The implications of abnormal stereopsis in typical and atypical development

DANIELLE SMITH, BSc, Msc

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Thesis abstract

A remarkable feature of the human visual system is that it is possible to extrapolate a large amount of information about the three-dimensional structure of the environment simply from the pattern of light that falls on the retinae. This information is derived from a number of different cues to depth. The mechanisms by which these are encoded in the brain, combined into an overall percept, and subsequently interpreted are reasonably well understood. However, individuals who participate in studies of depth perception tend to have acute sensitivity to certain depth cues, meaning that the consequences of individual differences in depth perception have been largely ignored. In this thesis I investigate how individual differences in the ability to utilise a single cue, binocular disparity, affects overall perception of depth and then go on to explore the wider function significance of such a deficit. I also examine whether an underlying deficit in stereopsis may account for some of the perceptual differences observed in autism spectrum disorder (ASD).

The first set of experiments explored the consequences of individual differences in stereopsis upon perception. The initial study of this thesis used a shape constancy paradigm to identify how individual cues to depth are utilised and combined in typical children and adults. I report that while children are more sensitive to certain depth cues compared to adults, they still show some degree of cue combination (though only for higher-level information). In addition, I observed that an inability to use binocular information appears to cause re-weighting to occur in favour of monocular cues, regardless of age. In the second study, I used the same paradigm to explore depth cue sensitivity and combination in typically-developing (TD) and ASD teenagers. The results from this experiment indicated that contextual and binocular information interact when creating an overall percept of depth. A main effect of ASD diagnosis was found, with this group reporting perception that was less biased and closer to the raw sensory input. Although participants with ASD exhibited poorer stereoacuity than their TD counterparts, this did not explain the differences between the groups. I propose this indicates that perceptual differences in autism likely stem from underlying neurological differences specific to the disorder as opposed to a more general stereopsis deficit. The third study assessed the combination of ordinal and metric depth cues in TD and ASD adults. Cue integration did not depend on sensitivity to disparity or autism diagnosis. Unlike previous research, and inconsistent with perceptual theories of autism, I found that individuals with ASD automatically integrated depth cues, even when it was not advantageous to do so. Additionally, I found that the processing of uncrossed disparities was particularly difficult for those with an ASD.

The second part of the thesis aimed to characterise the functional significance of impaired stereopsis. For the fourth study, I wanted to establish whether the functional significance of stereopsis followed a developmental trajectory. I was also interested if the motor deficits observed in those with poor stereopsis were limited to hand-eye coordination tasks. Using three tasks derived from a standardised test of motor proficiency – catching a ball, balancing on one leg, and bead-threading – I measured the effect of binocular vision and stereoacuity on motor ability. Stereoacuity affected performance across a range of tasks involving the use of fine and gross motor skill, and – importantly – the effect of stereopsis did not change with age. In the final study, I enquired as to the further-reaching consequences of poor stereopsis. Using a quantitative survey I aimed to establish how stereopsis, motor skills, and social skills related to one another. While motor ability mediated the relationship between stereopsis and social skill, stereopsis also directly contributed to social skill, causing me to suggest that the functional significance of stereopsis is not limited to motor ability.

It is concluded that while individual differences in stereoacuity may affect the amount of depth experienced, they do not affect the ability to combine different cues to depth. While those with ASD experience differences in perception, these cannot be attributed to the increased prevalence of stereopsis impairment. It does, however, seem that individual differences in stereoacuity impact upon the development of motor proficiency and social skill, which are typically compromised in those with ASD.

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- Data from Chapter 3 were presented in:

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- The code used for experiments and analyses, all raw data, and the LaTeXsource-code used to typeset this thesis are available with permission at:

  `https://github.com/smithdanielle/thesis/`

Contents

List of Figures

List of Tables

Acronyms

χ^2 chi square

χ^2**/df** chi square/degrees of freedom

2D two-dimensional

3D three-dimensional

ADC Adult Developmental Coordination Disorder Checklist

ADOS Autism Diagnostic Observation Schedule

ANCOVA analysis of covariance

ANOVA analysis of variance

AQ Autism Spectrum Quotient

ASA Autostereogram Self-Assessment

ASD autism spectrum disorder

BHP Bayesian hypo-prior

BOT-2 Bruininks-Oseretsky Test of Motor Proficiency, Second Edition

BPVS-2 British Picture Vocabulary Scale, Second Edition

CFA confirmatory factor analysis

CFI comparative fit index

CL confidence limit

DCD developmental coordination disorder

EFA exploratory factor analysis

EPF enhanced perceptual functioning

LMM linear mixed-effects model

LSM least squares mean

M-ABC-2 Movement Assessment Battery for Children, Second Edition

MAD median absolute deviation

MCAR Missing Completely at Random

Ravens SPM Ravens Standard Progressive Matrices

RMSEA root mean square error of approximation

RT reaction time

SAS Social Aptitudes Scale

SCQ Social Communication Questionnaire

SD standard deviation

SE standard error of the mean

SEM structural equation modelling

SRMR standardized root mean square residual

SRS Social Responsiveness Scale

SSI Stereopsis Screening Inventory

TD typically-developing

TLI Tucker-Lewis index

VIF Variance Inflation Factor

WASI Weschler Abbreviated Scales of Intelligence

WCC weak central coherence

Glossary

amblyopia

A disorder of sight which results in decreased vision in an eye that otherwise appears normal, or out of proportion to associated structural problems of the eye. Amblyopia has three main causes: strabismus, anisometropia, and deprivation by vision-obstructing disorders such as congenital cataract.

anaglyph

A means of displaying stereoscopic three-dimensional (3D) by encoding each eye's image using filters of different (often chromatically opposite) colours, typically red and cyan. When anaglyph images (containing two differently coloured images) are viewed through spectrally opposed filters, each eye can see a different image. This creates a sensation of stereopsis when processed by the visual cortex.

anisometropia

A condition in which the two eyes have unequal refractive power (usually a difference $\geq$ 1 diopter).

convergence insufficiency

A sensory and neuromuscular anomaly of the binocular vision system, characterized by a reduced ability of the eyes to turn towards each other for a sustained length of time.

fovea

A small dimple in the retina (also known as fovea centralis) that approximates 1.5mm in diameter. It contains a large number of closely packed cone cells and therefore is the center of the eye's sharpest vision and the location of most colour perception.

strabismus

A condition that interferes with binocular vision because it prevents a person from directing both eyes simultaneously towards the same fixation point; the eyes do not properly align with each other.

CHAPTER 1

General Introduction

1.1 Introduction

WHILE natural variation occurs among the individuals of any population of organisms, certain adaptations to the environment which enhance an animal's ability to survive (and subsequently reproduce) are more likely to be passed on to future generations. One persistent and important adaptation is the development of visual perception: this is the ability to interpret and respond to visual information acquired from the environment. This information is particularly useful to humans as it provides awareness of features and events within our surroundings – with this knowledge, an individual may generate an appropriate response towards the physical source of visual information. An organism which can perceive and interact appropriately with the environment around it (for example, the detection of predators) will be more likely to survive and pass on its characteristics than an organism with no visual perception[1].

Visual perception requires that an organism is sensitive to stimulation by light, and has the capability to process and interpret this information. In humans, light reflected or omitted from objects enters the visual system through the cornea, which focuses it onto the pupil. The image is further focused by the lens to form a sharp projection onto the retina, at the back of the eye (Walls, 1963, p. 6-41). Here, light-sensitive cells called photo-receptors are responsible for the conversion of light into electrical signals (Yau, 1994). This information is conveyed through the optic nerve to the lateral geniculate nucleus, which in turn projects to the primary visual cortex where the input from both eyes is processed (Sherman & Guillery, 2002).

Numerous day-to-day skills can be described as a function of vision. For instance, the ability to discriminate different colours and determine the boundaries and edges of objects is essential when identifying whether food is safe to eat. More importantly, vision plays a significant role in the accurate localisation of objects in space. This sense has the

[1]As evidenced by the fact that 96% of animal species possess a complex optical system (Land & Fernald, 1992).

unique ability to recover the 3D structure of the environment and by doing so generate an estimate of distance and depth. This process is generally referred to as depth perception. The ability to perceive distance and depth is a vital skill, as the 3D geometry of our surroundings and the spatial properties of the objects within is an important determinant of our behaviour. It allows us to safely navigate through our environment while avoiding dangerous objects; facilitates fine motor actions such as grasping the handle of a cup of coffee; and guides in interactions with others, for instance aiding judgement of interpersonal distance and where a proffered hand is located in space in order to shake it.

1.1.1 The problem of depth perception

Generally, we perceive the world as being 3D, filled with objects which have spatial properties such as distance and direction. These properties are recovered by humans with deceptive effortlessness, as shown by the ease of picking up a pen. It is tempting to speculate that the brain builds a detailed 3D representation of the world solely through using the information delivered through the eyes. However, recovering depth from two-dimensional (2D) retinal input is computationally challenging and presents the brain with a series of complex problems (Marr & Poggio, 1979).

In order to estimate depth, the brain relies upon signals whose interpretation is inherently ambiguous, since depth information is not directly available from retinal images. Though the rules for projecting a 3D object onto a surface such as the retina are clearly defined by way of simple geometry, the inverse operation – that is, mapping from the 2D retinal image to the 3D structure of the world – is almost unfathomable, as every 2D image is consistent with an infinite number of 3D scenes. This is known as the inverse optics problem (Pizlo, 2001). In the time since Wheatstone's (1852) seminal paper on binocular vision, a vast body of research has explored the processes which help recover 3D layout from 2D retinal input (for a review, see Howard, 2012), but the distinct mechanisms underlying these processes remain elusive.

The vast majority of research in vision science is conducted with observers who have 'normal' or 'corrected to normal vision'. Data from those who have visual abnormalities (such as strabismus[2] or convergence insufficiency[3]) are usually rejected for studies which have a non-clinical basis. However, individual differences are well-suited to probing for the presence of distinct mechanisms, as well as gaining understanding of the nature of such functions. This notion carries particular weight in the case of developmental disorders, where individual differences are more prominent due to an increased preva-

[2]A condition that interferes with binocular vision because it prevents a person from directing both eyes simultaneously towards the same fixation point; the eyes do not properly align with each other.

[3]A sensory and neuromuscular anomaly of the binocular vision system, characterized by a reduced ability of the eyes to turn towards each other for a sustained length of time.

lence of abnormalities of vision and resulting hetereogeneity (Galaburda & Duchaine, 2003; Ghasia, Brunstrom, Gordon, & Tychsen, 2008; Tsiaras, Pueschel, Keller, Curran, & Giesswein, 1999; Atkinson et al., 2001; Simmons et al., 2009). In recent years, individual differences haven begun to be embraced by the research community – for instance, Wilmer (2008) has proposed that a focus on individual differences would be particularly enlightening in the case of depth perception.

1.1.2 Thesis aims

Wilmer (2008) argues that the information contained in the perceptual vagaries that arise as a consequence of individual differences is a substantial resource for learning about vision. In an attempt to explore the repercussions of individual differences in depth perception, this thesis is broadly split into two parts. The first section assesses how multiple cues to depth are combined into a unified percept when the ability to utilise a certain cue (stereopsis from binocular disparity) is reduced. It also aims to explore whether the differences in visual perception present in some developmental disorders such as ASD are due to altered cue integration mechanisms specific to the disorder, or if these patterns of results can be explained by individuals in these clinical populations being disproportionately affected by stereopsis impairment.

