way to improve the impact of sensory sensitivities.

> *"when I notice my balance is not the best, I try to calm down and breathe deeply" P31b*

Other participants also mentioned utilising "breathing techniques" to cope with the impact of sensory fluctuations.

Participants wrote about how sensory sensitivities can have a severe impact on their mental well-being and initiate a meltdown.

> *"I get very stressed in loud environments which can lead to a meltdown" P50a*

One participant also made an interesting point about the interaction between sensory reactivity and coping mechanisms. When the sensory difference affects their ability to use a coping strategy, this can cause them to experience a meltdown. When talking about fluctuations to sound they wrote:

> *"It makes it difficult to self soothe occasionally. Most of the time I like to listen to very loud music (rock/metal etc.) to control my stimulus and it also makes me happy. But sometimes, for reasons unknown to me, it's like it doesn't scratch the itch and instead ramps it up. I often don't know what to do in these scenarios and it often leads to a meltdown as other forms of stimming aren't as effective for me" P3a*

Another participant highlighted how being in a meltdown can change their sensory experience, in this case to touch:

> *"If I am in the middle of a meltdown I do not even want my mother to touch me."*

Across this whole sub-theme, the data reflect a cycle of sensory fluctuations affecting mental well-being and copying strategies, which in turn affects sensory experience.

Sub theme 2.1 Physical

This theme was identified due to the number of individuals reporting experiencing changes in their physical well-being due to sensory fluctuations. Many people reported experiencing physical discomfort or even pain in response to sensory reactivity.

> *"i'm really sensitive to some touch... that feels genuinely painful when it isn't." P31c*

This quote captures how sensory input can cause intense physical discomfort and pain. It is perhaps particularly notable that touch input which typically wouldn't cause pain is reported to be painful by several participants.

Participants also noted that some sensory fluctuations can cause other changes in physical well-being, this participant wrote about their experience with fluctuating reactivity to smell:

> *"some smells I like can become nausea-making and sometimes if I think of that smell or the item associated with that smell (e.g., food) I can feel slightly nauseous." P27*

When writing about changes in body awareness, a participant said:

> *"It makes me feel physically dizzy or like I'm not real or like I am too much in my body and I'm not supposed to feel EVERYTHING, like it's unbearable," P47*

Sensory fluctuations could therefore cause individuals to feel intensely dizzy or nauseous.

These changes in body awareness can also lead to further impact on physical well-being by increasing the susceptibility to injury, the same participant as the above quote wrote:

> *"Sometimes I might get undersensitive and cut, bruise or burn myself." P47*

Physical well-being can also influence the fluctuation of sensory input. Many participants reported that tiredness made a significant impact to their sensory sensitivities.

> *"Having less sleep beforehand makes strong smells bother me more as I have less patience." P32*

This appeared particularly salient when participants were talking about interoception and body awareness, with lack of sleep being commonly reported as the cause of sensory fluctuations.

> *"Tiredness and stress increase 'something's wrong' alerts but decrease accuracy." P7*

> *"If I'm tired, I have no idea where my limbs are & will walk square into doorframes". P49*

The quote from P7 particularly highlights how tiredness can mediate the effectiveness of the interoceptive signals to be able to alert the individual to their needs. P49 highlights the significant impact that tiredness can have on their body awareness and their ability to safely navigate their environment.

When experiencing reduced awareness of interoception, individuals often described using trial and error strategies to improve physical well-being. They described trying to eat, drink or sleep in an attempt to improve how they felt physically.

> *"Try to fix the most likely cause of the 'something's wrong' alert first, then go down the list until I end up just trying to sleep it off." P7*

Theme 2. Cognitive

This theme was created to describe the cognitive processes which are affected by sensory fluctuations, how cognitive processes affect sensory experience and what cognitive-based strategies are used to overcome sensory difficulties.

Theme 2.1 Representation of self

Here we define 'representation of self' to include 1) self-concept; which is a collection of beliefs that an individual holds about themselves as well as 2) the body representation; which refers to the perception and cognition related to the body.

The data reflected descriptions of the representation of bodily self and the connection participants feel between themselves, their brain, and their body. Some participants explicitly described how sensory fluctuations affected how they felt to their body.

“Depending on my stress levels and how busy my brain is, it changes how connected I feel with my body.” P50a

When describing their sensory experience, many participants used language that indicated a representation of themselves that was separate from their brain and body.

“Once I stop hyperfocusing I can suddenly feel hunger-nausea, tiredness and like I REALLY need to loo because my brain just didn't tell me while I was excited about the other thing.” P7

Here, a participant implies that their brain didn’t communicate their needs to them. Perhaps suggesting that they are representing themselves as being separate from their brain and body.

In another example, a participant talks as though their body is separate from themselves and they treat it almost like a separate person.

“Just try to give my body things it might like (tea, snacks, etc) until it stops whining” P49

These quotes suggest a disconnection between self and body, as if the body isn’t communicating with the mind effectively.

Similarly, when talking about body awareness, some participants implied that they felt reduced control over their body, giving weird sensations that they no longer had agency over their body.

“other days it's like my hands are made of clay or they're badly controlled like puppet strings, they feel clumsy and incapable of anything”. P25

“It can be quite disorientating when I stop being able to feel my hands in my coat pockets, or when they feel like they've been taken off my arms, swapped over and reattached to the opposite arm.” P50a

Self-concept also appeared to be impacted by sensory fluctuations. Some participants reported viewing themselves differently when experiencing sensory fluctuations.

> *“emotionally I feel upset at the event and frustrated with myself for being so weird” P47*

Here, a participant is suggesting that the way they respond to, and experience sensory fluctuations perhaps influences their conceptualisation of self by making them feel as though they are ‘weird’. When talking further about the difficulty with reading internal bodily signals an individual said:

> *“its very frustrating and makes me feel disconnected from myself and almost incapable of being human” 24b*

This quote really encapsulates the self-representation theme, as they suggest that this disconnection between self and body leads them to feel less human. It’s not just their representation of bodily self which they describe, but also their conceptual self.

Sub theme. 2.2 Mental Stimulation

In this theme we include concentration, boredom, and distraction as the basis of “mental stimulation”.

Several participants reported having their focus impacted by their sensory fluctuations.

> *“Smells can be extremely distracting at times and hard to place, I cannot focus until I have figured out what they are” P50b*

Participants also described their state of mental stimulation as impacting how sensory fluctuations affected them. For instance, sensory input being more bothersome if they were trying to concentrate on a task.

> *“If I have to concentrate on something else or am tired then proprioception gets worse.” P17*

Some participants also said that their awareness of a particular sense would diminish if focussed on another task. This was described as problematic when talking about body awareness or interoception. When talking about the latter, a participant wrote:

"If I'm too distracted or engaged in a task then I will probably have less awareness." P17

In this context, the individual describes this as a negative consequence, as they become less aware of their internal bodily signals and as a consequence they don't attend to their needs.

Conversely, participants reported using distraction to reduce sensory awareness as a means of coping for senses such as touch, smell or sound.

"try to distract myself from focusing on the thing that's bothering me." P50b

These examples highlight that mental stimulation can mediate the awareness of a sense, which can be adopted as a strategy when reduction of awareness is beneficial.

Subtheme 3.3 Preparation/routine

A clear theme in the data was the use of preparation or routines to improve the predictability of the sensory input and thus overall coping.

Several participants mentioned routines when talking about strategies to manage fluctuations in interoception.

"Drink too much water, eat at the three regular times because that's routine and it's good and makes me feel like I'm not going off the rails :)" P31a

Other participants wrote about anticipating fluctuations in interoception by preparing for them.

"i usually make spaces to have food around quickly so when hunger sets in and i don't have the time or energy to go about meal preparation i have

> *something then and there, and then once my blood sugar is higher i can focus on preparing a more elaborate meal." P25*

Conversely, one participant described their experience with fluctuations in taste reactivity and how preparation doesn't necessarily work.

> *"It is really difficult because I can spend ages trying to decide what to eat and when meal planning I will set out what I want to eat every day of the week but then I can get to that day and the idea of the food disgusts me" P6b*

Another participant mentioned preparing for changes in taste reactivity in relation to their menstrual cycle:

> *"I think Tesco can probably track my menstrual cycle by my purchases. I prepare." P7*

Other participants talked about mental preparing themselves for sensory input that could be uncomfortable.

> *"If I know I'm going to be in a situation where I might have to shake hands with someone I try to mentally prepare myself." P22*

For other participants their preparation included taking physical aids (subtheme 2.1) with them before leaving the house, so they are able to reduce sensory input if needed.

> *"My noise-cancelling headphones. With me, on me, anytime I go out, to work, anywhere where isn't home." P47*

Subtheme 2.4 Level of Awareness

It is important to note that many participants reported being unable to attribute a cause to their sensory fluctuations or were unaware of strategies that would help them cope. This theme has been included to highlight this.

Several participants indicated that they didn’t really know what caused their sensory fluctuations.

> *“I really don't know, sometimes I just feel completely differently about being close to people and interacting with them. It's not always when I'm upset, sometimes I can feel really happy and in control but I still want to be left alone.” P35*

Other participants simply wrote they were unsure of the cause of their sensory fluctuations.

In addition, many participants reported to either not cope with their sensory fluctuations or not have any strategies to try and manage them.

When talking about strategies to manage changes in body awareness, a participant simply wrote:

> *“i haven't found a way to cope.” P25.*

Many other participants also stated that they don’t cope with sensory fluctuations or don’t know any strategies that would help.

Theme 3. External

Sub theme 3.1 Characteristics of sensory input

This theme was identified as many participants described elements of the sensory input that affected their sensory experience and contributed to fluctuations in sensory reactivity. Sensory input was also referenced when participants wrote about how they cope with sensory fluctuations.

Participants commonly described the amount of sensory input as dictating sensory fluctuations and their sensory experience. The more sensory input, particularly if this spans across multiple senses, the harder it is to deal with.

> *"An increase in the stimulation of other senses will also increase ly sensitivity (e.g. bright lights or lots of people talking) but it is difficult for me to say how much of this is related to the increase in stimulation making me more stressed and how much is some other connection between the senses." P6a*

This quote highlights the interrelated affect that sensory input across several senses has on sensory fluctuations.

A notable element of sensory input which many participants described was predictability. Sensory input was often described as being easier to manage when they knew it was going to happen.

> *"I think the difference is that one is in my control and I already know how it's going to sound and I anticipate it. An example of the same sound being overwhelming and other times not is my doorbell. It is an excruciatingly bad sound, the very loud and harsh "buzz" you hear in prison movies. It sets me off every time, unless I am expecting it to happen in the span of 10-20 seconds (e.g. I see delivery driver through my window so I know they're going to ring soon)." P47*

This quote gives a clear example of what many participants report, that the same sensory input can fluctuate in how it affects them depending on how predictable it is.

When participants reported being in control of the sensory input, therefore making the input predicable, the reported a better sensory experience.