The latter half of the thesis takes a closer look at the functional significance of stereopsis, one aspect of depth perception. Visual functions are in large part defined by their utility: to fully understand an aspect of vision, one must understand what it is used for. In the case of stereopsis we know much about how it works, but rather less is understood about its function (Fielder & Moseley, 1996; O'Connor, Patterson, Anderson, Draper, & the FSOS Research Group, 2010; Howard, 2012; Read, 2015) and what we do know comes from cross-species comparisons. This second section aims to identify some of the wider implications of impaired stereopsis in humans.

Discussion of these concepts requires understanding of the basic precepts of vision and depth perception. The remainder of this chapter is devoted to exploring some principles of depth perception and other pertinent topics. I will start by reviewing the cues used by the visual system in the judgement of depth. It should be noted that I do not aim to provide an exhaustive list: rather, sources will only be discussed where they are relevant to the experimental chapters in this thesis. I will then give an overview of depth cue combination and go through the decision to include a participant group with ASD as a comparison group in the studies involving cue combination. Penultimately, I shall review theories of the significance of stereopsis. The chapter ends with an overview of the experimental chapters.

1.2 Depth cues

1.2.1 Binocular information

Binocular visual information refers to the information available only when the images from the two eyes are combined. In the majority of animals, the two eyes are located on opposite sides of the head – this position serves to maximise the size of the visual field. Animals which have two eyes placed on the front of their head (including humans) have a field of vision with a large degree of overlap in the images presented to each eye (the binocular visual field); this overlap spans approximately 120° in humans (Howard & Rogers, 1995, p. 32) and brings two main advantages. Firstly, it allows the visual system a 'second chance' at processing the information present in the binocular visual field. Binocular viewing has been shown to reduce detection and discrimination thresholds in comparison to monocular viewing conditions, an effect known as binocular summation (see Blake, Sloane, & Fox, 1981 for a review). While this demonstrates an advantage of similarity between the two eyes' inputs, the second advantage arises from the differences between the two retinal images.

As a result of the horizontal separation between the eyes (average interocular distance is ~ 6.5cm), each eye registers a slightly different view of the world. The brain exploits these differences, or disparities, in the retinal images in order to retrieve a three-dimensional layout of our environment. There are two different types of disparity, absolute and relative. Absolute binocular disparity is defined with respect to the fovea[4], and indicates the difference in depth between a single point in space and the point of fixation (θ_F and θ_P; see Figure 1.1 for an illustration). Relative binocular disparity (δ) is defined between two visual points in space, and indicates the relative depth of these points independent of fixation:

$$\delta = \theta_Q - \theta_P \qquad (1.1)$$

These disparity signals are what drive the resulting sensation of depth, henceforth referred to as stereopsis (Wheatstone, 1852; Julesz, 1971; Howard, 2012), and encompass relatively straightforward geometry, as can be seen in Figure 1.1.

Humans are more sensitive to relative disparity than to absolute disparity (Blakemore, 1970; Julesz, 1971; Westheimer, 1979). This is because changes in the vergence angles of the eyes (where the eyes move in opposite directions to change fixation from a farther point to a closer point, or vice versa) affect a point's absolute disparity – when a point is fixated by the eyes it has an absolute disparity of zero, as both images are

[4] A small dimple in the retina (also known as fovea centralis) that approximates 1.5mm in diameter. It contains a large number of closely packed cone cells and therefore is the center of the eye's sharpest vision and the location of most colour perception.

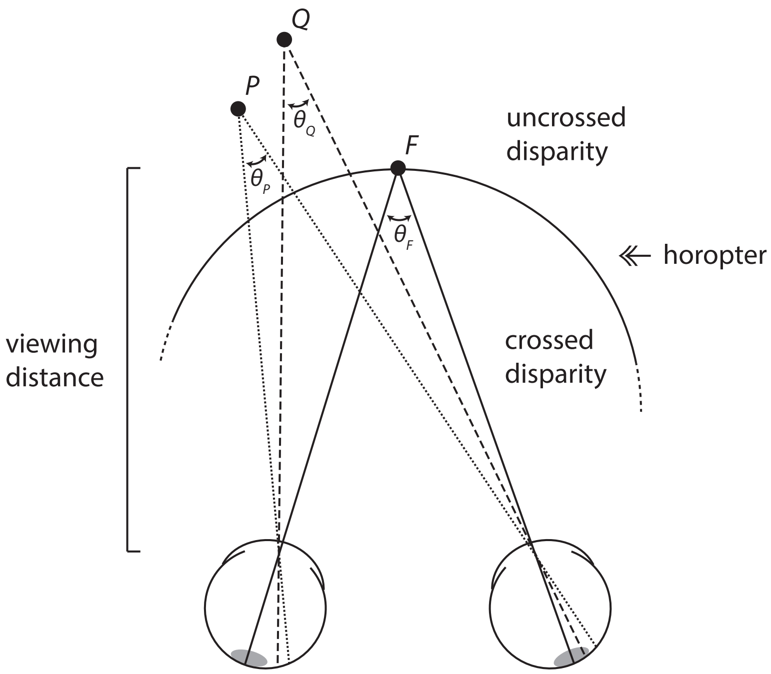
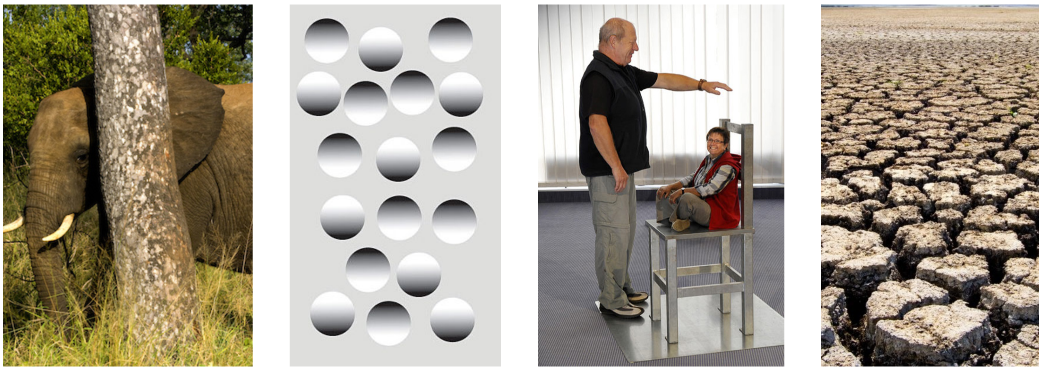


Figure 1.1: The geometry of binocular vision. The eyes fixate point *F*, whose image falls on the centre of the retina (the fovea) of each eye (grey areas). The absolute disparity of *F* is therefore zero. The retinal projections of points *P* and *Q*, which are further away than *F*, fall on disparate points in each eye. The absolute disparities of points *P* and *Q* are uncrossed, because they lie behind the horopter. See main text for further information.

focused directly on the retina. The relative disparity of two points is unaffected by changes in vergence. This is thought to be the reason why the visual system displays finer depth discrimination when relative disparities are the source of stereoscopic information (Westheimer, 1979).

In the example given in Figure 1.1, points *P* and *Q* lie beyond the fixation point *F*. Fixation notwithstanding, points in space generate a positive or negative value of absolute disparity (disparity 'sign'). When a point is closer than fixation, a positive value of binocular disparity is obtained. This is referred to as crossed disparity, as the visual lines to the object 'cross' in front of fixation. When the point is further than fixation (as in Figure 1.1), this results in a negative value and is called uncrossed disparity as the visual lines converge beyond the fixation point.

Human binocular function exhibits a large amount of individual variation. Stereoscopic acuity, or 'stereoacuity' is the smallest amount of disparity that elicits a sensation of depth. It varies from 'hyper acuity' of ~ 2 arc seconds (Wilcox & Harris, 2010, p. 167) to complete stereo-blindness, with some individuals who are unable to identify the sign of absolute disparity (crossed vs uncrossed) but are still able to appreciate relative disparity (van Ee & Richards, 2002). Around 60% of the general population have acute stereopsis (exhibiting disparity thresholds of ≤ 20 arc seconds), with the remaining 40% having moderate (able to perceive disparities between 21 and 300 arc seconds; 31% of popula-



(a) occlusion (b) shading (c) familiar size (d) texture

Figure 1.2: Examples of monocular depth cues

tion total), poor (sensation of depth only results from disparities > 300 arc seconds; 8% of population total), or nil (no perception of depth from disparity; 1% population total) stereopsis (Bohr & Read, 2013; Bosten et al., 2015; Coutant & Westheimer, 1993; Hess, To, Zhou, Wang, & Cooperstock, 2015; Zaroff, Knutelska, & Frumkes, 2003). However, the vast majority of research on binocular vision that screens for stereopsis excludes participants who have thresholds of > 40 arc seconds (between 3.9-17.6% of their sample; Heron & Lages, 2012). Individual differences in stereopsis are therefore grossly under-represented in depth perception research (Wilmer, 2008).

1.2.2 Monocular information

Although it is clear that binocular cues provide a strong sensation of depth on their own, two eyes are not necessary to appreciate depth. If a pair of eyes were essential in this regard people with only one eye, and those who are stereo-blind, would not be able to perceive distance. This is demonstrably not the case, as the vast majority of us are able to maintain some perception of depth when we close one eye. The reason for this is that when objects located at different depths are projected onto the retina, there are certain regularities and patterns present in the retinal image which allow us to identify depth relationships in the absence of disparity information. The visual system is sensitive to these regularities (cues), and can use them to derive an estimate of depth, a fact which has long been exploited by artists to create a convincing depiction of depth on a flat canvas. Below is a brief overview of a selection of monocular cues (which are presented visually in Figure 1.2) – for a comprehensive review, see Cutting and Vishton (1995) or Howard (2012).

Occlusion: One of the most robust sources of information about the relative distance of objects is interposition or occlusion. When one object is placed in front of another object so that the closer object partially obscures our view of the most distant one, it is quick and easy to tell which object is closer. However, this cue only allows the observer to create an ordinal 'ranking' of relative nearness and does not give detailed distance information.

Shading: Patterns of light and shadow in a scene can provide cues about the three-dimensional shapes of objects. Like occlusion, the cues provided by shading do not tell us much about relative distance between ourselves and said objects, instead telling us which parts of objects look closer or further away. For instance, view the second panel in Figure 1.2 – circles with shading on the lower half appear to pop out of the page and appear closer, whereas shading on the upper half causes them to recede inwards and look further away.

Familiar and relative size: Familiarity with sizes of objects is another important monocular cue. If an object such as a house or car casts a very small image on the retina, it will be perceived as being far away as the visual system can automatically compute the approximate distance given the retinal image and prior knowledge of an object's size. Similarly, if two objects are known to be the same size, but their absolute size is unknown, the object which subtends a larger visual angle on the retina is perceived as being closer.

Texture gradient: Uniform texture on a surface that is not fronto-parallel to the observer has three different qualities that vary systematically with depth and can thus be used to estimate distance. Firstly the separation of elements perpendicular to surface slant decreases with increasing distance (perspective gradient): linear perspective is a special example of this where the 'elements' are lines which converge on the vanishing point. Second, the separation of elements in the direction of surface slant decreases with increasing distance (compression gradient). Finally, density of elements increases with distance (density gradient). Texture gradient can only be considered a reliable cue when when elements of similar size, shape, and spacing repeat in the scene.

Monocular cues are diverse, and cover various distance ranges. However, not all cues are considered equal; while many cues vary in their effectiveness at different distances, there are a subset whose reliability is not attenuated by distance from the observer – see Figure 1.3. Some provide precise metric measurements of absolute or relative depth, whereas others only provide coarse ordinal estimates. These differences all have an affect on the overall percept of depth, when cues are combined.

1.3 Depth cue combination

Despite the multiplicity of cues to depth, subjective impressions indicate that we form a single coherent estimate of the depth of our immediate visual environment. Furthermore, when multiple depth cues are available, judgements of depth are more accurate than when only a single cue is present (Bruno & Cutting, 1988; H. H. Bülthoff & Mallot,

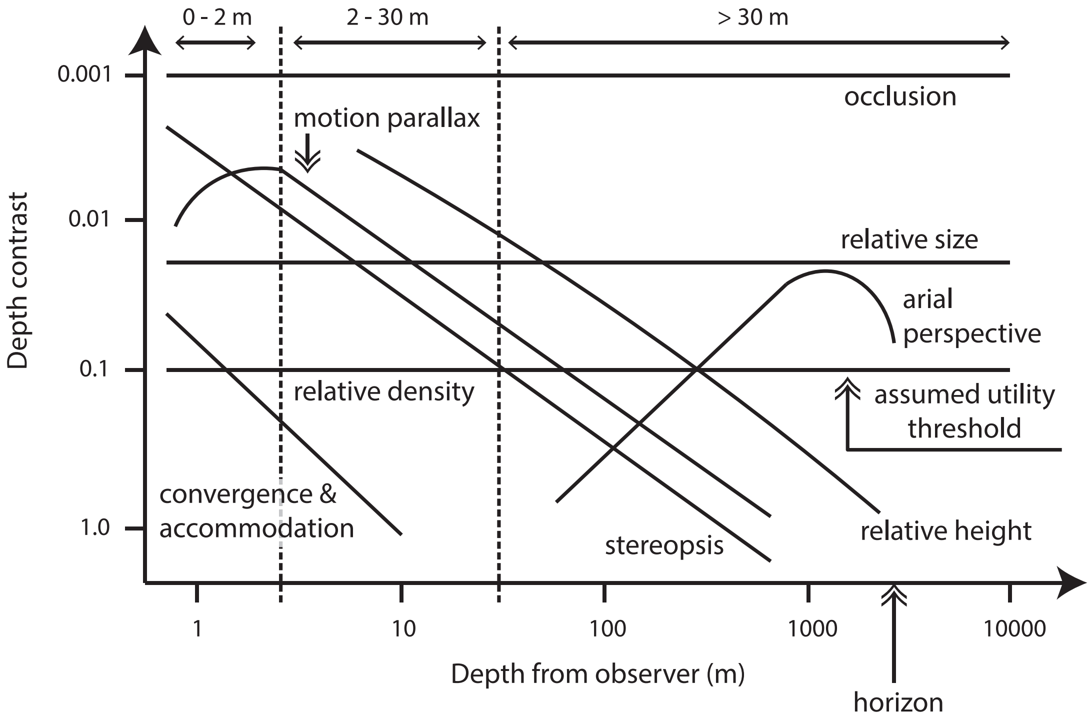


Figure 1.3: Just-discriminable depth thresholds as a function of the log of distance from the observer; plotted with analogy to contrast sensitivity functions ('depth contrast'). More potent sources of information are associated with smaller depth-discrimination thresholds; these threshold functions reflect suprathreshold utility. Each type of space around the observer (personal [0 - 2m], action [2 - 30m], vista [> 30 m]) is best served by different sources of information and therefore different cues may be given different weights depending on their distance from the observer. Note that the efficacy of some cues (such as occlusion) does not attenuate with distance. Adapted from Cutting and Vishton (1995).

1988; Dosher, Sperling, & Wurst, 1986). This is due to the fact that the visual system takes advantage of the presence of more than one cue by attempting to integrate or combine all available information. Cue combination has been well-studied over the past decades and has lead to the identification of a number of computation models, of which there are three main types. Weak fusion models are modular, independently processing each depth cue, and then linearly combining the resulting depth estimates (Clarke & Yuille, 1990). Strong fusion models differ in that they are non-modular, meaning that the outputs from each cue do not need to be combined in such a prescriptive way – instead, information from different cues is integrated in an unrestricted manner, giving the most probable three-dimensional interpretation for a scene (Nakayama & Shimojo, 1992).

The most comprehensive model of depth-cue combination lies somewhere between these two extremes. The *modified* weak fusion model (Landy, Maloney, Johnston, & Young, 1995) combines the modular aspect of weak fusion with the interactive properties of strong fusion, allowing constrained interactions between cues such as cue promotion and re-weighting. As seen previously, depth cues can provide qualitatively different

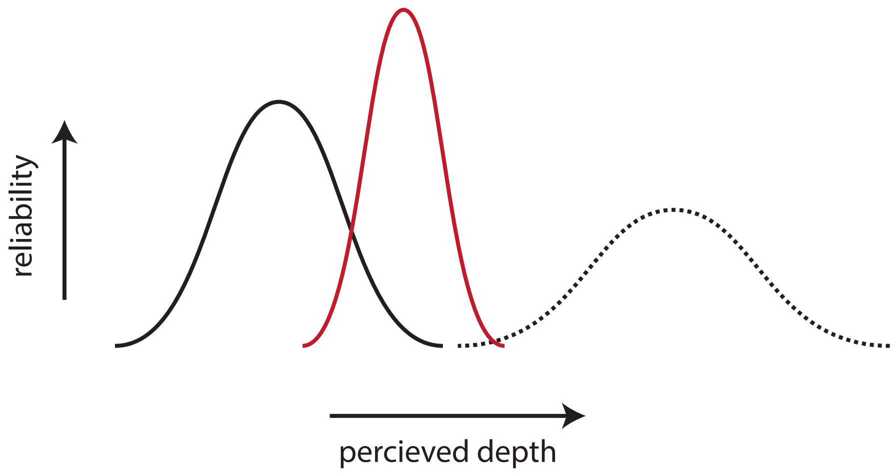


Figure 1.4: Optimal cue combination for two cues that specify different depths (i.e. there is cue conflict). Two estimates of depth resulting from two different cues (the black solid and dotted lines) are combined (red solid line). The cues specify different depth and have different variances. The cue with the lower variance is weighted higher, thereby 'pulling' the final estimate towards that cue. The variance of the final depth estimate is smaller than the variance for each individual cue.

types of information in the form of absolute (metric) or relative (ordinal) depth. In the cue promotion step, cues which provide an estimate of relative depth are transformed into metric-type cues using information derived from other cues at the same location in space. Next, the relative reliability of each cue is established; this is computationally difficult as all depth cues contain some amount of ambiguity owing to inherent neural noise and uncertainties within the stimulus, causing the information given to be consistent with a range of possible depths. Furthermore, the contribution of a cue may be context-dependent as the reliability of some cues is attenuated at greater distances (Cutting & Vishton, 1995; Johnston, Cumming, & Parker, 1993). Reliability of a cue is set by both the ambiguity of the cue and whether the depth estimate given by that cue correlates with another cue. The final stage of cue combination involves determination of a weighted average of the depth estimates provided by the cues. Here, the contribution (or weighting) of each cue is moderated by its reliability using Maximum Likelihood Estimation, in an attempt to minimise the variance of the final depth estimate. Since this combined estimate is the most reliable possible, the process by which this occurs is commonly referred to as 'optimal' or 'ideal observer' cue combination (Landy, Banks, & Knill, 2011). Figure 1.4 shows a visual representation of the Maximum Likelihood Estimation of two cues.

In adults, previous work strongly suggests that sensory cues are combined in an optimal manner, including for surface slant (Hillis, Ernst, Banks, & Landy, 2002; Hillis, Watt, Landy, & Banks, 2004; Knill & Saunders, 2003) and object shape (Ernst & Banks, 2002; Johnston et al., 1993). Relationships between cues are not fixed, as when cues are corrupted by the addition of noise or are made to conflict (Ernst & Banks, 2002; Hillis et al., 2002, 2004; Knill & Saunders, 2003; Alais & Burr, 2004), observers show a tendency to shift their overall perception in the direction of the most reliable cue. Unlike adults, children appear to be able to keep sensory information from multiple sources separate. When more than one cue is available, children do not experience an adult-like gain in sensitivity until around age 12; furthermore, young children do not show a reduction in sensitivity when cues are in conflict (Nardini, Bedford, & Mareschal, 2010). The vast majority of research assessing depth cue combination utilises stereopsis alongside another ordinal or metric cue. Like research on binocular visual information, the role of individual differences in how different cues to depth are weighted and combined remains largely unexplored (though it has been hypothesised that those with poor stereopsis may over-weight monocular depth cues; Hahn, Comstock, Connick, MacCarron, & Mulla, 2010). For this reason, the studies in this thesis which explore individual differences in cue integration have involved groups of individuals who are either TD and have a range of stereoscopic ability, or have a developmental disability such as ASD where individuals are disproportionately affected by stereopsis impairment.

1.4 Autism spectrum disorder as a comparison group

Autism is a developmental disorder characterised by difficulties with social interaction, social communication and an unusually restricted range of behaviours and interests (Frith, 2003). Previous diagnostic criteria conceptualised the disorder as a triad of impairments (American Psychiatric Association, 2000; WHO, 2010), and appeared to focus upon the behavioural and cognitive components of autism. The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2013) has implemented several significant changes to the content and structure of ASD, the foremost of which is replacement of the 'classic' triadic symptom structure with an dyad comprising of 'social communication' and 'restricted repetitive patterns of behaviour'. The collapse of social interaction and communication impairments into a single domain has been widely supported by a number of studies which have used confirmatory factor analysis to evaluate the construct validity of the new symptom structure (Frazier et al., 2012; Kamp-Becker, Ghahreman, Smidt, & Remschmidt, 2009; Mandy et al., 2012; Snow et al., 2009) on symptomatology data collected using a variety of instruments (including the Autism Diagnostic Observation Schedule, Social Responsiveness Scale and the Social Communication Questionnaire). Other changes to criteria include the removal of imagination impairment from the list of core autistic symptoms, collapsing stereotyped and repetitive use of language into the 'restricted and repetitive patterns of behaviour' domain and the inclusion of hypo- or hyper-reactivity to sensory stimuli as a new obligatory criterion within this domain.

The last of these changes to the diagnostic criteria reflects a new emphasis upon the neurologic features of autism, especially with regard to the perceptual experience of persons with ASD. Sensory abnormalities are observed in > 90% of cases (Geschwind, 2009) and atypical processing of sensory information has been reflected in even the earliest theories of autism (Kanner, 1943; Hutt, Hutt, Lee, & Ounsted, 1964). These early findings have been corroborated and extended by a number of clinical, parental and personal reports which focus on unusually intense attention to, or avoidance of, sensory stimuli from all modalities, including that of vision (Grandin, 2006; D. Williams, 1998; Ben-Sasson et al., 2008; Bogdashina, 2003). It has been proposed by several current theories of autism that sensory atypicalities are a core symptom of ASD which exert a downstream effect on the development of the various perceptual systems in individuals with ASD (Happé & Frith, 2006; Mottron, Dawson, Soulières, Hubert, & Burack, 2006).

1.4.1 Depth perception in ASD

While much is known about visual perception in ASD (see Simmons et al., 2009 for an overview), one evident gap in the literature concerns the area of depth perception. Both clinical (Kaplan, 2006; Bogdashina, 2003) and anecdotal reports (Grandin, 2006) have cited that depth perception is abnormal or reduced in those with ASD. On the surface, this is unsurprising – because stereopsis requires a precise registration of information from each eye, it is developmentally fragile (Atkinson, 2000) and can be easily disrupted. It has been reported that a larger proportion of individuals with ASD present with strabismus (squint) and convergence insufficiency (poor 'eye-teaming') compared to TD populations, supporting this proposition. However, studies that aim to establish the incidence of these conditions have been unable to come to a consensus.