> *"Loud sounds can be pleasing when under my control" P49*

> *"If I am expecting it [a smell] then it's not that bad, but if it's a surprised then it can be very difficult for me." P36*

Interestingly, the importance of predictability seems to be consistent across the senses. In the examples given above, you can see that predictability is discussed across sound, vision, touch, and smell. It seems that predictability and control make big impacts on the experience of sensory fluctuations.

As a way of coping with sensory fluctuations, several participants reported using physical barriers to avoid or reduce sensory input.

> *“I have, carry, and use a variety of ear plugs to cope with different sound environments - Flare Calmers, Flare Shades, Flare Isolates, Loop Quiets, and Loop Experiences.” P33*

Sensory input was also utilised by participant to improve the experience of sensory fluctuations. Participants described using physical aids to provide good sensory information to relieve sensory overload or discomfort. When describing how to cope with fluctuations in touch information, one participant wrote:

> *“My weighted blanket has become a key resource for this experience. I often rely on the weight of the blanket to numb any feeling of being touch or clothing that may be adding to my distress.” P20*

Other participants noted the importance of using sensory input to either increase or decrease awareness of a particular sensory input.

> *“Being outside in a t-shirt in the rain and/or wind massively increases my awareness and I absolutely love the feeling.” P50a*
>
> *“If it's an overwhelming sound, I play loud music, preferably heavy metal or something with a lot of beats per minute, so that I drown out the sound with something predictable and I associate with pleasure” P47.*

Participants also described how difficult it can be when the good sensory input that they usually use as a coping mechanism is no longer effective.

> *“It can actually be really distressing as I listen to music a lot to help me so then for that to become the thing that is making it worse is difficult.” P6b*

In this instance, the participant is referring to experiencing a fluctuation in sound reactivity and the impact this has on them when their coping strategy is listening to music.

Sub theme 3.2 Social

An important element that needs capturing in this data is the impact sensory fluctuations have on relationships and how other people can impact upon an individual's sensory experience.

Participants discussed how sensory fluctuations can have social impact.

> *"It makes socialising difficult unless I can sit apart from others - shared benches and tables are a problem" P33*

> *"When around people who don't have such issues it can feel a bit embarrassing as well because "even children can walk without falling over or can catch a ball", especially when I did pretty well at some sport the other day, for example." P17*

As noted in the last example, participants reported being aware of what other people might be thinking about them and feeling embarrassed at experiencing sensory fluctuations or fulfilling sensory needs in a social or public setting.

Several participants reported that their sensory fluctuations impacted upon their romantic relationships. Particularly when describing the experiencing and fluctuations in touch reactivity.

> *"Sometimes I enjoy my partner's touch, but other times I can't stand it ...This is obviously not ideal from the perspective of a romantic relationship, especially as it can be very unpredictable, meaning my partner has become increasingly anxious about spontaneously showing affection." P8*

This quote highlights that it is not just the experience of sensory reactivity that impacts their relationship, but the unpredictable fluctuations in tactile reactivity.

The social setting in which the sensory input is happening can also mediate the sensory fluctuation. For instance, several participants reported that their experience of a sensory input can change depending on who is causing the sensory input.

> *"Hearing my partner eat is not as difficult for me to experience as it is for a stranger who i have just met. I often become enraged when i hear people eating and more so if there is nothing i can do about it - such as ask them to be quiet." P20*

It is perhaps easier for individuals to process sensory input caused by someone they know as there is more potential for them to being able to do something about the input. This is reflected in latter half of P20's response. Thus, there is perhaps an interaction between social setting and control over the sensory input.

Participants also described how they used communication or help from others as a strategy to manage sensory fluctuations.

> *"My partner helps remind me to eat and go to the toilet when I'm in one of these states which helps." P3a*

This was particularly notable when talking about fluctuations in touch, many participants reported needing to communicate with a partner, family, or other people to make sure their sensory needs were met. Indeed, one participant even reported having to practice communication in these circumstances.

> *"I've also taught myself how to say that I'm not comfortable and practised having the strength to do so." P1b*

This individual exemplifies the idea that individual’s must be able to effectively communicate to others about their sensory needs, to help them have a better sensory experience.

Sub theme 3.3 Daily Activities

This theme was created to capture the impact that sensory fluctuations can have on the ability to complete everyday tasks.

Many participants reported that daily activities were more difficult when experiencing sensory fluctuations. When talking about interoception and body awareness fluctuations, a participant wrote:

> *“It makes it difficult to enjoy doing things sometimes because I'm so susceptible to burning myself out by associating the bad sensation afterwards with doing something I enjoy.” P3a*

Some participants described how sensory fluctuations impact their career.

> *“Another example is within my job, i do lots of admin - which includes typing for 80% of the day. Some days i am able to type very quickly and others i have to reduce my speed by 50% compared to the day before. This can make me feel stressed and somewhat confused as the days started the same and i am carrying out the same tasks, yet one day i am fully capable and the next i am struggling” P20*

These examples show how sensory fluctuations can have a far-reaching impact and really make it challenging for people to continue with daily activities.

Model of internal sensory experience

In addition to the quotations of participants' experiences, we present a model conceptualising the link between hyporeactivity to interoceptive senses and representation of self (see Figure 6.5). It describes the process described by participants whereby a reduction in awareness in internal senses (e.g., proprioception, interoception, and vestibular) leads to physical discomfort (e.g., extreme hunger, inability to balance, feeling clumsy) and a perceived disconnection between self and the body. In turn, this has impacts upon mental well-being and how individuals view themselves (self-concept). Subsequently this leads to a state of vulnerability to further sensory reactivity changes.

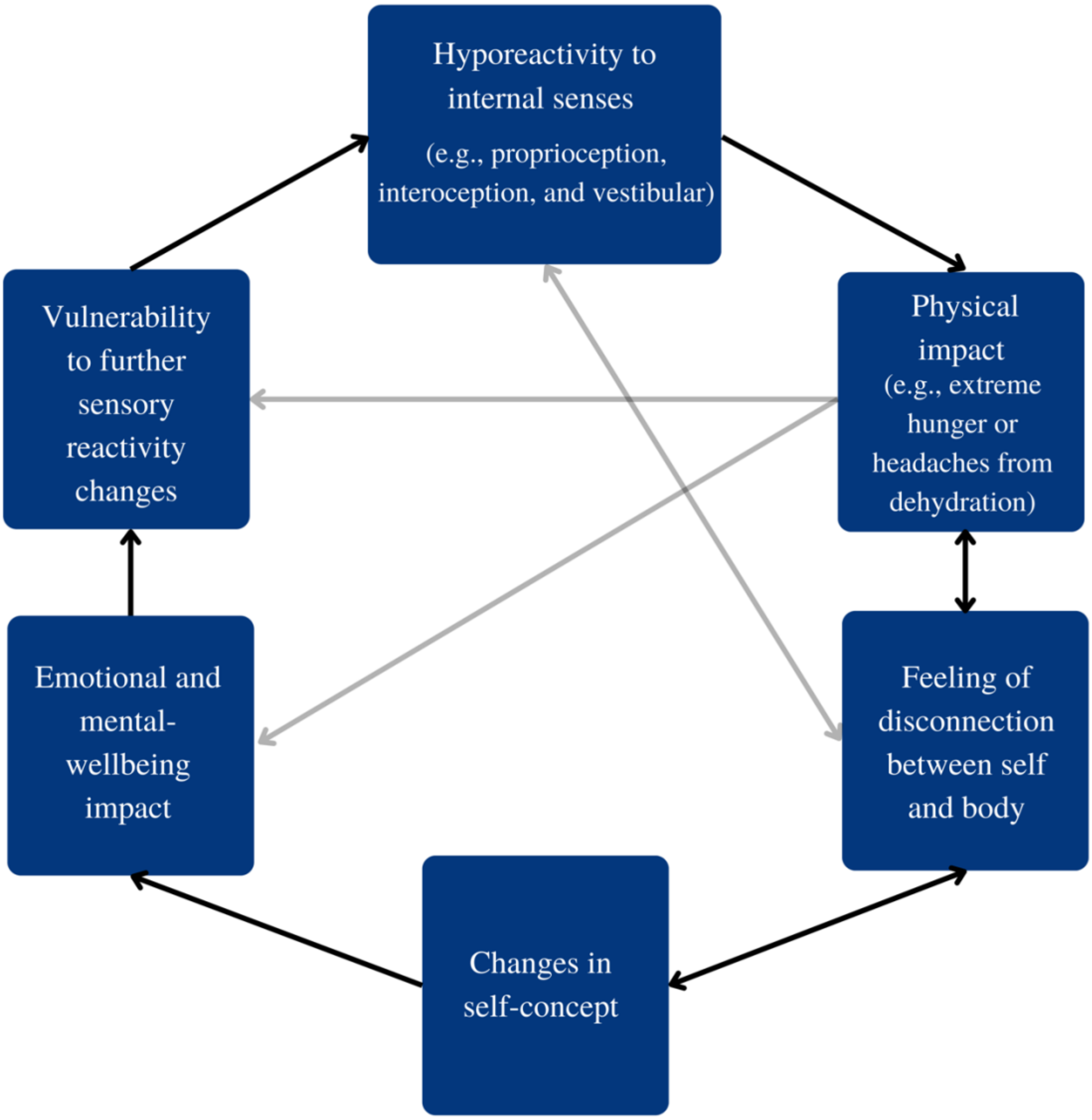


Figure 6.5. Theoretical model of the impact of hyporeactivity in internal senses on self-representation and well-being. Black arrows represent the cycle of how hyporeactivity in internal senses can impact upon physical well-being, self-representation (body and self-concept), and emotional well-being. Grey arrows represent how each component can influence another component outside of this cycle. Arrows can be bidirectional to represent the bidirectional relationship between two components.

6.7 Discussion

This mixed-methods study has provided an important insight into the sensory fluctuations of autistic adults across sensory domains. Our results have enhanced the understanding of hyperreactivity and hyporeactivity to sensory input in autism, with a particular focus on the experience of fluctuations in sensory reactivity. Importantly, we have provided comprehensive insight into the impact of sensory fluctuations from a multisensory perspective.

Our quantitative data provide a unique insight into the prevalence of sensory fluctuations across all major sensory domains; visual, auditory, olfactory, taste, tactile, vestibular, proprioception, and interoception. Similarly to previous work, we found that all autistic adults experienced a sensory difference to at least one sense (Crane et al., 2009). We found that only five participants reported exclusively experiencing hyperreactivity across sensory domains. Therefore, most participants reported experiencing a combination of hyper-, hypo- or mixed reactivity across sensory modalities. This highlights an important point, that individuals cannot simply be labelled as being hyperreactive or hyporeactive. Instead, we found most individuals experience different reactivity types depending on the sensory input. This finding supports previous work which has highlighted the complexity of sensory experience in autism (Jones & O'Neill, 1997; Jones et al., 2003; MacLennan et al., 2021; Smith & Sharp, 2013).