In the case of strabismus, prevalence between 10.5 - 60% has been reported in ASD populations (Scharre & Creedon, 1992; Denis, Burillon, Livet, & Burguiere, 1997; Kaplan, Rimland, Edelson, & Edelson, 1999; Milne, Griffiths, Buckley, & Scope, 2009). An early screening study that investigated binocular vision in a sample of 34 children with ASD found that 21% presented with strabismus (Scharre & Creedon, 1992). Later studies by Denis et al. (1997) and Kaplan et al. (1999) reported higher incidence of strabismus (50% and 60% of the sample, respectively), however participant recruitment for both pieces of research was biased in a manner that may have caused an overestimation of prevalence. Although Denis et al. (1997) found that 60% of their ASD sample had strabismus, their data were based on 10 participants who were recruited from the ophthalmology department of the local hospital. Kaplan et al. (1999) had a larger sample of 34 participants (50% of which had strabismus) but the overall level of functioning in this group was lower. Increased severity of developmental delay and neurological impairment has been found to result in a significantly higher incidence of strabismus and refractive errors (Levy, 1984; Orel-Bixler, Haegerstrom-Portnoy, & Hall, 1989).

Figure 1.5: An example of lateral vision in a child with autism (Coulter, 2009, p. 172)

A recent study by Milne et al. (2009) that included 51 participants with ASD who were a mixture of low (LF, IQ<70; N = 15) and high functioning (HF, IQ≥ 70; N = 36) found that 10.6% of their overall ASD sample had strabismus (18% of the LF subgroup and 8% of the HF subgroup). Although this latter estimate - which can be argued to be the most robust - is lower than that reported by previous research, the incidence was nonetheless higher than in the typical population where the frequency of strabismus is between 2-5% (P. A. Graham, 1974; Stayte, Reeves, & Wortham, 1993). Milne et al. (2009) also reported a higher prevalence of convergence insufficiency in those with ASD compared to individuals who are TD. Though the aetiology of convergence insufficiency has not yet been completely determined (Arnoldi & Reynolds, 2007; von Noorden & Campos, 2002), both strabismus and convergence insufficiency prevent maintenance of binocular fusion which is a necessary prerequisite of stereoscopic vision (Elliott, 2007).

Visual symptoms used in the screening and diagnosis of ASD have also hinted that stereoscopic vision may be either poor or absent in this population. Lateral vision is one such visual behaviour in which there are persistent attempts to look at an object of interest by means of turning the head and looking out of the corner of the eye (see Figure 1.5). This behaviour has been attributed to faulty binocular processing caused by poor inter-hemispheric integration. Information enters the visual system with a great deal of overlap - the region of space that can be seen with both eyes looking straight ahead may be defined as the full visual field. This space is divided into the left and right visual hemifields, which are represented in the right and left hemispheres of the brain respectively. The central portion of both visual hemifields overlaps when looking straight ahead - in order to be able to combine binocular images, both hemispheres must be sufficiently integrated. When an individual looks out of the corner of their eye using peripheral vision, functioning of only one hemisphere is required. In a study that investigated inter-hemispherical information transfer in children with and without ASD, it was found that those with ASD took longer to point to objects presented to both visual fields simultaneously than those who were TD (Nydén, Carlsson, Carlsson, & Gillberg, 2004). For individuals with ASD who have problems with inter-hemispheric integration, lateral vision may be a compensatory strategy to complete a task more quickly and with less effort (Coulter, 2009). It also prevents maintenance of binocular fusion due to the gross inequality in the two retinal images, which prevents the occurrence of diplopia and encourages suppression of one of the retinal images.

Despite these indications that stereopsis may be disrupted in persons with ASD, the research community are not in complete agreement as to whether this is the case (see Table 1.1 for an overview). This lack of consensus may, in part, be attributed to the variety of different tests used to estimate stereoacuity ('stereotests'). Stereoacuity tests seek to determine the smallest amount of recognisable retinal disparity, measured in seconds of arc. Although stereopsis would appear to be one of the most heavily-weighted depth cues, it is only capable of providing relative distance information and is easily influenced by other depth cues. Introduction of monocular cues can lead to powerful biases in depth perception due to conflict, where an unambiguous cue may disambiguate another, ambiguous, cue. A number of popular clinical stereotests are thought to contain monocular cues in the largest levels of disparity (Cooper & Feldman, 1979; Fawcett, 2005; C. Hall, 1982; Hahn et al., 2010; Francis & Leske, 1999) – this may give a false indication of stereoscopic ability in populations who have poor or nil stereoacuity and thus be the reason for the disagreement between the screening studies reported in Table 1.1. Regardless of this potential confound, the majority report that those with ASD appear to exhibit worse stereopsis than their TD peers, making them a useful comparison group when ascertaining what happens in cue combination when the ability to utilise a certain cue (namely, stereopsis) is reduced.

Table 1.1: Comparison of studies which have screened the stereoacuity of individuals with ASD.

Study	N (ASD)	Stereotest	Result
Scharre and Creedon (1992)	34 (34)	Lang I	~ 80% ASD ≥ 550 arc sec
Milne et al. (2009)	85 (41)	Frisby	No difference between ASD/TD
Adams et al. (2010)	44 (44)	Randot Preschool	ASD sig. worse than TD normative data
Anketell et al. (2013)	292 (88)[5]	Frisby	AU sig. worse than TD/AS
Coulter et al. (2013)	61 (34)	Randot 2 Randot E Lang I	ASD sig. worse than TD
Black et al. (2013)	30 (30)	Titmus	75% ASD > 40 arc sec

[5]Diagnosis was classified as; Autism (AU) n = 50, Asperger's syndrome (AS) n = 33, unspecified n = 5.

1.4.2 Cue combination in ASD

While those with ASD are more likely to have reduced stereopsis, other underlying causes for abnormal depth perception through differences in how depth cues are combined may also be present in this population. There is consistent evidence of an atypical visual processing style of ASD (Dakin & Frith, 2005; Behrmann, Thomas, & Humphreys, 2006; Simmons et al., 2009), commonly manifesting as deficits in global processing (i.e., processing of the whole object or scene) or superior low-level processing. Most current theories of ASD attempt to provide explanations for this in terms of atypical integration.

Weak central coherence (WCC) (Happé & Frith, 2006) proposes that individuals with ASD have a detail-focused cognitive style where they are unable to bind details into more global forms. There also appears to be a bias away from integrating higher-level information such as context in those with ASD (supported by faster performance of this group on embedded figures (Shah & Frith, 1983; Jolliffe & Baron-Cohen, 1997), and block design tasks (Shah & Frith, 1993)). The consequences of such a pattern of perception may theoretically mean that those with ASD can utilise certain cues to depth – those processed in early visual areas such as texture (Welchman, Deubelius, Conrad, Bülthoff, & Kourtzi, 2005) – better than others (for instance shape-from-shading, where though light direction is discriminated relatively early on, the grouping of contrast edges and subsequent identification of convex or concave shapes occurs in higher visual areas; Gerardin, Kourtzi, & Mamassian, 2010).

A contrasting alternative framework, the enhanced perceptual functioning (EPF) hypothesis (Mottron & Burack, 2001; Mottron et al., 2006) states that while autistic individuals may have enhanced low-level perception, the integration of 'higher-order' information – which is automatic in TD populations – is optional in those with ASD, meaning that the default setting of perception is more locally-oriented. Basic visual functioning may be superior in ASD populations but low-level integration of features may be impaired. This is supported by the literature that has demonstrated that although people with ASD appear to have intact or superior processing of simple dynamic stimuli (Bertone, Mottron, Jelenic, & Faubert, 2005; Pellicano, Gibson, Maybery, Durkin, & Badcock, 2005), they exhibit poor performance when required to combine simple visual features such as in texture-defined second-order gratings (Bertone et al., 2005) or motion coherence tasks (Milne & Szczerbinski, 2009; Koldewyn, Whitney, & Rivera, 2011).

Both WCC and EPF conceptualize high-level and low-level processes as separate entities. However, these processes are not so easily dissociable; neurons in the visual cortex receive feedforward information (from the retina), feedback (from higher cortical areas) and have inputs from lateral connections. Bayesian hypo-prior (BHP) takes this into account, framing the perceptual atypicalities found in ASD in terms of a failure to incorporate modulatory feedback. BHP proposes that sensory differences in ASD reflect weaker 'perceptual priors' (Pellicano & Burr, 2012), where priors encode biases towards attributes that are most likely, based on previous experience. They can improve the efficiency of neural computations (including in instances of cue combination) by acting as constraints and reducing noise or error. Reduced priors lead to a decrease in the influence of context and prior knowledge causing superior performance in certain tasks and being deleterious for others. In individuals with ASD, attenuated or flattened priors would cause a percept that is closer to the raw sensory input and may mean that this group fails to integrate multiple cues to depth, similar to performance in younger TD children.

Throughout the first part of this thesis, individuals with ASD and those who are TD will be recruited with the aim of exploring the implications of individual differences in stereopsis. I also wish to investigate whether differences in cue utilisation and combination in ASD are specific to the disorder (as hypothesised by the various perceptual theories of ASD), or if abnormal cue integration in this group is driven by a disproportional amount of individuals with stereopsis deficit.

1.5 Significance of stereopsis

Thus far, stereopsis has been considered purely in terms of the role it plays in the perception of depth –by "provid[ing] a vivid and accurate relative depth experience" (Fielder & Moseley, 1996, p. 235), it can produce a stronger sensation of depth than many monocular cues (Hillis et al., 2004; Johnston et al., 1993; Knill & Saunders, 2003; Lovell, Bloj, & Harris, 2012; Vuong, Domini, & Caudek, 2006). Moreover, when stereopsis is recovered in individuals who were previously unable to perceive disparity, the quale of depth undergoes a striking change (Barry, 2009). Other, more tangible, benefits of intact stereopsis seem obvious when other species are our frame of reference; after all, an animal could not survive for long if it were unable to estimate where in depth its prey were located. However, the functional importance of stereopsis in humans remains a topic of debate (as evidenced by a post to vision mailing list CVNet on this topic ["CVNet - Stereoscopic vision: advantages, consequences;"; August 2006], which garnered 94 replies). After Fielder and Moseley (1996) identified motor control as a possible candidate, research assessing the utility of stereopsis has focused almost exclusively on this topic. Presence of binocular disparity has been shown to help guide hand movements and allow their execution with increased precision (Watt & Bradshaw, 2000; Bradshaw et al., 2004; Melmoth & Grant, 2006; Melmoth, Storoni, Todd, Finlay, & Grant, 2007; B. Hu & Knill, 2011), and both children and adults with poor stereopsis perform worse on a range of fine (Grant, Melmoth, Morgan, & Finlay, 2007; O'Connor et al., 2010; Suttle, Melmoth, Finlay, Sloper, & Grant, 2011; Webber, Wood, Gole, & Brown, 2008;

Murdoch, McGhee, & Glover, 1991; Hrisos, Clarke, Kelly, Henderson, & Wright, 2006) and gross (Buckley, Panesar, MacLellan, Pacey, & Barrett, 2010) motor tasks than peers with normal stereoacuity. Aside from the impact of stereoacuity on motor proficiency, the wider ramifications of stereo-impairment remain undiscussed.

1.6 Conclusions

Despite much research on the topic of depth perception, few have considered the role individual differences in stereopsis might play. This is a critical omission, as a sizeable proportion of the general population (and a great number of individuals with developmental disorders) have impairments in this domain. This thesis therefore aims to better characterise the implications of reduced stereopsis in typical and atypical development across a range of perceptual and motor tasks, in addition to addressing the farther-reaching repercussions of abnormal binocular vision.