When looking at reactivity across sensory domains, we found that all participants described experiencing a sensory difference to touch, of which all reported being hyperreactive or mixed reactive to touch. This supports previous qualitative work reporting that found autistic adults reported being hyperreactive to touch from other people and clothing and were not likely to experience only hyporeactivity to touch(MacLennan et al., 2021). A unique finding from our quantitative analysis revealed that experiencing mainly hyporeactivity was most commonly reported for internal body- related senses (proprioception, vestibular, and interoception). This seems to suggest that sensory differences in internal signals are largely experienced as reduced awareness, which corresponds to previous work which has identified a decrease in internal bodily signals and body awareness in autistic adults compared to non-autistic adults (Fiene & Brownlow, 2015). By comparison, smell, sound, taste, touch, and visual signals were most commonly reported to elicit hyperreactive responses. Together, these findings may suggest that internal and external sensory inputs may lead to a different patterns of sensory experience in autistic individuals.

This study also aimed to understand the frequency of sensory fluctuations - when responding to the same sensory input can change on different occasions. All but one participant reported experiencing different reactions to the same sensory input on different occasions in at least one sensory modality. Participants reported experiencing the most fluctuations in interoception and touch and the least in taste and visual inputs. Even at the lowest end, nearly one fifth of participants reported experiencing fluctuations in taste. These findings exemplify the complexity of sensory experience as most participants seem to experience fluctuations in how they react to the same sensory input across a range of sensory domains. From a theoretical point of view this has important implications as it suggests we need to broaden our conceptualisation of sensory differences to include fluctuations. Moreover, this finding suggests that quantitative measures of sensory experience need to accommodate sensory fluctuations to full represent the experience of sensory differences in autism.

Our qualitative findings provide a rich understanding of the autistic experience of the sensory world. For the first time, we have been able to elucidate the experience of sensory fluctuations and reactivity from an autistic perspective. Similarly to previous work, participants described how sensory sensitivities can have a huge impact on their mental and physical well-being and their ability to go about day-to-day life (MacLennan et al., 2021; Smith & Sharp, 2013).

Notably, participants reported that changes in sensory experience could be quick and unpredictable. Typically, this meant that a sensory input which had previously had a positive impact could quickly become a negative experience. This unpredictability was particularly salient when individuals were talking about their social experience. For example, several participants reported that fluctuations in touch input could make it very difficult for their partner to express physical affection. Sensory changes that could not be predicted were therefore not able to be communicated to a partner, subsequently negatively impacting both the individual and their romantic relationship. Sensory experiences also had a wider impact on social well-being. Participants described how social input from others could increase their sensory reactivity, particularly if the other person was a stranger. Moreover, participants described how sensory reactivity issues could create a barrier to social interactions and often lead them to avoid social environments and interactions. Conversely, support from close others was reported to help them cope with negative sensory experience. This finding builds on previous work which found that understanding and support from others can mediate outcomes of sensory input (MacLennan et al., 2021). Building on this, findings in the current study demonstrate that the unpredictability of sensory fluctuations can interact with social experience and negatively impact upon important social interactions with romantic partners. Additionally, sensory experience can isolate individuals by reducing their access to social environments thus affecting their social well-being more broadly. Importantly, these findings contribute to our understanding of how sensory experience can influence social interactions in autistic adults.

Importantly, our findings have provided insight into the experience of hyporeactivity, particular with regards to body-related senses. As reflected in our quantitative findings, participants were more likely to report hyporeactivity to the internal body-related senses (e.g., proprioception, interoception and vestibular) compared to the external senses (e.g., vision, audition). A unique finding was that participants described or implied feelings of disconnection between themselves and their bodies because of this decreased awareness of their bodies. The body was often referred to as a separate entity that they had little control over or reduced communication with. For some individuals this also led to wider changes of viewing themselves as weird or incapable of being human. Thus, hyporeactivity not only significantly impacted their physical well-being (e.g., getting a headache form dehydration) but led individuals to feel disconnected from their own bodies. The impact of hyporeactivity of interoceptive senses has been further conceptualised in the model presented in Figure 6.5. This model highlights the impact of hyporeactivity, how this can affect self-concept in addition to well-being. Note the bidirectional arrows in the model which represent how these factors may mutually influence each other. For example, reduced interoceptive awareness may lead to physical impact such as a headache from dehydration which may have direct emotional impact or may induce a self-body distinction which could in turn effect mental well-being. Similarly to previous work, we suggest that this impact may induce a state of vulnerability whereby individuals are more likely to experience further sensory reactivity changes (Smith & Sharp, 2013). These findings emphasise the importance of addressing a reduction of body awareness when understanding the sensory experience of autistic individuals as it has such a significant impact on mental and physical well-being. Crucially, both research and the measures used in research (e.g., self-report questionnaires) need to account for all sensory domains to fully understand the experience of hyper- and hypo- sensory reactivity.

Perhaps one of the most notable findings was the cyclical nature of the relationship between the impact of sensory fluctuations and the cause of sensory fluctuations. Most participants described the outcomes of sensory fluctuations as also contributing to the changes in sensory reactivity. This supports previous work which found that outcomes of sensory reactivity also feed into the cause of sensory reactivity (MacLennan et al., 2021; Smith & Sharp, 2013). A unique finding in the current study was that outcomes such as mental and physical well-being not only made individuals more reactive to a sensory input but could also cause fluctuations in reactivity within a sensory domain. In other words, poorer well-being could alter the reactivity of a particular sensory input from being hyper- to hypo- and vice versa. Additionally, reduced well-being could cause a sensory input to change from a positive experience to being a negative one. The autistic adults in our study also described how these changes can happen suddenly and without warning, making them even more challenging. This finding elucidates the complexity of the autistic sensory experience as individuals can experience changes in sensory reactivity across and within sensory domains.

Individuals reported using a range of coping mechanisms, of which avoidance of sensory input was commonly stated. Similarly to previous work, individuals described removing themselves from the setting or attempting to remove the sensory input itself (MacLennan et al., 2021). A key finding relating to coping strategies was that most mechanisms used to try and manage sensory fluctuations centred around gaining control over the sensory experience. This ranged from using physical aids to reduce or avoid sensory inputs, to communicating with others to improve the sensory experience. This also corresponds to previous work which highlighted the importance of predictability when managing sensory reactivity (MacLennan et al., 2021; Robertson & Simmons, 2015). Indeed, participants reported using preparation and routines to improve the predictability of the sensory input and manage sensory fluctuations. This is perhaps why sudden and unexpected changes in sensory reactivity are the hardest to manage and are often reported to lead to meltdown. Participants also reported using trial and error fixing when they experienced a reduction in interoception and body awareness. As individuals reported to be unaware of when they needed to eat, sleep or drink, they described 'going through the list' of options to see what would make them feel better.

Similarly to previous work, sensory seeking behaviour was also commonly described as a way to improve sensory experience through pleasant input (MacLennan et al., 2021). Individuals typically talked about seeking positive auditory (i.e., music) and touch (i.e., hugging, squeezing self) to reduce hyperreactivity, however one participant did report seeking sensory input to increase body awareness. Therefore, it is perhaps too simplistic to conclude that sensory seeking is only used to manage hyperreactivity. Individuals also described how sensory seeking coping strategies can be inhibited by a sensory fluctuation. This can have serious impact on the cycle between sensory input and outcomes if individuals are no longer able to manage their sensory experience. This builds on previous work that has highlighted the vicious cycle of sensory input and outcomes by providing insight into how sensory fluctuations can impact upon coping mechanisms (MacLennan et al., 2021; Smith & Sharp, 2013).

Whilst the current study has provided important insight into the sensory experiences of autistic adults across all major sensory domains, it is not without limitations. Firstly, it is not known whether the current findings are uniquely applicable to the autistic population. Indeed, previous work has found that sensory differences are widely experienced by individuals with

ADHD (Kamath et al., 2020; Lane & Reynolds, 2019). Further research is therefore required to understand whether sensory fluctuations are uniquely experienced by autistic individuals. Secondly, the current study recruited participants with low levels of support needs to take part in the study. Subsequently the results may not be representative of autistic individuals who are unable to express themselves through written words to describe their sensory experiences. This is particularly important to consider in the quantitative results as such findings cannot be generalised to the entire autistic population. Future research should endeavour to include individuals with higher support needs in work exploring the sensory experiences of autistic adults. Lastly, although the use of online methods facilitated the potential for diverse perspectives and experiences from different geographical locations it has potential limitations. For example, participants could not be formally diagnostically assessed for autism, thus we cannot be 100% confident that all participants met clinical diagnostic criteria for autism.

*Conclusion*s

Our quantitative findings demonstrate that sensory reactivity differences and sensory fluctuations are prominent in autistic adults. Our quantitative results further suggest that hyporeactivity is more likely to be experienced in internal senses whilst hyperreactivity is more likely to be experienced in external senses. From our qualitative findings we show the impact of sensory differences is wide and complex, affecting physical, mental, and social well-being. Notably, we found that the unpredictability of sensory fluctuations can significantly impact upon social interactions and access to social environments. Importantly, this contributes to our understanding of how sensory experience can influence social interactions in autistic adults. Interestingly, we found reduced awareness of internal sensory inputs can have a significant impact on the subjective experience of the body and on self-concept. Our findings have important implications for our understanding of autistic sensory experience. Crucially, the findings emphasise the need to include sensory fluctuations from a multisensory perspective in theoretical frameworks and in quantitative measures of sensory experience. Future research should seek to understand how autistic individuals can be best supported to manage their sensory differences.

General Discussion

The predominant objective of the present thesis was to investigate the relationship between sensorimotor integration and social processing. Namely, focus was given to investigating the relationship between sensorimotor integration and self-related processing, visual perspective taking, and interpersonal synchrony. This was achieved using a combination of online and in-person research techniques, working with both autistic and non-autistic individuals. Online research methods were used to investigate the relationship between sensorimotor integration and self-related processing in non-autistic (Chapter 2) and autistic (Chapter 3) adults. Mediated reality technology was utilised to assess the contribution of sensorimotor integration in visual perspective-taking (Chapter 4) and interpersonal synchrony (Chapter 5) in non-autistic individuals. To contextualise the findings of the experimental chapters, mixed (qualitative and quantitative) online research methods were used to gain insight into the sensory experiences of autistic adults from a multisensory perspective (Chapter 6).

Within the current chapter, an outline of all empirical chapters will be presented with a summation of the main findings from each study. The implications of the presented work will be discussed in relation to the impact on theory and research practice. The strengths and limitations of the empirical chapters will be considered and used to provide possible direction for future research.