1.7 Overview of chapters

Chapter 2. The next chapter, General Methods, describes the reasoning behind the various analytical procedures carried out as part of this thesis. This includes justification for the use of Linear Mixed Models over the classic Analysis of Variance, as well as the use of the Median Absolute Deviation when identifying outliers in the data. The details concerning the procedures and methods of each experiment are provided in their respective chapters.

Chapters 3-4. These chapters are closely related. The first experimental chapter (*Chapter 3*) investigates how individual cues to depth are utilised and combined in typical children and adults using a shape constancy paradigm. I show that while children are more sensitive to monocular cues than adults, they still show some degree of cue combination. In addition, I observe that an inability to use binocular information appears to cause re-weighting to occur in favour of monocular cues, regardless of age. In *Chapter 4*, the same paradigm was used with groups of TD and ASD teenagers. The results from this experiment indicated that contextual and binocular information interacted when creating an overall percept of depth. A main effect of ASD diagnosis was found, with this group reporting perception that was unbiased and closer to the raw sensory input. Although participants with ASD exhibited poorer stereoacuity than their TD counterparts, this did not explain the differences between the groups.

Chapter 5. This chapter assessed the combination of ordinal and metric depth cues in TD and ASD adults. Cue integration did not depend on level of stereoacuity or autism diagnosis. Unlike previous research, and inconsistent with perceptual theories of autism, I found that individuals with ASD automatically integrated depth cues, even when it was not advantageous to do so. Additionally, I found that the processing of uncrossed disparities was particularly difficult for those with an ASD.

Chapter 6. In this chapter I wanted to establish whether the functional significance of stereopsis followed a developmental trajectory. I was also interested if the motor deficits observed in those with poor stereopsis were limited to hand-eye coordination tasks. Using three of tasks derived from a standardised test of motor proficiency – catching a ball, balancing on one leg, and bead-threading – I measured the effect of binocular vision and stereoacuity on motor ability. Stereoacuity affected performance across a range of tasks involving the use of fine and gross motor skill, and – importantly – this effect of stereopsis did not change with age.

Chapter 7. In the final experimental chapter, I enquired as to the further-reaching consequences of poor stereopsis. Using a quantitative survey I aimed to establish how stereopsis, motor skills, and social skills related to one another. Surprisingly, I found that while motor ability mediated the relationship between stereopsis and social skill, stereopsis also directly contributed to social skill, suggesting that the functional significance of stereopsis is not limited to motor ability.

Chapter 8. Ultimately, I summarise my findings and discuss the implications of these results within the context of the two issues brought forward in this introductory chapter: what can individual differences tell us about how we perceive depth from multiple cues; and what are the functional consequences of stereopsis impairment.

CHAPTER 2

General Methods

THE experiments presented within this thesis draw upon a wide range of data collection methods, including psychophysics (Chapters 3–5), behavioural observation (Chapter 6), and on-line surveys (Chapter 7). For this reason, the details concerning the procedures and methods of each experiment are provided in their respective chapters. However, most of the studies in this thesis utilise the same methods for outlier identification and removal, as well as analysis and reporting of the data. The purpose of the current chapter is to justify the particular methods used in data cleaning and analysis.

2.1 Outlier removal

Most data sets contain outliers, points with an unusually large or small value compared to others in the data set. While outliers may be legitimate data points containing valuable information about the process being studied, often they reflect misunderstanding of the task, participant inattention, or equipment malfunction. The presence of outliers can have a disproportionate influence on the conclusions drawn from analyses, as these commonly assume that data are normally distributed. It is therefore important to correctly identify outliers, and make the decision to remove, correct, or leave such data points (see McClelland (2002) for a discussion on this topic) In this thesis, all outlying data points were removed from the dataset on a case-by-case basis.

A common method for the detection of outliers is use of the mean ±3 standard deviations – 99.87% of the data within a normal distribution are included within this range (Howell, 1998). Unfortunately, three major problems can be identified in the use of the mean as a measure of central tendency. Firstly, it assumes the distribution of the data is normal (inclusive of the outlying data points). Secondly, the mean and standard deviation are strongly impacted by outliers. Thirdly, this method is unlikely to detect outliers in samples where $N < 100$ (Cousineau & Chartier, 2010). Therefore, the mean as outlier indicator is fundamentally problematic: how can it provide a robust guide to outlier detection when the indicator itself is altered by the presence of outlying values?

To give an example, consider a set of 10 data points with values 1, 1, 2, 3, 6, 7, 8, 8, 9, 100. Clearly, one of the data points is an outlier (made particularly salient here for the purpose of the current argument). The mean of this data set is 14.5, and the standard deviation is 30.197, with a clearly non-normal distribution (kurtosis = 7.953, skewness = 2.615). Therefore, using the conservative criteria of three standard deviations, values smaller than -76.09 and larger than 105.09 are identified as outliers. Not only is the mean inconsistent with the majority of the values contained within the data set, the clearly out-of-place largest value (100) is not identified as an outlier, demonstrating the limitations of the mean $\pm n$ standard deviations method.

A more robust method of identifying outliers includes the use of the median absolute deviation (Leys, Ley, Klein, Bernard, & Licata, 2013). While the median (*M*) – like the mean – is a measure of central tendency, it is comparatively insensitive to the presence of outliers. Absolute deviation from the median is a measure of the variability present in a data set and can be used as a robust alternative to standard deviation. Calculation of the median absolute deviation (MAD) is straightforward, as it involves finding the median of absolute deviations from the median:

$$MAD = b \times M_i(|x_i - M_j(x_j)|) \tag{2.1}$$

where x_j is the number of data points in the set, and M_i is the median value. Typically, $b = 1.4826$, a constant linked to the assumption of normality of the data, disregarding the abnormality induced by outliers (Rousseeuw & Croux, 1993). After the MAD is calculated (MAD = 4.448 for the example data set above), the rejection criterion threshold must be chosen. Miller (1991) proposed a number of threshold values for the identification of outliers, and the value chosen depends on the stringency of the researcher's criteria: typically-used values in the domain of psychology are 3 (very conservative), 2.5 (moderately conservative), and – somewhat less often – 2 (poorly conservative). If I use the same limit as the mean and standard deviation example above (3), the MAD-based decision criterion becomes:

$$M - 3 \cdot MAD < x_i < M + 3 \cdot MAD \tag{2.2}$$

Using the example dataset, all values greater than 19.843, or smaller than -6.843 are considered outliers and can be dealt with accordingly.

Extending this to a more representative data set, consider a series of points ($n = 200$) randomly sampled from a normal distribution: this series can be observed in Figure 2.1. Figure 2.1A shows the normally-distributed data, and reports the mean, standard devi-

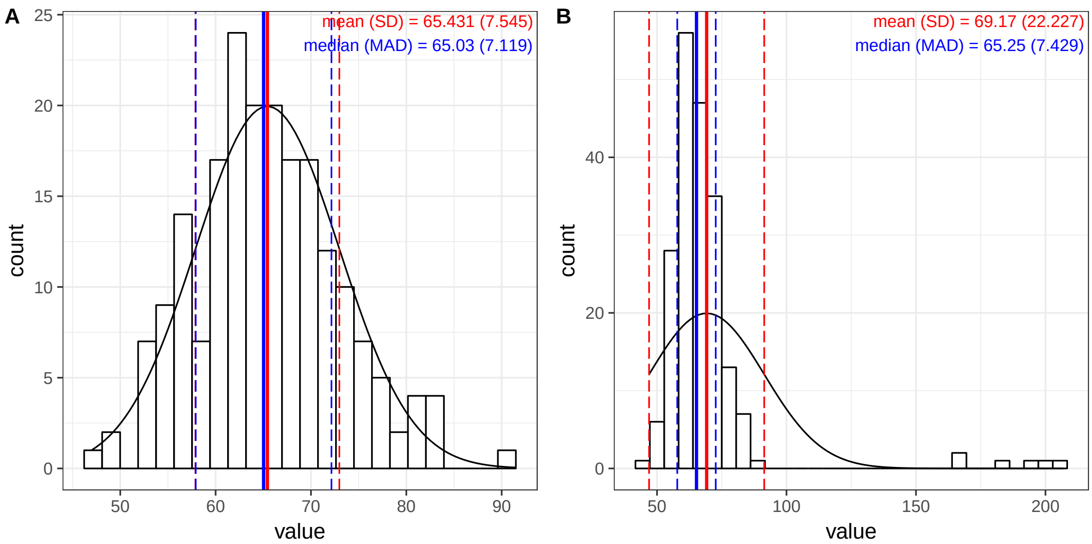


Figure 2.1: Outliers have an inordinate effect on the mean and standard deviation. Left panel shows a normal distribution, with mean and standard deviation (SD) in red and median and median absolute deviation (MAD) in blue (central tendency = solid and dispersion = dashed line). Right panel shows how randomly generated outliers cause asymmetry which disproportionately affects mean and SD, but has a negligible influence on median and MAD.

ation (SD), median, and MAD. Figure 2.1B shows the same distribution but with 3% of the observations randomly changed into outliers (by multiplying their original values by 3). Note that the mean and SD have drastically changed, whereas the median and MAD are comparatively stable regardless of the presence of outliers. It can therefore be inferred that the MAD is the more robust measure of dispersion than SD in the presence of outliers.

I have therefore used the median $\pm\, n \cdot$ MAD decision criterion throughout this thesis to identify outlying data points and remove them from further analysis, instead of more typically-used mean $\pm\, n \cdot$ SD.

2.2 Using linear mixed models in place of analysis of variance

Factorial experiments, like the ones reported in this thesis, are commonly used in the field of psychology. The design of such studies consists of two or more factors, each with discrete values or 'levels'. Participants can either be exposed to a subset of factor levels (between-participants design), all factor levels (within-participants design), or a mixture of the two (mixed design). The data which result from these kinds of experiments is typically analysed using analysis of variance (ANOVA). However, while ANOVA can model random effects (expressed in terms of the intercept), this only accounts for between-subject variation in the *dependent variable*. Between-subject variation in the factorial *independent variable(s)* is not accounted for; it may be that an apparently significant interaction effect is actually driven by a small subset of participants who are particularly sensitive to one of the experimental manipulations. Consequently, associations between independent and dependent variables can be caused by both within- and between-subject effects on either of the variables, but the traditional ANOVA is unable to dissociate the source of the variation.

Previously in the field of psychology, methods which model a variety of participant- and item-dependent effects, known as ‘hierarchical regression’, ‘multi-level regression’, or ‘mixed-effects modelling’ (Baayen, 2008; Pinheiro & Bates, 2000; Barr, Levy, Scheepers, & Tily, 2013), have been mostly limited to psycholinguistic research. However, in recent years the methodological perspectives provided by these techniques have been acknowledged in other areas of psychological research and their use is becoming more widespread (Kliegl, Wei, Dambacher, Yan, & Zhou, 2010). Throughout this thesis I will refer to this type of analysis as a linear mixed-effects model (LMM).

There are three main advantages of LMMs over ANOVAs. The chief benefit is that they are not restricted to factors with a fixed set of categorical levels, but also allow tests of effects of continuous variables; a useful feature within the context of this thesis, where I aim to identify the presence of developmental trajectories and the effect of initial differences in stereoacuity. This also results in a substantial gain in statistical power.

Conventionally, tests of between-subject covariate effects have been analysed using analysis of covariance (ANCOVA), and within-subject covariates with repeated-measures multiple regression analysis. However, while ANCOVA has been used to test for the presence of an effect of a continuous variable (M. S. Thomas et al., 2009), this disregards its true purpose. An ANCOVA is intended to statistically control for continuous variables not of primary interest, known as covariates or nuisance variables: if using a mixed design, an ANCOVA can only identify interactions between the covariate and a within-subjects factor. ANCOVA assumes that the regression coefficients are homogeneous across the categorical variable. Violation of this assumption (i.e. when the covariate differs depending on a between-subjects grouping factor) can lead to erroneous conclusions. It has been demonstrated through simulations that use of ANCOVA for this purpose may lead to anti-conservative estimates (Baayen, 2008). For this reason I propose that ANCOVAs are not suited for testing the effects of continuous variables that are not considered nuisance variables.