7.1 Summary of Thesis Findings

As a fundamental component of social cognition, **Chapter 2** investigated the mechanisms underlying self-related processing. Specifically, whether sensory integration and body schema are implicated in the perceptual processing of self-related information. Sensory integration was assessed using a novel visuotactile simultaneity judgement task and body schema was evaluated using the hand laterality judgement task. Self-related processing was assessed using a basic self-tagging paradigm in which individuals learnt pairs of labels (e.g., self, friend, and stranger) with simple geometric shapes (e.g., circle, triangle, and square) and had to complete a recognition task of these pairs. Results from *Study 1* revealed that non-autistic individuals showed a significant self-bias compared to stranger-related information. Moreover, body schema significantly and uniquely predicted performance on the *Self*, but not *Friend* or *Stranger*, related trials. This finding suggests that an internal dynamic representation of the self (i.e., the body schema), may be implicated in the processing of basic perceptual self-related information. In *Study 2*, results similarly showed that non-autistic adults show a significant bias to process self- compared to stranger-related information. Visuo-tactile-motor sensory integration ability was found to significantly and uniquely predict performance on self-related processing. Conversely to the results of *Study 1*, *Study 2* found that body schema may predict friend-related, but not self-related processing. Together, these results may suggest that successfully integrating body-related sensory information may enhance the tendency to prioritise the processing of self-related or socially salient information. Importantly, this finding elucidates our understanding of the relationship between sensory integration and social processing, by showing how self-related processing, which is thought to relate to crucial social processes such as self-awareness and mentalising, may subsequently rely on sensorimotor integration. Whilst the results across the two studies were mixed, these findings provide a useful foundation for further research to understand the mechanisms underlying social processes by elucidating the relationship between the bodily self and the conceptual self.

Next, with theory suggesting that autistic individuals exhibit self-awareness differently, **Chapter 3** aimed to understand self-related processing and its underpinning mechanisms, in autistic adults. Body schema, sensory integration, and self-related processing were assessed using the same methods as in Chapter 2. Results showed that autistic adults exhibit a strong bias to process self-related information compared to friend *and* stranger related information. This finding provides important insight into how autistic individuals process information related to the self and provides evidence to suggest that self-prioritisation is not diminished in autism. Indeed, this finding may suggest that autistic individuals hold typical self-awareness, and thus atypical self-related processing may not explain the differences exhibited in social function in autism. Conversely, and counter to previous work, non-autistic adults did not show a significant self-bias in perceptual processing. In addition, we found no evidence to suggest that body schema or sensory integration relates to this self-bias in autistic adults. However, as the non-autistic group did not exhibit a self-bias, this could not be directly compared with the non-autistic group. Yet, findings from Chapter 2 suggest that the body schema and sensory integration may relate to self-referential processing in non-autistic adults. Findings from Chapter 3 may therefore suggest that an internal representation of the body formed through multisensory integration is not implicated in self-related processing in autism. Instead, autistic individuals may solely rely on cognitive networks for self-referential processing and not embodied mechanisms. These findings provide a basis for further research to understand if self-related processing is underpinned by the same mechanisms in autistic and non-autistic adults. Future research may subsequently uncover the extent to which self-bias is key for social processing in autism.

Chapter 4 sought to understand the role of sensorimotor integration in visual perspective-taking. Whilst previous research has demonstrated that level two visual perspective taking (VPT2) is an embodied process, no study has directly evaluated how disrupting the body schema through manipulation of self-location may impact perspective taking. Therefore, we investigated whether the use of a visuo-proprioceptive body illusion could disrupt the body schema and thus diminish VPT2 ability. This was achieved using a multisensory body illusion in the mediated reality system MIRAGE, which induced the sensation of a missing hand and disrupted the experience of self-location. Susceptibility to this illusion is grounded within multisensory integration, such that more optimal MSI is associated with greater susceptibility to the illusion. As such, the greater the mislocalisation of the hand due to the illusion, the better the MSI. Results showed that whilst the illusion significantly impacted whether individuals could accurately locate their hand (i.e., their self-location was disrupted) this did not impact upon accuracy or processing times of level VPT2. Moreover, we found no relationship between MSI, as measured by hand localisation error, and VPT2 ability (accuracy or reaction times). Overall, findings from this chapter suggest that disrupting self-location of the right hand in non-autistic adults is not sufficient to diminish VPT2 ability. Moreover, it suggests that integration of visual and proprioceptive inputs associated with the hand may not be directly related to the ability to take another individual's perspective. As such, VPT2 may instead be underpinned by full-body representations that are formed through multiple sensory signals from multiple regions of the body.

To further elucidate the relationship between sensory and social processing, **Chapter 5** investigated the role of sensorimotor integration in interpersonal synchrony. Interpersonal synchrony, whereby two or more individuals coordinate their movements in spatial and temporal synchrony, is associated with facilitating social interactions. Indeed, children and adults are more likely to help, like, and be affiliated with individuals they have been moving synchronously with. Such coordination can occur spontaneously (uninstructed), without conscious effort or intentionally (instructed), where individuals try to synchronise their movements with another object or person. Whilst research has found that this ability to synchronise and integrate sensory information develops through childhood, little is known about how sensorimotor integration may contribute to interpersonal synchrony, and its social bonding outcomes, in children and adults. Moreover, it is unknown if uninstructed synchrony can elicit similar social bonding outcomes as instructed synchrony. Thus, Chapter 5 investigated how a context which promoted greater opportunities for sensorimotor coupling (social vs non-social stimulus) and instruction (instructed vs uninstructed) influenced synchronisation accuracy and social bonding in adults and children. Visuomotor synchrony was improved within a social, compared to non-social, context in adults and children. Children, but not adults, synchronised more accurately when instructed to synchronise than when uninstructed. This finding suggests that for adults, the ability to integrate another person's movements into one's own motor representation is not dependent on the top-down input of instruction. Comparatively, the visuomotor synchrony of children appears more influenced by the instruction of another person to coordinate their movements. For both children and adults, synchronisation in a social context elicited stronger social bonding towards an interaction partner as compared to synchronisation in a non-social context. Importantly, this demonstrates that pro-social behaviour is facilitated by coordinating movement with the interaction partner (social context) and not when the interaction partner is merely present (non-social context). Finally, for children, but not adults, the degree of synchrony with the partner was significantly associated with their feelings of social closeness. This finding highlights that for children, it is the ability to perform visuomotor synchrony through sensorimotor coupling which predicts social bonding following interpersonal synchrony. Therefore, sensorimotor integration appears to play an integral role in the development of interpersonal synchrony and the expression of pro-social behaviour in childhood. Together, these findings illuminate the role of sensorimotor integration in interpersonal synchrony and further demonstrates how multisensory processes play a key role in social interactions.

The chapters thus far have sought to experimentally understand how sensorimotor integration is implicated in social processing in autistic and non-autistic individuals. To fully understand whether such theoretical findings correspond to lived experience in autism, research needs to consider reports from autistic individuals. **Chapter 6** used mixed research methods (qualitative and quantitative) to investigate the sensory experiences of autistic adults. Whilst research has largely focussed on the experience of sensory hyperreactivity (over sensitivity to sensory input) from exteroceptive signals (e.g., vision, audition, touch) autistic individuals can experience hyperreactivity and hyporeactivity (under sensitivity to sensory input) across multiple sensory modalities (e.g., interoception, proprioception, and vestibular) sensory inputs. Additionally, little is understood about how autistic individuals experience fluctuations in sensory reactivity – whereby reactivity to a particular sensory input can shift from hyperreactive to hyporeactive and vice versa. Subsequently, Chapter 6 focussed on understanding the experience of sensory fluctuations across all major sensory domains (vision, audition, gustation, olfaction, touch, proprioception, interoception, and vestibular) from the perspectives of autistic adults. The quantitative analysis revealed the pervasive nature of sensory differences in autism, with all participants reporting a sensory difference in at least one sensory domain. There appeared to be different reactivity profiles for the internal and external senses, with hypo- and mixed-reactivity being most commonly reported for vestibular, interoception and proprioception, whilst hyperreactivity was most commonly reported for olfaction, audition, gustation, touch and vision. Lastly, all but one participant reported experiencing sensory fluctuations in at least one sensory domain. Fluctuations were most commonly reported for interoception and least for taste. The qualitative analysis revealed the widespread implications that sensory differences have on the mental, physical, and social well-being of autistic adults. Vulnerability to sensory fluctuations was reported to be heightened by emotional state, anxiety, interactions with others, amount of sensory input, and predictability of input. Importantly, sensory experience was found to have an intertwined relationship with social experience, with sensory differences both being heightened and mediated by interactions with others. Interestingly, shifts into hyporeactivity appeared to impact how connected individuals felt towards their bodies, which affected the way individuals conceptualised themselves. The findings from Chapter 6 emphasise the importance of considering sensory differences across all senses, particularly as internal and external inputs are associated with different sensory reactivity profiles and can interact within an individual's sensory experience. Both clinical and research contexts need to consider reactivity and fluctuations from a multisensory perspective to fully represent the sensory experiences of autistic individuals.

7.2 Thesis Implications

The empirical chapters presented with the current thesis provide a novel contribution towards our understanding of the role of sensorimotor integration in social processing. Subsequently, it is important that such findings are discussed within the context of previous research as well as clinical and theoretical implications, which are summarised in the following sections.

7.2.1 Embodied Cognition in Non-autistic Individuals

The embodied cognition framework postulates that thinking is grounded within the body (Gallese & Sinigaglia, 2011; Goldman & de Vignemont, 2009; Wilson, 2002). That is, cognition, including social skills, can be influenced by states of the body (Eerland et al., 2011) or the environment (Adam & Galinksky, 2012) such that there is a bidirectional relationship between abstract cognitive states and body states (Goldman & de Vignemont, 2009; Wilson & Golonka, 2013).

Findings from Chapter 2 suggest that body schema and sensorimotor integration may predict the processing of self-related information and thus contribute to our understanding of which social processes might be grounded within the bodily self. These findings correspond to the Bodily Self Consciousness model of self-reference (Park & Blanke, 2019), which stipulates that there is an integration of the conceptual representation of the self and the bodily representation of the self, such that the body can be used as a tag for memory consolidation. Indeed, research utilising the Full Body Illusion (FBI) has suggested that the experience of self-location, a key component of the body schema, can influence how self-relevant information is processed (Canzoneri et al., 2016). Findings from Chapter 2 may provide further evidence to suggest that internal representations of the body, formed through multisensory integration may reinforce the processing of self-related information. The body schema may facilitate the connections between external information and internal representations of the self, reinforcing self-other distinctions and thus enabling the prioritisation of self-related information. This may serve as an explanation of previous findings that have extensively demonstrated how individuals will prioritise the processing and remembering of information that is paired with themselves (Sui & Gu, 2017; Sui & Humphreys, 2015a, 2015b, 2017; Sun et al., 2016). Importantly, self-prioritisation may act as a foundation for other social cognition. Indeed, holding a representation of oneself, and knowing that one is separate from other people is key to understanding that others have distinct views and thoughts (Conway et al., 2019; Nijhof & Bird, 2019). Thus, prioritising information related to the self may further reinforce a self-other distinction on a conceptual level, allowing for higher-order social cognition such as empathy to occur (Lombardo et al., 2007). Current findings may suggest that the ability to know that other people are distinct from ourselves, and subsequently prioritise information that is related to ourselves, is dependent on holding a body representation, formed through multisensory integration.