A second advantage of LMMs is the option to specify participants as a random factor, which allows by-participant intercepts and slopes that are grouped by factor level. This acknowledges the fact that participants do not only vary in their baseline level of response, but also in terms of the changes in their response to a given experimental manipulation.

The third and final merit of LMMs over ANOVAs is that the former has a less severe loss of statistical power in cases where an experimental designs are unbalanced, either by design or due to missing data (see Pinheiro and Bates (2000) and Quené and van den Bergh (2004) for simulations supporting this assertion). This is particularly pertinent given the intended participant groups for the current thesis, as data from those with ASD often has to be dropped due to generalised inattention or increased error (Koldewyn, Whitney, & Rivera, 2010).

2.3 Reporting least-square means over arithmetical means

When reporting the results of analyses, it is typical to include descriptive statistics in the form of the mean and a value indicating variation within the sample (such as standard deviation or standard error). Least squares mean (LSM), also known as population or marginal means, are the group means after holding certain factors or covariates constant and are therefore of great use when inferential comparisons must be made. For fully-balanced designs, LSM is the same as the arithmetical mean. In simple analysis-of-covariance models, LSM are the same as covariate-adjusted means (Searle, Speed, & Milliken, 1980). In unbalanced factorial experiments, LSM for each factor mimics the main-effects means but are adjusted for imbalance. In the case of linear mixed models, the covariance matrix used for the calculation of LSM takes the random effects into account (Harvey, 1982). Least squares mean and standard error of the mean are the statistics used throughout this thesis to describe the outcome of linear mixed-effects models.

CHAPTER 3

The developmental trajectory of the contribution of low- and high-level cues to shape perception

This chapter examines how different cues to depth-defined slant are utilised in childhood and adulthood, with particular emphasis on whether the effects of modulatory feedback between higher-level information and low-level depth cues are different for children compared to adults. Twenty-eight adults and 61 children altered the height of an oval to match the retinal projection of a viewed shape in situations where low- (disparity, texture) and high-level (prior knowledge) cues to real shape (a slanted circle) were present. Both children and adults exaggerated circularity of the viewed shape when disparity or texture were present, though the texture cue induced a larger amount of shape constancy in children. Modulatory feedback was exhibited by both groups; when both the disparity and prior knowledge cues were available, the reproduced shape was closer to the retinal projection than when disparity was the only cue to real shape. A curvilinear developmental trajectory was exhibited for the effects of the texture cue and prior knowledge of real shape, but this differed depending on ability to make use of the disparity cue. It is concluded that although low-level and high-level information are utilised in similar ways by children and adults, the relative contribution of each type of information changes throughout development.

3.1 Introduction

In Chapter 1, the ambiguity of the images projected onto our retinae and their interpretation was discussed. Consider, for instance, the specific case of an ellipse on the retina – it could just as easily result from an obliquely-viewed circle as from a frontally-viewed ellipse. Generally, we do not perceive this ambiguity. In order to interpret the retinal image, the visual system must employ extra-retinal knowledge. This can however bias perception away from the veridical. This can be seen in the phenomenon of shape constancy where, regardless of an object's orientation, the shape of the object is perceived as the same. Take as an example a cup viewed obliquely. In this case the retinal projection of the lip of the cup forms an ellipse. Despite the apparent transformation, the viewer knows that the 'real shape' of the lip of the cup is circular. When asked to reproduce the retinal projection of the lip of the cup (i.e. the ellipse), shape constancy means that the observer is unable to accurately determine the true retinal projection and the subsequent reproduced shape is somewhere between the retinal projection and the real shape.

The developmental trajectory of shape constancy is uncertain. It has been shown to be present from as early as birth (Cook & Birch, 1984; Slater & Morison, 1985). From 3 years of age, children can perceive differences in projective shape. By 4 years of age, children can understand the relationship between projective and real shape (Osaka & Osaka, 1983; Pillow & Flavell, 1986). Beyond these milestones, however, no clear pattern has been observed. Studies have reported a linear increase in the effect of shape constancy with age (Kaess, 1971), a linear decrease with age (Vurpillot, 1964; Meneghin & Leibowitz, 1967) and a curvilinear trend, with a maxima in adolescence (Klimpfinger, 1933; Brault, 1962). These divergent results may be explained by the instructions given to the participants (Carlson, 1977; Lichte & Borresen, 1967); in some cases the children were instructed to replicate the real shape and in others the retinal projection. For the majority of experiments, the real and projected shapes differed, possibly allowing for ambiguity over which was supposed to be reproduced (Howard, Fujii, Allison, & Kirollos, 2014). This issue is compounded by the fact that there are a variety of cues which indicate real shape and can thus induce shape constancy.

Cues to real shape come in two different forms, low- and high-level. Low-level cues may be defined as the elementary features of a visual scene such as local contrast, orientation, colour, binocular disparity, spatial location and motion. This information is processed in the geniculostriate pathway from the retina through the lateral geniculate nucleus into the primary visual cortex (Hubel & Wiesel, 1962). Shape constancy encompasses a wide range of geometric situations, including the ability to recognise simple and complex two-dimensional objects irrespective of orientation, as well as the shape of a 3D object in different orientations, sizes, or distances (Howard, 2012). Simple shape constancy (such as that elicited by simple two-dimensional objects such as a circle or square) is commonly measured using paradigms which involve viewing of an inclined shape and subsequent matching of the retinal projection or real shape. Simple shape constancy is stimulated by indication of real shape (i.e. that the shape is viewed at a slant or incline) and early research into shape constancy surmised that low-level cues to real shape were entirely responsible for the phenomenon (Thouless, 1931b, 1932).

These early experiments by Thouless (1931a, 1931b, 1932) measured shape constancy by asking participants to select an ellipse that best matched the retinal projection of an observed inclined circle. When shape constancy was present, the frontal ellipse that was selected by the participant was intermediate between a circle and the retinal projection of the inclined circle. Thouless (1931b, 1932) manipulated the presence of two factors that might contribute to shape constancy; the prior knowledge that the stimulus was a circle, and ambient perspective cues; in an attempt to investigate whether prior knowledge alone was sufficient to provoke exaggeration of circularity. Participants were allowed to see that the object was a circle and it was then presented at a slant in a darkened chamber, allowing perspective cues to be eliminated. Under this condition, participants' reproductions regressed to the retinal image (i.e. they became more ellipse-like and less circular), allowing Thouless to conclude that shape constancy was caused exclusively by low-level cues.

The orientation or slant of an object may be demonstrated using monocular cues, that require input from a single eye, or binocular cues, which require input from both eyes. A number of different monocular cues to slant have been shown to induce shape constancy, including linear perspective and texture (Osaka & Osaka, 1983; Ropar & Mitchell, 2002; Howard et al., 2014), and are effective even when the stimulus is a 'perspective picture' and thus has no corresponding real shape (Hammad, Kennedy, Juricevic, & Rajani, 2008; Mastandrea, Kennedy, & Wnuczko, 2014).

Binocular viewing can induce strong shape constancy; due to the eyes' horizontal separation, binocular viewing introduces a difference (or disparity) in image location of an object seen by the left and right eyes. For a slanted object, absolute disparity increases across the surface and can be characterised as a disparity gradient. When care is taken to remove all monocular cues to 'real' shape (i.e. the stimulus is 'sparse'), binocular disparity can induce shape constancy, even when a participant does not explicitly know the 'real' shape of the object (Thouless, 1931b; Johnston, 1991; Hanada, 2005; Scarfe, Scarfe, Hibbard, & Hibbard, 2011; Hibbard, Goutcher, O'Kane, & Scarfe, 2012; Scarfe & Hibbard, 2013). Additionally, it has been observed that shape constancy is reduced when vision is blurred (which is deleterious to all low-level cues; Leibowitz, Wilcox, & Post, 1978).

The contribution of single low-level cues to shape constancy exhibits a developmental trajectory. Constancy induced by binocular disparity tends to peak at 4.5 years of age and declines thereafter (Meneghin & Leibowitz, 1967), whereas the efficacy of monocular cues such as texture appear to increase throughout childhood, plateauing in adulthood (Osaka & Osaka, 1983).

Judgement of depth-defined slant becomes increasingly accurate with the introduction of multiple low-level cues. This is because the visual system attempts to integrate sources of information into a single coherent percept of depth, which reduces uncertainty or ambiguity (Hillis et al., 2004). Hillis et al. (2004) demonstrated that this type of cue combination is automatic in adults by presenting pairs of virtual planes slanted about a vertical axis and asking participants to indicate which stimulus had the greater apparent slant, while independently manipulating two cues to slant, disparity and texture. Slant could be defined by a single cue presented in isolation (disparity or texture) or two cues at the same time (both disparity and texture). When both cues were present, disparity and texture could be congruent (i.e. the same degree of slant was depicted by both the disparity and texture cues) or incongruent (i.e. different amounts of slant were specified by the disparity and texture cues). With congruent combined cues, the participants' ability to judge slant was improved by having the two cues together over either one alone. Hillis et al. (2004) attribute this benefit to a reduction in sensory noise or uncertainty due to averaging of the two cues, leading to an optimal estimation of slant. Yet, when the two cues conflicted and signalled different slants, this averaging was shown to cause a reduction in precision by making the slant differences between the two stimuli appear less than when they were judged via either single cue. Participants could not help but average the cues, even when this made them worse at the task; Hillis et al. (2002) called this effect 'mandatory fusion'.

Although the combination of multiple cues to depth appears automatic in adults (Hillis et al., 2004; Alais & Burr, 2004; Ernst & Banks, 2002), children do not show the same accuracy gains when given access to multiple low-level cues to slant (Nardini et al., 2010). Nardini et al. (2010) repeated Hillis et al.'s (2004) study with children who were 6, 8, 10, and 12 years of age, also including a group of adult participants. Younger children did not show an accuracy gain when both cues were congruent compared to performance with their single best cue. Furthermore, the six-year-old children did not show the mandatory fusion that can be detrimental to adult performance in situations involving cue conflict; it appeared that they were able to evaluate the sensory estimate from each cue separately, and used the fastest available cue to make their decision. However, Nardini et al. (2010) found that 8-year-olds began to exhibit some degree of low-level cue combination and that mature sensory fusion, like that observed in adults, is established by the age of 12 years.

Therefore, if multiple low-level cues to real shape are available, for adults the perception of slant should become closer to veridical, increasing the effects of shape constancy beyond that elicited by a single cue. In the case of younger children (< 8 years of age) it would be expected that the presence of multiple low-level cues to real shape would not cause an increased effect of shape constancy. Instead, in cases where multiple cues are available, the amount of shape constancy elicited in younger children would be the same as in cases where only a single cue was available. As children mature, it is to be expected that they will begin to combine cues to slant and exhibit increased shape constancy in circumstances where multiple cues are present.

Information about real shape can also come in higher-level form. Once low-level visual features are consolidated, they are projected to higher levels of the cortex such as the inferotemporal and prefrontal areas, where sensory input is integrated with attention and task demands. Within the context of shape constancy, one possible high-level cue that enables the transition from the features or structure of the image on the retina to description of an object in the external world is direct knowledge *of* the real shape being viewed and its orientation relative to the observer.