Understanding how others view the world is a fundamental component of social cognition (Schurz et al., 2015), and thus key for social interactions. Level two visual perspective-taking is an embodied social process, relying on a representation of the body to perform egocentric transformations to understand how others see the world (Hamilton et al., 2009; Pearson et al., 2013; Surtees et al., 2013a, 2013b). As such, forming a body schema through optimal sensorimotor integration may be implicated in the ability to understand how another person views the world. Findings from Chapter 4 contribute to our understanding of this link by demonstrating that disruption of self-location of a limb is not sufficient to disrupt VPT2 ability. Considering the embodied cognition framework, egocentric transformations of the bodily self may subsequently rely upon multiple components of bodily self-consciousness (ownership, agency, self-location, and perspective) and as such, disruption of self-location of a single limb may not be sufficient to inhibit VPT2 performance. Instead, it is possible that disruption of multiple components of bodily self-consciousness would be needed to inhibit VPT2. Alternatively, if self-location of the entire body was disrupted, this may hinder the ability to perform egocentric transformations of the body and thus affect VPT2 performance. Findings from Chapter 4 additionally showed that sensory integration of visual and proprioceptive inputs pertaining to the hand was not directly related to VPT2 ability. This may suggest that effective integration of visual and proprioceptive signals is not predictive of the ability to perform motor imagery of whole-body rotations. Instead, VPT2 may rely on a representation of the entire body, formed through integration of multiple sensory inputs from multiple limbs. Future work could aim to understand whether the different components of bodily self-consciousness offer distinct contributions to VPT2 ability (see section 7.3.1).

Chapter 5 has further elucidated our understanding of the link between the bodily self and the social self by showing how interpersonal synchrony is dependent on sensorimotor processing *and* can elicit significant social benefit. Importantly, results showed that irrespective of whether synchrony was instructed, both children and adults showed facilitation of social bonding following interpersonal synchrony. This suggests that regardless of whether a context promotes joint action through instruction, moving in coordination with another person can improve feelings of social closeness. Thus, the ability to represent one's own body, and incorporate the movements of another person into that representation, is key for social bonding outcomes of interpersonal synchrony. Importantly, we found that children's degree of visuomotor synchrony with an interaction partner predicted how socially close they would feel to that partner following interpersonal synchrony. This demonstrates that sensorimotor integration of visual and motor information is key for children to experience the pro-social benefits of coordinating one's movements with another. This finding may highlight the link between sensory integration and social processing. Indeed, as sensory integration ability develops through childhood (Cowie et al., 2016, 2018; Greenfield et al., 2017; Ratcliffe et al., 2021), it could be theorised that as this ability develops, interpersonal synchrony would also become more socially advantageous. Future research could therefore investigate the developmental trajectories of sensorimotor integration and interpersonal synchrony to clarify if sensorimotor integration is a foundational skill on which the social bonding outcomes of interpersonal synchrony are built. Findings from Chapter 5 contribute to the embodied social cognition framework by demonstrating that a representation of the bodily self, formed through efficient sensorimotor integration, can impact upon how we coordinate with others, how we feel about other people, and how they feel about us.

In summary, findings in the current thesis have contributed to the embodied cognition literature by demonstrating the role of sensorimotor integration in self-related processing, visual perspective-taking, and interpersonal synchrony. As such, these findings have elucidated our understanding of how the integration of sensory information relating to the bodily self is connected to human social interaction.

7.2.2 An Enactive Account of Autism

The enactive account of cognition builds upon the embodied cognition framework by emphasising the role the body has in reciprocal and dynamic interactions with the environment and with other people (de Jaegher, 2013). It stipulates that sense-making, the coupling of an embodied agent with their environment, is the mechanism by which agents make meaningful connections with the world (de Jaegher, 2013). For example, 12-month-old infants will look towards a visual target for longer when an adult is facing the target with their eyes open compared to having their eyes closed (Brooks & Meltzoff, 2002). This exemplifies how our own past sensory experience shapes how we make sense of the world and others' actions and behaviours. As such, how an agent moves and perceives, how an agent experiences emotions, and the context the agent is in, all combine to determine how the agent thinks (Kyselo, 2019). Thus, the body does not just hold physiological function, it is interrelated with cognitive and social identities, making cognition inherently embodied (Sheets-Johnstone, 1999). Social cognition is thought to be dependent upon participatory sense-making which is how individuals participate in each other's sense-making during social interactions (de Jaegher, 2013). As we are able to coordinate with others, we can coordinate our sense-making activities such that we not only affect how *we* make sense of the world but how *others* make sense of it and of ourselves. It is argued that we participate in each other's sense-making, generating, and transforming knowledge together through interacting (de Jaegher, 2013). This goes beyond merely observing others but actively interacting with others to generate new domains of sense-making that were not previously available to individuals prior to an interaction. For example, an individual may coordinate their movements with another person and feel increased likeability towards that individual. They may subsequently interpret the actions of that individual differently, and thus make sense of the world in a different way than they had prior to the social interaction.

Extending this framework to autism, the enactive approach suggests that autistic individuals experience differences in sense-making and participatory sense-making. Firstly, evidence for different sense-making is demonstrated by findings showing that autistic individuals experience senses differently (Jones & O'Neill, 1997; Jones et al., 2003; MacLennan et al., 2021; Smith & Sharp, 2013 and Chapter 6 of the current thesis), integrate their senses differently (Foss-Feig et al., 2010; Greenfield et al., 2015; Kwakye et al., 2011; Ropar et al., 2018), and represent their bodies differently (Cascio et al., 2012; Conson et al., 2016; Fiene & Brownlow, 2015; Ropar et al., 2018). Secondly, differences in participatory sense-making are reflected by differences in how autistic individuals attend to salient social stimuli (Klin et al., 2002,2003), coordinate with others (Fitzpatrick et al., 2016; Marsh et al., 2013), and imitate or mimic others (Forbes et al., 2016; Hamilton, 2008). It is argued that these differences in embodiment and sense-making cause difficulties in the mutual alignment of sense-making, thus hindering participatory sense-making. Importantly, this framework does not emphasise the social deficits of an autistic individual, instead, it acknowledges that interactions are dependent on two or more individuals. Therefore, any communication failure is due to the dynamical misalignment of sense-making between the individuals and not due to a deficit in one individual.

Findings from the current thesis further inform the enactive approach to autism. In Chapter 3 we investigated the role of sensorimotor integration and body schema in self-related processing in autistic adults. Despite showing a significant tendency to prioritise the processing of self-related information, no relationship was found between this self-bias and body schema or sensorimotor integration. This may suggest that whilst the conceptual self is represented similarly in autistic and non-autistic individuals, the role of embodiment in self-bias is different in autism. In relation to the enactive approach, this could suggest that differences in embodiment may lead to alternate mechanisms underpinning self-processing in autistic compared to non-autistic individuals. Conversely to the Bodily Self Consciousness model of self-reference effects, this may suggest that autistic individuals do not use the body as a tag for memory consolidation (Bréchet et al., 2020; Park & Blanke, 2019). Instead, purely cognitive-based strategies may be used to process and remember self-related information (Sui & Humphreys, 2015a). Looking at wider literature, this finding corresponds to previous work investigating visual perspective taking in autism. Whilst level two visual perspective-taking typically relies upon an embodied motor strategy to understand the viewpoint of another person, autistic individuals have been found to adopt non-embodied strategies to complete VPT2 tasks (Pearson et al., 2014). For example, autistic individuals may use rule-based or spatial rotation-based strategies to complete VPT2 tasks (Pearson et al., 2013, 2014). Within the enactive framework, this might be explained due to alterations in embodiment which lead to differences in sense-making and consequently distinct mechanisms underpin social skills which are typically embodied. Within an experimental context, using non-embodied strategies may elicit sufficient performance (e.g., Pearson et al., 2014). However, expanding such strategies into the real world may be more cognitively demanding and less efficient (e.g., Zacks & Tversky, 2005). Thus, in relation to self-referential effects, the use of non-embodied strategies could have consequences for social behaviours such as mentalising and empathy. However, it is important to note that the non-autistic participants in Chapter 3 failed to show a significant self-bias effect and therefore did not demonstrate a relationship between sensorimotor integration, body schema and self-related processing. Therefore, further research is needed to tease apart whether the lack of relationship between embodied processes and self-bias in autistic individuals is due to task limitations or a reduced reliance on embodied mechanisms. Further work utilising in-person research methods could significantly contribute to our understanding of the underlying mechanisms of self-related processing in autistic and non-autistic individuals (see section 7.3.2).

Contributions to the enactive approach of autism have similarly been made in Chapter 6 of the present thesis, which explored how autistic adults experience sensory input. In addition to demonstrating the significant impact of sensory reactivity on the lives of autistic individuals, it was found that sensory differences can impact upon the experience of embodiment. This finding was summarised in a model (see Chapter 6, Figure 5) whereby reduced bodily sensory awareness could lead to a feeling of disconnection between self and body. This finding may highlight an important aspect of the enactive approach, that efficient sensory integration and perception are key to experiencing a fully embodied sense of self. When this is disrupted, individuals can experience a disconnect between their conceptual identity and their body - thereby experiencing reduced embodiment. In turn, this can lead to changes in self-concept, well-being, and exacerbate sensory difficulties. Indeed, we also found that sensory difficulties could have a significant impact upon social well-being, with sensory fluctuations impacting upon romantic relationships and avoidance of social contexts. Thus, it is important to understand social behaviours in autism within the context of a multisensory experience, as sensory and social experience are interconnected. Crucially, the enactive approach may provide a framework to explain how a disruption in the experience of embodiment could interrupt participatory sense-making and thus social interactions. These findings therefore contribute to our understanding of the link between sensorimotor processing and social cognition in autism.

Importantly, findings from Chapter 6 may also contextualise the empirical findings presented within the current thesis. A key finding from Chapter 6 was that changes in sensory reactivity can occur rapidly and unpredictably. As MSI differences are thought to be central in autism, it has been proposed that there is a link between multisensory integration and sensory difficulties in autism (Iarocci & McDonald, 2006; Kojovic et al., 2019). Thus, fluctuations in sensory reactivity may also reflect a lack of stability in sensory integration processes. Whilst on one occasion an individual might be able to effectively integrate sensory information from multiple modalities, this may change depending on the environment they are in, the people they are with, and the mental and emotional state they are in. Moreover, in Chapter 6 we found that sensory reactivity across modalities can interact to heighten sensory difficulties. As such, optimal sensory integration within an individual may depend on the type of sensory input and how it interacts with other sensory inputs. Considering the findings from Chapter 3, this may suggest that exploring individual variability in sensorimotor integration and body schema, may not encapsulate the complexity of sensory processing in autism. Indeed, such experimental tasks as used in Chapter 3 provide a momentary insight into sensory processing at that particular point in time. Therefore, from a theoretical perspective, sensory processing differences in autism may not be consistently disrupted or delayed. Instead, they may fluctuate similarly to their sensory reactivity differences. Thus, research may need to consider that sensory integration is not a stable process which will consistently predict an individual's social experience.

7.2.3 Clinical Implications

Knowing more about sensory and social differences in autism is crucial for informing clinical practice that is targeted at supporting autistic individuals. Importantly, autistic individuals must be supported in ways they desire and that contribute to better physical and mental well-being.

Findings from Chapter 6 highlight the significant impact that sensory differences have on the lives of autistic adults. A key clinical step to be able to offer support is to identify individuals with sensory differences. Self-report measures have largely been used to ascertain whether and how individuals experience sensory differences. As discussed in Chapter 6, the Glasgow Sensory Questionnaire (GSQ) (Robertson & Simmons, 2013) and the Sensory Processing (SP) Scale (Miller & Schoen, 2012) are self-report questionnaires which evaluate the frequency of sensory behaviours across vision, audition, gustation, olfaction, touch, proprioception, and vestibular processing. The GSQ and SP (among other similar measures) have been used as clinical indicators of sensory differences (Tavassoli et al., 2016). Findings from Chapter 6 emphasise the necessity for clinical evaluation measures to include questions pertaining to sensory fluctuations across all sensory domains. Until they do, they cannot truly be used to identify areas of support needs in autistic individuals.

Beyond the identification of sensory differences, autistic individuals may receive clinical support in the form of interventions. Within the National Institute for Healthcare Excellence (NICE) guidelines, several behavioural interventions were described to be applicable to autistic adults (NICE, 2012) which aim to reduce the expression of certain behaviours. However, such interventions have been criticised by the autistic community, put simply "viewing autism as a list of deficits that can be corrected through a series of discrete trials will not make an autistic person any less autistic", (Zurcher, 2012). These interventions are built upon what has been termed the 'outside-in' perspective of autism (Bradley et al., 2014) where behaviours and symptoms are described by the DSM and practitioners. Conversely, the 'inside-out' perspective of autism pertains to the personal narratives of autistic individuals. Work has found that the 'outside-in' perspective has often pathologized behaviours which are actually coping mechanisms, whilst the 'inside-out' perspective can correctly characterise behaviour in autism (Bradley et al., 2014). Findings from Chapter 6 contribute to the 'inside-out' perspective of autism as sensory differences have been described from the viewpoints of autistic individuals. Applying these findings clinically would suggest that support needs to be targeted at helping autistic individuals manage their own sensory experiences. This support would need to be bespoke as individuals can have varying experiences across several sensory domains. Importantly, support would need to adopt a multisensory perspective, accounting for how sensory differences are experienced interdependently across multiple sensory modalities. Moreover, findings from Chapter 6 show the impact of interoceptive under-awareness can be wide-reaching, affecting physical, mental, and social well-being. This may suggest that support systems which can improve how aware individuals are of their internal bodily signals could have a significant beneficial impact on their lives. Crucially, rather than existing interventions which aim to reduce the expression of pathologized behaviours, clinical support should centre the views of autistic people to understand ways in which they believe they can be supported.

Future research should aim at working with autistic individuals to develop sensory support systems that can be utilised by autistic individuals.

7.2.4 Strengths and Limitations

A predominant strength of the current thesis was the inclusion of women and non-binary autistic individuals in autism-related research. Historically women and non-binary individuals have been unrepresented in autism research (Lai et al., 2015; Loomes et al., 2017; Philip et al., 2012). As a consequence, the research which has informed clinical practices of diagnosis and support has been largely male-centric (S. Goldman, 2013). The implications of this are significant, with women and non-binary individuals often receiving a diagnosis much later in life or struggling to receive a diagnosis at all (Zener, 2019). This can mean access to support, acceptance within the autistic community and even self-acceptance can be delayed for women and non-binary autistic individuals (Leedham et al., 2020). To combat the gender bias in autism research, the current thesis aimed to encourage the participation of women and non-binary individuals in the experimental work. Moreover, to counteract diagnostic biases, self-identification of autism was accepted as diagnostic criteria for participation in the research in this thesis. Whilst this may have presented issues with potential fraudulent participation (Pellicano et al., 2023), it was felt that the benefits of including the self-identification of autism outweighed potential issues. Further, as autistic participants were recruited through local autism organisations, this reduced the chance of potential fraudulent participation.

Whilst the above measures strengthen the methods and ethical practices of the current thesis, there are still opportunities for improvement. Although autistic individuals were consulted in the design and experimental planning stages of the thesis, they were not consulted in 1) the application of the funding grant or 2) the generation of the research questions. It is crucial that research focussing on understanding autism must ensure the desires and needs of autistic individuals are centred at the heart of the research (Gowen et al., 2020). This means that research is conducted which aims to improve the lives of autistic individuals, in the ways that have been requested - rather than identifying research areas from a neurotypical perspective (Bradley et al., 2014). Therefore, the current thesis could be improved by adopting a participatory research framework in which autistic individuals have input on the research conducted from conception through to dissemination.

Further strengths of the current thesis lie in the research methods utilised in the experimental chapters, in particular the use of the mediated reality system MIRAGE. For example, in Chapter 4, the MIRAGE system allowed for the induction of the sensation of a missing limb to disrupt the body representation. The MIRAGE system has two key advantages compared to classic body illusion paradigms (e.g., the classic rubber hand illusion). Firstly, the virtual hand in MIRAGE looks the same as the participants' own hand and moves in real time. Secondly, the reported onset of illusions is reliably quicker in MIRAGE and thus does not require extensive periods of sustained attention (Greenfield et al., 2017; Newport et al., 2010). This was particularly important in Chapter 4, as the sensation of a missing limb needed to be quickly established to investigate the impact of body schema disruption on visual perspective-taking.

Furthermore, in Chapter 5, the MIRAGE system allowed for close control of the experimental conditions. Whilst previous work has investigated the mechanisms of interpersonal synchrony, they can be subject to methodological criticism. Indeed, previous work found that children were more likely to synchronise with auditory stimulus created by a human actor compared to a robotic mechanism (Kirschner & Tomasello, 2009). Limitations of such a design can arise as these different contexts can consist of varying levels of sensory information – social contexts including a human are often much richer in sensory information. Thus, previous work is unable to determine if such contexts elicit social bonding due to the level of sensory information of the social nature of the environment. In this present thesis, this was accounted for using MIRAGE which can tightly control the sensory information presented in the social and non-social contexts. Indeed, the contexts were identical (both had a partner present) and only the stimulus type (e.g., hand or ball) differed. Consequently, the results from Chapter 5 provide robust evidence that sensorimotor coupling in a social context can facilitate visuomotor synchrony and subsequent social bonding.

Whilst the methods in Chapter 5 improved methodological issues exhibited previously in the literature, they are not without limitations. The experimental design used in Chapter 5 was unable to differentiate fully between the contributions of joint action and sensorimotor processes. Future research could create four contexts in which the social stimulus (e.g., a hand) is presented as being attached to an actor or not and the non-social stimulus (e.g., a bouncing ball) is presented as either being controlled by an actor or not. This would allow a comparison of the joint action influence of the actor and the sensorimotor influence of the corporeal stimulus.

Although not in the original concept for the current thesis, the use of online methods can be considered a strength. Chapters 2-3 have provided a novel contribution to how sensory integration can be investigated online. Across two experiments, we demonstrated how a sequential simultaneity judgement task could be used to evaluate visuo-tactile-motor integration in autistic and non-autistic adults. Moreover, the use of online methods meant that a diverse sample of participants could be reached. For example, online research methods made it easier to recruit women and non-binary autistic adults in Chapter 3. Further, using online methods in Chapter 6 may have made it easier for participants to anonymously share details of their sensory experience. Perhaps resulting in richer data than what may have been generated using in-person research methods in which the social context of an interview or focus group may have been a barrier to sharing very personal details.

However, using online methods also presented certain limitations. For example, for the recruitment of non-autistic adults in Chapter 2, Study 2, the study participation platform Prolific was used (Prolific, 2022). Although this allowed for quick and effective participant recruitment, it resulted in a sample of mostly white, Eastern European, 18-year-old men. Future research using this platform could release participant slots in small numbers and specify eligibility demographics to produce a more diverse and representative sample. Moreover, using online methods made it difficult to verify whether participants correctly understood the experimental tasks. Measures were taken to ensure participants understood the tasks and maintained attention; video and comprehensive written instructions were provided for complex tasks, training and practice trials were included, accuracy thresholds were set for the practice trials, attention checks were used, and extended study sessions were timed out. However, compared to in-person methods, it is difficult to confirm whether a participant has understood and maintained attention to all tasks.

7.3 Future Directions

Due to the significant disruption of COVID-19 on the research presented in the current thesis, a limited amount of in-person research was able to be conducted. The following sections will outline potential avenues for future research based on in-person research methods which would have been utilised in the present thesis.

7.3.1 The Bodily Components of Level Two Perspective Taking

The use of multisensory illusion paradigms has been a valuable research method that has contributed to our understanding of bodily self-consciousness and sensorimotor integration. The full body illusion (FBI) is an immersive virtual reality technique in which participants embody a virtual body identical to their own (Lenggenhager et al., 2007). Importantly, this paradigm can be used to dissociate the components of bodily self-consciousness (ownership, agency, perspective, and self-location). For example, individuals can view a virtual image of their own body viewed from behind to manipulate feelings of self-location (Lenggenhager et al., 2007; Petkova & Ehrsson, 2008). When the virtual body is seen to be stroked in temporal synchrony and spatial congruency to their own body, individuals can feel a shift in self-location towards the virtual body being displayed in front of them – creating an 'out of body' experience. Therefore, this technique may offer a promising method to investigate the role of bodily self-consciousness in social cognition. More specifically, the FBI could be utilised to gain an understanding of how ownership, self-location, agency, and perspective are implicated in VPT2. Future research could therefore create conditions in which these components are manipulated to investigate the subsequent impact on VPT2. 1) Ownership could be manipulated by creating asynchronous visuotactile signals between the real and the virtual body, thus reducing perceived ownership over the virtual body 2) agency could be manipulated by applying a temporal delay to the visual input such that subsequent movement of the virtual body is not perceived to be under the control of the participant 3) first-person perspective could be manipulated through synchronous visuotactile or visuomotor signals of a virtual body viewed from a third person perspective, 4) self-location could be manipulated as previously described above. Participants could then view a virtual scene within virtual reality in which they make judgements about the orientation of an object placed in front of a virtual avatar. The quicker and more accurate participants are at judging the orientation of an object from the avatar's viewpoint, the better their level two perspective-taking ability. This task could be used following each of the aforementioned conditions to ascertain the impact of disrupting each component of bodily self-consciousness on VPT2.

7.3.2 Self-related Processing and Multisensory Integration

Self-referential effects are thought to provide an insight into self-awareness and how the self is internally represented (Duval & Wicklund, 1972; Morin, 2006) . In turn, self-related processing is thought to relate to important social skills such as empathy (Lombardo et al., 2007) and mentalising (Dinulescu et al., 2021). As empathy and mentalising are cornerstones of social interactions (Malle, 2012), it is important for research to ascertain the mechanisms underlying self-related processing. Future work could therefore investigate whether sensory integration and body schema underpin self-related processing in autistic and non-autistic individuals using mediatedch reality techniques.