Initial research by Thouless (1932) which minimised low-level visual cues found that prior knowledge of the real shape being viewed did not induce shape constancy. However, Taylor and Mitchell (1997) and Mitchell and Taylor (1999) were unable to replicate this finding. Instead, when asked to replicate the retinal projection of an inclined circle, both adults and children exaggerated circularity when they possessed knowledge of real shape. It is worth noting that Mitchell and Taylor (1999) found that the shape constancy induced by prior knowledge was greatest for children < 6 years of age; after this point, shape constancy followed a downwards-trending developmental trajectory across childhood.

Thus far, high- and low-level cues have been conceptualised as being processed in isolation. This is highly unlikely; neurons in the visual cortex receive feed-forward information (from the retina), feedback (from higher cortical areas) and have inputs from lateral connections (Lamme, Supèr, & Spekreijse, 1998). If both high- and low-level cues to slant are available, feedback connections could mean that high-level cues (such as prior knowledge of true shape) produce a qualitative change in perception by adjusting receptive field size and sensitivity to a low-level cue (such as disparity; I. Bülthoff, Bülthoff, & Sinha, 1998). This would provide an explanation for the mixed findings regarding the development of shape constancy. Although feedback projections appear anatomically mature by 2 years of age (Burkhalter, 1993), the development of high-level integration mechanisms throughout the brain have been found to progress throughout childhood until stabilisation in adolescence (Bitan, Cheon, Lu, Burman, & Booth, 2009; Hwang, Velanova, & Luna, 2010). It may therefore be the case that the modulatory effect of high-level information only affects low-level visual processing in adults. Additionally, participants may interpret the same set of instructions in different ways. This can change a participant's expectations, modulating the importance and/or salience of different features of the stimulus, thus affecting the strength and nature of low-level processing and modulatory feedback. This consideration is particularly important in the case of children, whose interpretation of instructions may depend upon their developmental level.

In summary, previous research regarding the developmental trajectory of shape constancy and the utilisation of cues to real shape across the lifespan has shown mixed results. The purpose of the current study was to examine the contribution of both top-down (induced by high-level cues such as prior knowledge) and bottom-up (low-level binocular and monocular cues to slant) mechanisms to shape constancy in both adults and children. I was particularly interested in: whether the effect of shape constancy changed with age; if the majority of children interpreted instructions similarly; whether children interpreted instructions in a different way to adults; and whether modulatory feedback, induced by prior knowledge of real shape, changed how low-level cues were processed in a different way for children compared to adults. I am unable to predict the direction of the magnitude of the effect induced by shape constancy as previous research has exhibited no clear pattern. Regarding the effect of modulatory feedback upon the processing of low-level cues, it is hypothesised that although children will show evidence of the same pattern of feedback, it will not be as strong as that observed in adults due to the relative immaturity of the relevant neural connections.

Two low level cues and one high level cue to slant were used in this study. The low level binocular and monocular cues to slant were the same used by classic studies of depth cue combination - binocular disparity and a texture gradient composed of Voroni cells (Hillis et al., 2004). The high level cue to slant used was prior knowledge of real shape. In order to assess the impact of a stereoscopic cue to slant on shape constancy, two measures were taken. First, all binocular conditions were also performed monocularly. Second, the stereoscopic ability of all participants was measured using a clinical test. Conditions where the presence of binocular disparity was manipulated were performed both with and without prior knowledge.

This chapter details the use of a shape constancy paradigm to explore low- and high-level cue utilisation and integration in TD adults and children. The adult and child data will be reported and discussed separately, after which the data will be brought together to examine any further age-related effects. This will be followed by a short general discussion.

3.2 Experiment 1: adults

The aim of the first experiment was to measure the degree of shape constancy elicited by a variety of low- and high-level cues in typically-developed adults. I was interested whether stereoacuity affected the utilisation of certain cues and the consequent amount of shape constancy elicited, and also as to how adults combined the different cues to real shape; i.e. if there was an additive effect of low-level cues as expected from classic cue-combination studies (Hillis et al., 2004), or evidence of feedback from high- to low-level cues.

3.2.1 Methods

3.2.1.1 Participants

Twenty-eight adult participants were recruited from the University of Nottingham School of Psychology's online database ('Research Participation Scheme'). All participants were students at the University and were given course credit in return for participation. The study was approved by the University of Nottingham School of Psychology Ethics Committee. All participants had normal or corrected-to-normal visual acuity, but presence of stereopsis was not required.

3.2.1.2 Measuring sensitivity to stereopsis (stereoacuity)

Stereoacuity was measured using the TNO stereoacuity test (18^{th} edition), which was designed by the Institute For Perception at the Netherlands Organisation for Applied Scientific Research (NL: *Nederlandse Organisatie voor* T*oegepast* N*atuurwetenschappelijk* O*nderzoek*; TNO) and is distributed by Laméris Ootech BV (`http://www.ootech.nl/`). The TNO stereotest uses an anaglyphic[1] technique and random-dot patterns to present a combination of gross disparity screening plates (approximately 2000 seconds of arc) and finer disparity 'test plates' (480 to 15 seconds of arc) which are able to measure stereoacuity threshold. The screening plates involve locating shapes on the two-dimensional plate surface, all of which contain a monocularly visible shape so that individuals who cannot detect the disparity do not know that they failed the test. The test plates contain no monocularly visible features and present discs with a 60-degree sector missing from each in one of four possible positions. The participant is asked to locate the missing sector of the disc.

3.2.1.3 Apparatus

A wooden chamber (30 × 39 cm) was constructed, with a matte black interior that was completely darkened when the lid was closed (see Figure 3.1). It had a viewing slot (1 × 12.5 cm) that allowed participants to see inside using both eyes (situated 12 cm from the top of the chamber and positioned centrally in the horizontal plane). A square frame (14 × 14 cm) was mounted centrally on a rod inside the box that traversed the interior of the box horizontally, and was situated 12 cm from the top of the box and 31 cm from the viewing slot. Inside the frame, there was a sheet of electroluminescent material that could be illuminated by passing an electric current through it. This gave the sheet a 'glow-in-the-dark' appearance. Four masks (13.5 × 13 cm) were constructed to place inside the frame; two had a circular window whose diameter was 7.6 cm (14 degrees of visual angle viewed from the aperture) and two had an elliptical window where the major axis was 7.6 cm (14 degrees) and the minor axis was 3.8 cm (7 degrees). Both circular windows were always presented at a slant of 60° away from the fronto-parallel plane, whereas the elliptical windows were presented at 0° of slant. The retinal image

[1] A means of displaying stereoscopic 3D by encoding each eye's image using filters of different (often chromatically opposite) colours, typically red and cyan. When anaglyph images (containing two differently coloured images) are viewed through spectrally opposed filters, each eye can see a different image. This creates a sensation of stereopsis when processed by the visual cortex.

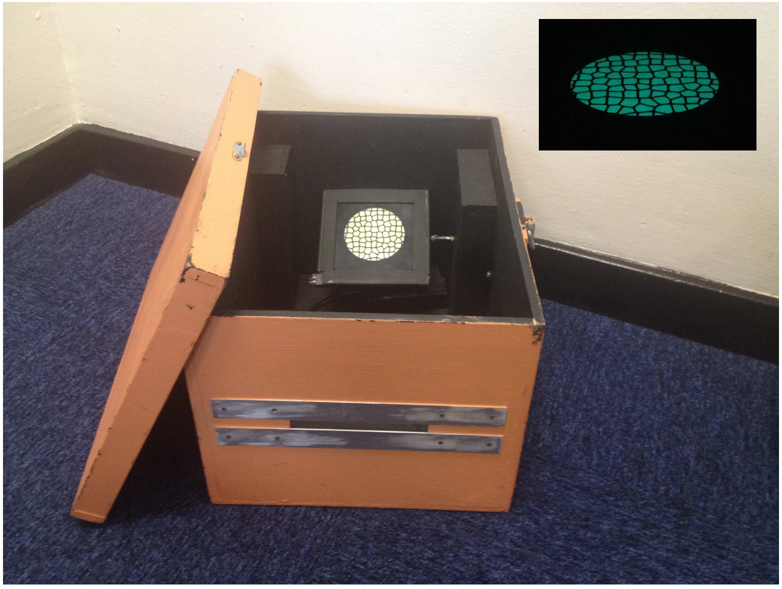


Figure 3.1: The chamber for housing the stimulus, in this case a slanted and textured circle. Inset is the view through the viewing aperture when the lid is closed - this is the 'retinal projection'

elicited by the slanted circle (the 'retinal projection') was therefore identical in dimension to the frontally-viewed ellipse window stimulus described above – both projected an ellipse with a vertical axis that was 50% of the horizontal. One of the circular windows included a Voroni pattern with an average of 64 cells and one of the elliptical windows had a perspective projection of the slant of the textured circular window. See Figure 3.2 for an illustration of the different types of mask.

A second box similar to the stimulus housing chamber was constructed to fit over a laptop computer which recorded participants' responses. Psychopy (Peirce, 2007, 2008) was used to display 'starting shapes' of either a white circle or ellipse on a black screen. Both starting shapes had the same major axis as the windows in the masks. The vertical axis of each starting shape was set to randomly jitter by up to 0.554 degrees at the beginning of each trial. A keyboard connected to the laptop extended outside the box to allow participants to adjust the vertical axis of the shape on the computer screen in steps of 0.1 cm.

3.2.1.4 Design

The design of the adult study included three within-subject factors: binocular disparity, texture, and prior knowledge of real shape. Each of these within-subject factors had two levels consisting of 'present' and 'not-present'. Additionally, all adult participants underwent each unique condition twice, once with the circular mask and once with the corresponding elliptical mask. Presence of binocular disparity was manipulated by means of an eye-patch. In the 'prior knowledge present' condition, participants knew

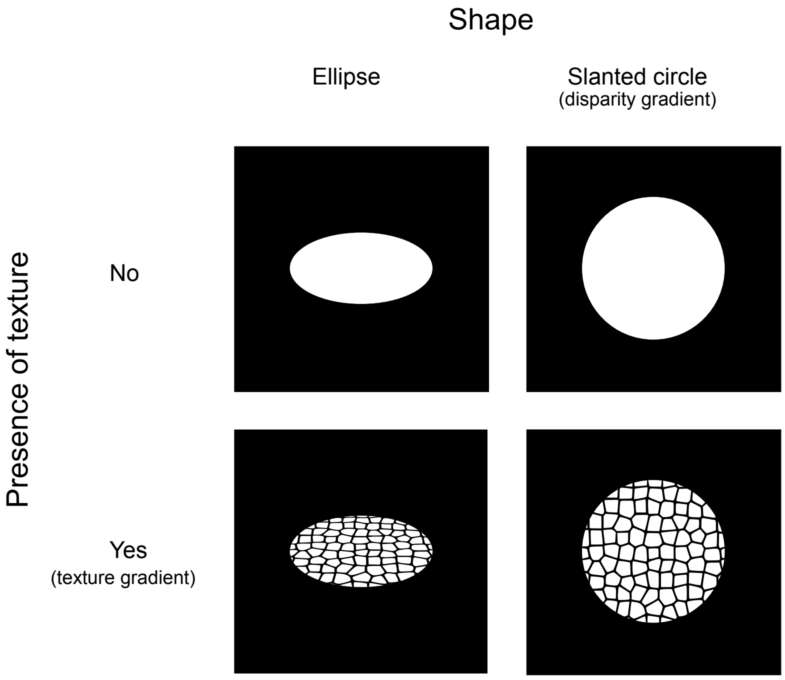


Figure 3.2: Slant could be specified by disparity, texture or both. Disparity was manipulated by monocular or binocular viewing of the stimulus. When working with children (see Section 3.3), masks with ellipse-shaped windows were used for catch trials in the first part of the experiment only.

that the stimulus was a slanted circle, but the chamber was darkened and only the stimulus was visible. The study was conducted in two parts: first, participants underwent all conditions involving the binocular disparity and texture cues. They were then given the a priori knowledge of the real shape, and were asked to complete two more conditions, one where binocular disparity was present and one where it was not. The presentation order of the conditions within first and last parts of the study was counterbalanced according to a balanced Latin square.