Previous research has demonstrated that the experience of a bodily self is built upon efficient multisensory integration (de Vignemont, 2011; Ehrsson et al., 2005; Greenfield et al., 2017; Newport et al., 2010; Newport & Gilpin, 2011). Temporal processing of sensory information is particularly important to ensure that sensory inputs are bound into a single sensory event (Colonius & Diederich, 2004). The MIRAGE system could be utilised to investigate whether efficient temporal processing of sensory information predicts the processing of self-related perceptual information. The supernumerary illusion could be utilised such that when participants place their hands inside the MIRAGE system, they view two identical virtual hands displaced either side of the spatial location of their real hand (Newport et al., 2010). A temporal delay could then be applied to the video image of one hand so that when participants tap their finger, only one of the virtual hands synchronously moves in time with them. Participants could then be asked to select which hand they believe is their hand. This could be repeated multiple times, with the length of the temporal delay varying to allow evaluation of the sensitivity of individuals' visuomotor integration. The greater the participant's accuracy at selecting the synchronous virtual hand at shorter delays, the more sensitive their temporal processing of sensory information. Participants could complete an in-person version of the self-prioritisation task (as used in Chapters 2 and 3) with extensive training and practice trials to evaluate their self-bias in perceptual processing. The predictive relationship between the sensory integration measure self-related processing could then be evaluated. This research could be performed with both autistic and non-autistic individuals to investigate whether similar mechanisms underpin self-related processing in both populations. If differences are exhibited between the groups, this could contribute to explaining individual differences in the expression of empathy and mentalising (Dinulescu et al., 2021; Lombardo et al., 2007).

7.3 Conclusions

The present thesis investigated the link between sensorimotor integration and social processing using a multi-method approach of in-person and online research techniques. Online methods were used to investigate the roles of body schema and sensorimotor integration in perceptual processing of self-related information. Qualitative research methods were adopted to gain insight into the sensory experiences of autistic adults. The mediated reality system MIRAGE was utilised to investigate the role of sensorimotor integration in visual perspective-taking and interpersonal synchrony. Findings within the present thesis contribute to the research literature in autistic and non-autistic groups, supporting previous work which has highlighted the embodied nature of key social processes.

Crucially, novel findings show that non-autistic individuals exhibit a bias in perceptual processing grounded within a bodily self (Chapter 2). Conversely, autistic individuals show a strong self-bias in perceptual processing that does not appear to be underpinned by a representation of the bodily self (Chapter 3). Together, these findings suggest that whilst in non-autistic individuals self-referential processing might be an embodied process reliant on an internal representation of the body informed by multisensory input, in autistic individuals self-related processing may rely on purely cognitive networks. Furthermore, temporarily disrupting the body schema through visuo-proprioceptive integration in non-autistic adults does not appear to impact visual perspective-taking ability (Chapter 4). Instead, visual perspective-taking may rely on multisensory integration from multiple body parts and the experience of full-body consciousness. For the first time, we demonstrated the significant role of sensorimotor integration in uninstructed and instructed synchrony and its social bonding outcomes in children and adults (Chapter 5). Our findings suggest that an interaction of sensorimotor coupling and joint action mechanisms conjoin to promote interpersonal synchrony and subsequent feelings of social closeness. Importantly, sensorimotor integration appears particularly significant in the development of interpersonal synchrony and social bonding in children, as the degree of visuomotor synchrony with a partner predicts feelings of social closeness. Finally, findings in the current thesis evidence the prominent impact that sensory fluctuations across all major sensory domains have on the physical, mental, and social well-being of autistic adults (Chapter 6). Qualitative findings from this chapter suggest that interoceptive awareness may be pertinent to the subjective experience of the bodily self and how the self is conceptualised. These findings may serve as a foundation for future research to investigate the links between internal body awareness, the experience of the bodily self and social processing. Moreover, the reported findings emphasise the need for clinical and research contexts to comprehensively represent the complexity of the sensory experience of autistic individuals from their perspectives. Together, the present thesis offers novel methods and insights into the link between sensorimotor integration and social processing in autistic and non-autistic individuals, which can be built upon to inform future research and clinical practice within this area.

Appendices

Chapter 2

2.1 Analyses to check for order and SPT version effects on SPT and HLJT performance in *Study* 1

A mixed ANOVA showed no significant main effect of task order on SPT performance across the labels (Self, Friend, or Stranger); F(1,32)=.74, *p*=.40.

A mixed ANOVA showed no significant main effect of SPT version (label-shape pair combinations) on SPT performance across the labels (Self, Friend, or Stranger); F(2,31)=.10, *p*=.91.

A between subjects ANOVA showed no significant main effect of SPE version (label-shape pair combinations) on HLJT performance F(2,31)=.13, *p*=.88.

2.2 Analyses to check for order and SPT version effects on SPT, HLJT and sensory integration performance in *Study 2*

A mixed ANOVA showed no significant main effect of task order on SPT performance across the labels (Self, Friend, or Stranger); F(5,31)=.67, *p*=.65.

A mixed ANOVA showed no significant main effect of SPT version (label-shape pair combinations) on SPT performance across the labels (Self, Friend, or Stranger); F(2,34)=.79, *p*=.46.

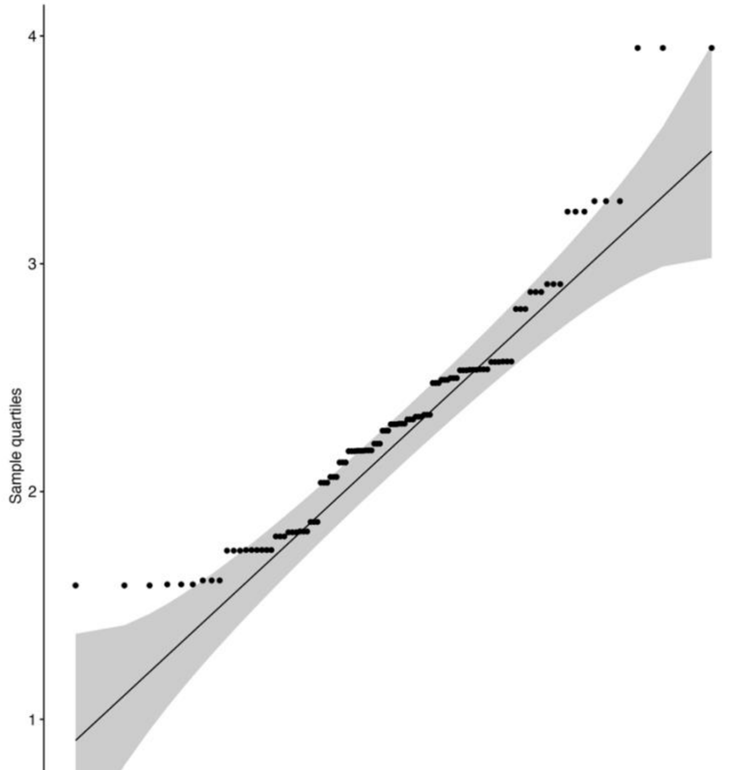
A between subjects ANOVA showed no significant main effect of task order on HLJT performance; F(5,31)=1.22, *p*=.32.

A between subjects ANOVA showed no significant main effect of SPE version (label-shape pair combinations) on HLJT performance; F(2,34)=1.18, *p*=.32.

A between subjects ANOVA showed no significant main effect of task order on sensory integration accuracy; F(5,31)=1.6, *p*=.18.

A between subjects ANOVA showed no significant main effect of SPE version (label-shape pair combinations) on sensory integration accuracy; F(2,34)=.02, *p*=.98.

2.3 QQ plot for results in Study 2



2.4 Robust linear mixed modelling results for Study 2 using skew.lmm package in R (R Core Team, 2022)

Likelihood ratio tests revealed that the full model was a significantly better fit of the data than the null model (*p*<.001) and simple main effects model (*p*<.001), see Table 2.3 for model summaries and comparisons.

Table 2.3 Predictors of d-prime scores on the SPT for the skew adjusted models. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	283.889	297.437	
Simple Main Effects (Null + Label, Body Schema, Sensory integration)	284.599	303.566	<0.001 vs Null
Full (Simple Main Effects+ Label*Body Schema)	275.109	282.914	<0.001 vs Simple Main Effects

2.5 Linear mixed modelling results for Study 2 with removal of two outliers

The full model was the best fit in explaining variance in the d-prime scores on the self-prioritisation task, explaining 11.5% of the variance by fixed effects and 70.6% of the variance by random effects. The *Self* label was a significant predictor of SPT performance *p*=.008, as was the stranger label *p*=.033. The interaction between the *Self* label and *Body Schema* performance *p*=.043 was a significant predictor of SPT performance, as was the interaction between the *Self* label and *Sensorimotor Integration* accuracy *p*=.037. The *Stranger* label also significantly interacted with *Body Schema* scores to predict SPT performance *p*=.026, see Table 2.4.

Table 2.5

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	289.42	297.47	
Simple Main Effects (Null + Label, Body Schema, Sensory integration)	272.11	290.89	>0.001 vs Null
Full (Simple Main Effects+ Label*Body Schema)	266.08	288.87	>0.01 vs Simple Main Effects

Chapter 3

3.1 Analyses to check for order and SPT version effects on SPT, HLJT and sensory integration performance

A mixed ANOVA showed no significant main effect of task order on SPT performance across the labels (Self, Friend, or Stranger); F(6,65)=.70, *p*=.65.

A mixed ANOVA showed no significant main effect of SPT version (label-shape pair combinations) on SPT performance across the labels (Self, Friend, or Stranger); F(2,69)=0.36, *p*=.70.

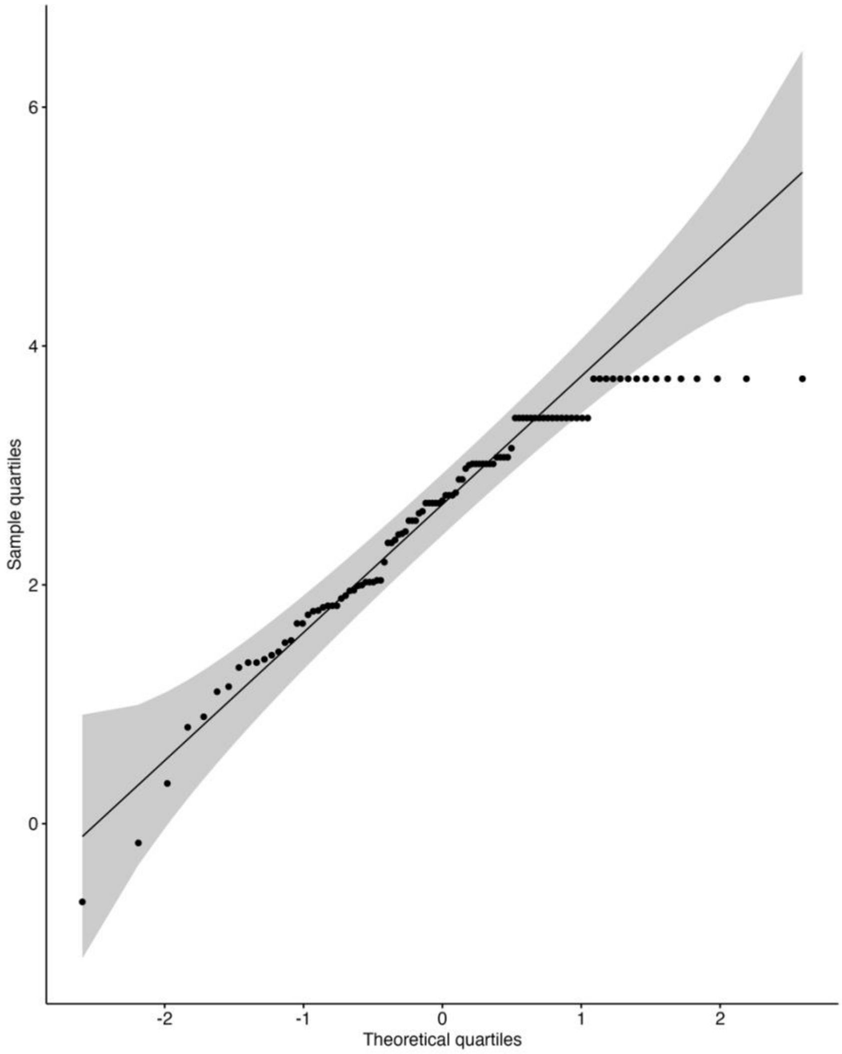
A between subjects ANOVA showed no significant main effect of task order on HLJT performance; F(6,65)=1.15, *p*=.35.

A between subjects ANOVA showed no significant main effect of SPE version (label-shape pair combinations) on HLJT performance; F(2,69)=.74, *p*=48.

A between subjects ANOVA showed no significant main effect of task order on sensory integration accuracy; F(6,65)=.71, *p*=.64.

A between subjects ANOVA showed no significant main effect of SPE version (label-shape pair combinations) on sensory integration accuracy; F(2,69)=1.87, *p*=.16.

3.2 QQ plot of SPT performance



3.3 Robust linear mixed modelling results for the autistic group using skew.lmm package in R (R Core Team, 2022)

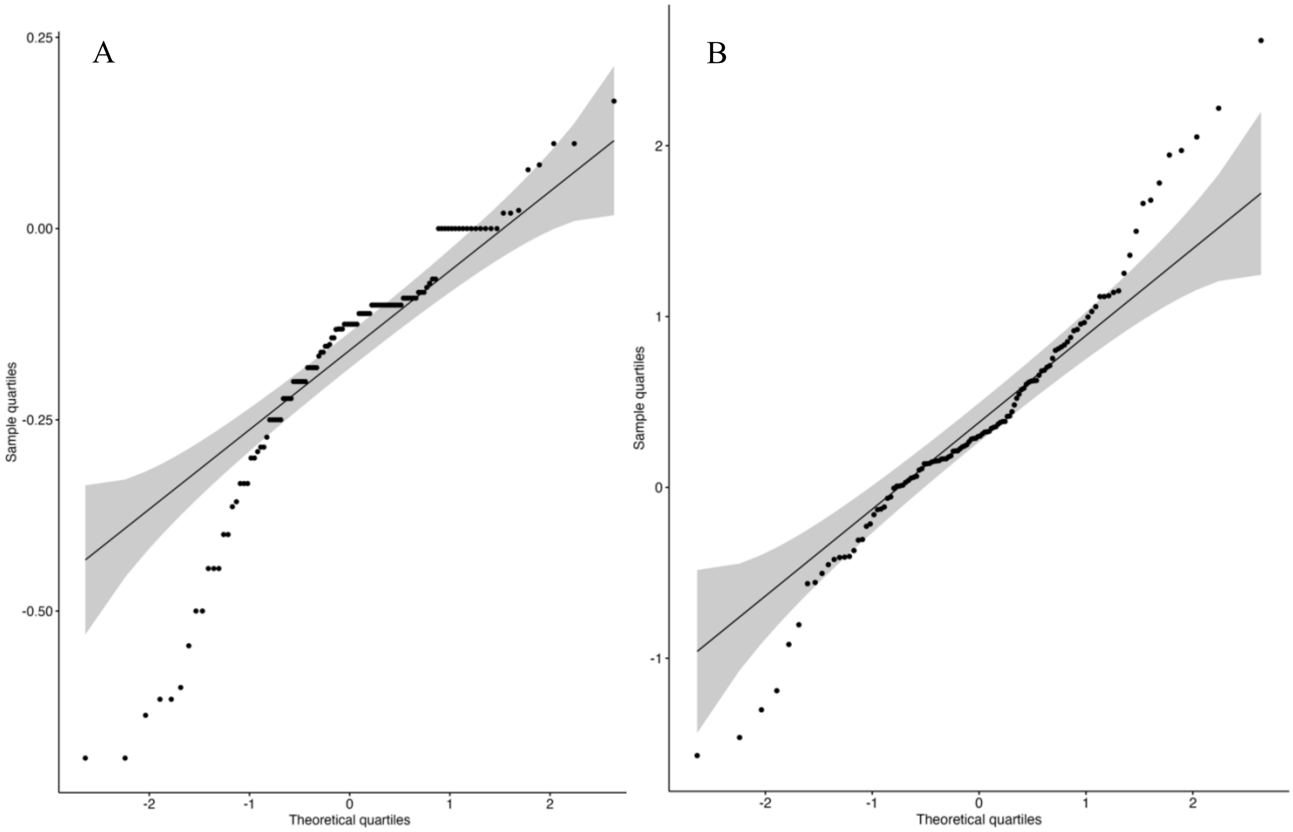
Likelihood ratio tests revealed that the full model was not a significantly better fit of the data than the null model (*p*=.055) and neither was the simple main effects model (*p*=.058), see Table 3.2 for model summaries and comparisons. The null skew-adjusted model is therefore the best fit of the data.

Table 3.2 Predictors of d-prime scores on the SP task for the skew adjusted models. Smaller AIC and BIC values indicate the better fitting model.

Model	**AIC**	**BIC**	***p***
Null (Participant ID)	261.011	274.281	
Simple Main Effects (Null + Label, Body Representation, Sensory integration)	259.331	277.909	=.0584 vs Null
Full (Simple Main Effects+ Label*Body Representation)	260.674	289.968	=.155 vs Simple Main Effects

Chapter 4

4.1 QQ plots for the accuracy (A) and reaction time (B) differences scores



4.2 Parametric tests for the correlation between VPT2 *Baseline* performance and localisation error.

Multiple Pearson's correlations were conducted

4.2 Parametric tests for the correlation between VPT2 *Baseline* performance and localisation error.

Multiple Pearson's correlations were conducted to investigate the relationship between hand localisation error and VPT *Baseline* performance. We found there was no significant relationship between localisation error and VPT accuracy; *r*(38)=-.106*, p*=.29. In addition, we found no significant correlation between localisation error and VPT reaction times; *r(*38)=-.55*, p*=.59.

4.3 Analyses to check for condition order effects

A mixed ANOVA showed there was no main effect of order (*Illusion* or *Non-Illusion* condition first) on VPT accuracy; F(2,37)=.14, *p*=.87, or reaction times; F(2,37)=1.85, *p*=.17, across conditions.

Chapter 5

5.1. Non-significant results from *Study 1.*

Table 5.1. Table outlining the non-significant results from Study 1.

Test	Result
ANOVA main effect of instruction on synchronisation accuracy	F(1,37)=0.15, *p*=0.7
ANOVA interaction between context and tempo on synchronisation accuracy	F(1,112)=0.75, *p*=0.39
ANOVA interaction between context and instruction on synchronisation accuracy	F(1,45)=0.009, *p*=0.92

ANOVA interaction between tempo and instruction on synchronisation accuracy	F(1,112)=0.52, *p*=0.47
ANOVA interaction between tempo, instruction and context on synchronisation accuracy	F(1,112)=1.08, *p*=0.30
ANOVA main effect of instruction on social closeness	F(1,38)=1.79, *p*=0.19
ANOVA main effect of tempo on social closeness	F(1,114)=0.006, *p*=0.94
ANOVA interaction between context and tempo on social closeness	F(1,114)=0.52, *p*=0.47
ANOVA interaction between tempo and instruction on social closeness	F(1,114)=0.16, *p*=0.69
ANOVA interaction between tempo, instruction and context on social closeness	F(1,114)=0.006, *p*=0.93

5.2 Effect of context on normalised synchronisation accuracy in Study 1.

Table 5.2. Results of a mixed 2x2x2 ANOVA investigating the effects of context (social vs non-social) and instruction (instructed vs uninstructed) on the normalised synchronisation accuracy metric (i.e., RMS inter-tap intervals divided by the stimulus tempo) in adults (Study 1).

Predictor	DF	**SS**	F value	p value
Context (social vs non-social)	38	.38	38.26	< .0001
Instruction (instructed vs uninstructed)	59	.002	.10	.76
Context * Instruction	59	.01	1.16	.28

5.3. Non-significant results from Study 2.

Table 5.3. Table showing the non-significant results from Study 2.

Test	Result
ANOVA interaction between instruction and context on synchronisation accuracy	F(1,45)=0.11, *p*=0.74
ANOVA interaction between context and tempo on synchronisation accuracy	F(1,47)=0.48, *p*=0.49
ANOVA interaction between context, tempo and instruction on synchronisation accuracy	F(1,47)=0.19, *p*=0.66
ANOVA main effect of instruction on social closeness	F(1,50)=3.68, *p*=0.06
ANOVA main effect of tempo on social closeness	F(1,50)=1.08, *p*=0.30
ANOVA interaction between context and tempo on social closeness	F(1,50)=0.81, *p*=0.37
ANOVA interaction between context and instruction on social closeness	F(1,50)=2.58, *p*=0.11
ANOVA interaction between context, instruction and tempo on social closeness	F(1,50)=0.028, *p*=0.87
ANOVA main effect of tempo on mimicry	F(1,50)=0.12, *p*=0.87

5.4. Effect of context on normalised synchronisation accuracy in Study 2. *Table 5.4. Results of a* mixed 2x2x2 ANOVA investigating the effects of context (social vs non-social) and instruction (instructed vs uninstructed) on the normalised synchronisation accuracy metric (i.e., RMS inter-tap intervals divided by the stimulus tempo) in children (Study 2).

Predictor	DF	**SS**	F value	p value
Context (social vs non-social)	41	.07	4.77	.03
Instruction (instructed vs uninstructed)	43	2.36	67.11	< .0001
Context * Instruction	43	.07	1.87	.18

6.1. Examples of senses given to participants in the online questionnaire.

Sense	**Example**
Tactile	The feeling of certain clothing, being touched by someone.
Proprioception	How we perceive the position and movement of our body. An example of having good proprioception / body awareness would be being able to place your finger on your nose whilst your eyes are closed.
Vestibular	If you have an oversensitive sense of balance, you may experience difficulties or an unsteady feeling during activities that require balance, whereas if you have an under sensitive sense of balance you may feel a need to rock, swing or spin your body
Interoception	Awareness of our bodily sensations e.g., hunger, pain, our heart rate.

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