3.2.1.5 Procedure

No prior knowledge: Participants were invited to look into the closed box through the viewing aperture and saw the elliptical projection. The experimenter said 'I want you to make the shape on the computer screen the same as how the glow-in-the-dark shape looks through the hole'. The participant was encouraged to look back and forth between the glowing shape inside the box and the shape on screen while making adjustments. Once the participants had verbally indicated that they were satisfied with the shape they had created, their response was recorded and the next trial began. No feedback was given. For monocular trials, their non-dominant eye was covered with a patch.

Prior knowledge: Participants looked through the top of the opened box and saw that the circular mask was oriented at a slant. They then looked at the stimulus through the viewing slot. The experimenter said 'Inside the box is a shape that is a circle. Notice that when looking through the hole, the shape looks different, like an oval or ellipse'. The experimenter then encouraged the participant to look back and forth between the open lid of the box and the viewing aperture. She continued, 'Now I am going to close the box, and I want you to try to make the shape on the computer screen the same as it looks through the hole'. Participants proceeded as in the 'no prior knowledge' condition.

Participants performed a practice trial to ensure they understood how to change the shape presented on the laptop screen using the keypad. Subsequently, each person participated in all six conditions. Both the circular and elliptical masks were used in experimental trials, with 6 repeats of each condition for each mask shape (for a total of 72 trials).

Steps were taken to hide manipulations – when the mask was changed, a curtain was discreetly drawn between the box and the laptop. The participant was then directed to take part in a balloon-popping game, where they had to quickly press a coloured key which matched the colour of a balloon on screen in order to pop as many balloons as possible. Focusing on this task prevented participants from knowing which mask was being used at any one time.

3.2.2 Results

Stereoacuity (as measured by the TNO test) of the adult sample ranged from 0.008 - 2.778 degrees, with a median value of 0.025 degrees. Six adults had no measurable stereoacuity (were 'stereoblind', with a TNO score of 2.778 degrees).

For each unique combination of condition and shape, there were six attempts at replication of the height of the ellipse by each participant. The median height of the replicated ellipse was calculated for each participating individual for each unique combination of condition and shape; these values were used for the main analysis. Before the analysis was carried out, the data were screened for potential outliers using a criterion based on the Median Absolute Deviation (MAD; Leys et al., 2013). The threshold for rejection was set at 2.5·MAD (a moderately conservative value) based on the recommendations of Leys et al. (2013). The data points identified using this method (24 data points across 13 participants) were not retained in the subsequent analysis.

3.2.2.1 Prediction of degree of shape constancy using a linear mixed-effects model

Linear mixed-effects modelling was used to evaluate the extent to which stereoacuity and low- and high-level cues to real shape (i.e. slant) predicted the amount of shape constancy elicited. Predictors included in the model were stereoscopic ability (log-transformed mean-centred TNO scores), mask shape (ellipse, circle), disparity (present, not-present), texture (present, not-present), and prior knowledge of real shape (present, not-present), while the criterion variable was the vertical height of the reproduced ellipse. Sum contrast coding was used for the categorical variables.

Using the `mixed` function of the R package `afex` (Singmann & Bolker, 2014), an initial attempt was made to fit a model with a maximal random-effects structure justified by the design, as recommended by Barr et al. (2013) – this comprised of random intercepts and fully-crossed random slopes for participants. However, likely due to the relatively small number of observations, the model failed to converge using the maximal random effects structure. Iterative reduction of the model complexity, by removing random effects which explained zero variance in the model (as recommended by Bates, Kliegl, Vasishth, and Baayen (2015)), allowed for model convergence. In this parsimonious model, the random effects consisted of random intercepts for each participant and random slopes for the disparity predictor only. I report the standardised and unstandardised coefficient estimates, standard error, *t*-value, and Kenward-Roger approximated p-values (Halekoh & Højsgaard, 2014) in Table 3.1. Only the mask shape, disparity, and texture predictors and two-way interactions between presence of disparity and either shape or texture were statistically significant ($p < 0.05$).

3.2.2.2 Low-level cues to slant

In terms of the low-level cues to slant, presence of disparity (β = 0.213, p = <0.001) or texture (β = -0.142, p = <0.001) accounted for a significant proportion of variance; when either of these low-level cues were present, the effect of shape constancy increased and participants created a more circular ellipse.

There was also an interaction between presence of disparity and texture (β = 0.087, p = 0.038). Shape constancy was only induced to a significant degree by the texture cue when disparity was not present (t(261.495) = -3.938, p = <0.001, least-squares mean difference = -0.517 [SE = 0.131]). When both the texture and disparity cue were present, texture did not contribute to the perceived circularity of the viewed shape above and beyond that created by the disparity cue (t(262.335) = -0.928, p = 0.354, least-squares mean difference = -0.125 [SE = 0.135]), indicating there was no additive effect of multiple cues; Figure 3.3, Panel A.

3.2.2.3 Effect of mask shape

There was also a main effect of mask shape (β = 0.502, p = <0.001). The slanted circular mask induced a larger amount of shape constancy (i.e. the vertical axis of the replicated shape was larger; least-squares mean = 5.014 [SE = 0.103]) then the elliptical mask (least-squares mean = 3.88 [SE = 0.105]). This effect appeared to be

Table 3.1: Linear mixed-model analysis of adult participant characteristics and low- and high-level predictors that contribute to the perceived circularity of the viewed shape.

	β	B	B Std. Error	t value	p
Intercept		4.447	0.093	48.020	NA
Shape	0.502	0.567	0.047	11.970	**<0.001**
Disparity	0.213	0.240	0.051	4.718	**<0.001**
Texture	−0.142	−0.161	0.047	−3.414	**<0.001**
Stereo	−0.015	−0.017	0.103	−0.164	0.870
Prior	0.051	0.057	0.048	1.207	0.229
Shape:Disparity	0.233	0.263	0.047	5.537	**<0.001**
Shape:Texture	−0.012	−0.013	0.047	−0.284	0.777
Disparity:Texture	0.087	0.098	0.047	2.086	**0.038**
Shape:Stereo	0.056	0.063	0.053	1.192	0.235
Disparity:Stereo	0.030	0.034	0.057	0.592	0.557
Texture:Stereo	−0.024	−0.028	0.052	−0.534	0.594
Shape:Prior	0.057	0.065	0.047	1.366	0.174
Disparity:Prior	0.002	0.003	0.047	0.058	0.954
Stereo:Prior	−0.026	−0.030	0.053	−0.565	0.573
Shape:Disparity:Texture	0.035	0.039	0.047	0.833	0.406
Shape:Disparity:Stereo	0.025	0.028	0.053	0.529	0.598
Shape:Texture:Stereo	−0.056	−0.063	0.052	−1.221	0.223
Disparity:Texture:Stereo	0.013	0.015	0.051	0.292	0.771
Shape:Disparity:Prior	0.029	0.032	0.047	0.679	0.498
Shape:Stereo:Prior	−0.057	−0.064	0.052	−1.218	0.224
Disparity:Stereo:Prior	0.039	0.044	0.052	0.844	0.400
Shape:Disparity:Texture:Stereo	0.000	0.000	0.051	−0.006	0.995
Shape:Disparity:Stereo:Prior	0.033	0.038	0.052	0.722	0.471

driven by the presence of binocular disparity, as there was also a significant interaction between mask shape and viewing condition (see Figure 3.3, Panel B). Shape constancy was increased by the presence of binocular disparity only when viewing the slanted circular mask ($t(178.607) = 7.434$, $p = <0.001$, least-squares mean difference = 1.006 [SE = 0.135]) – binocular viewing had no effect on the percieved shape of the elliptical mask ($t(178.607) = -0.312$, $p = 0.755$, least-squares mean difference = -0.045 [SE = 0.143]).

3.2.3 Discussion

The presence of texture or disparity induced shape constancy in the adult sample, replicating previous findings (Howard et al., 2014; Thouless, 1931a; Hanada, 2005; Scarfe et al., 2011; Hibbard et al., 2012). However, the effects of these cues were not additive; this disparity-dependent effect of texture was unexpected as theories of cue combination predict that slant estimation becomes closer to veridical when multiple depth cues are

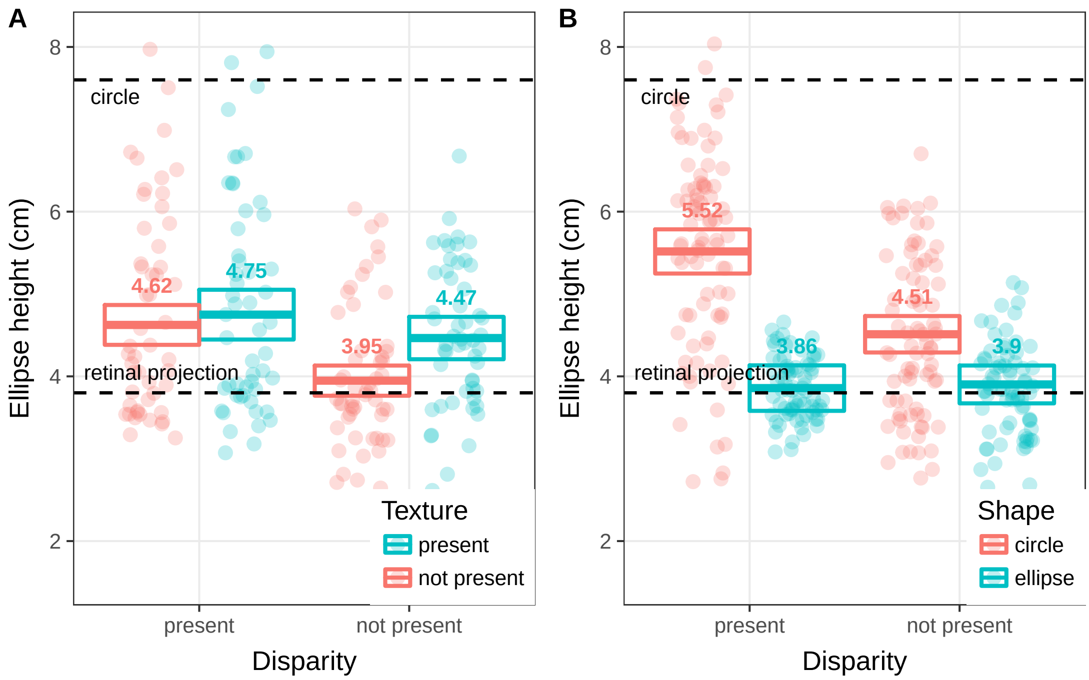


Figure 3.3: Mean height (± 95% confidence interval) of retinal image reproduction for adult participants with a two-way interactions between presence of disparity and texture gradient (Panel A) or presence of disparity and mask shape (Panel B). Thick bars and number annotations are mean values, bounding box is 95% confidence interval, and points are the scores of individual participants.

available (Hillis et al., 2004). If an observer's perception of slant was close to veridical, shape constancy could reasonably be expected to increase due to the resolution of shape ambiguity, which is characterised by the failure to discriminate shapes of objects which result in identical retinal images despite differences in orientation (i.e. 'Is this shape an upright ellipse or a slanted circle').

The disparity-dependent relative contribution of texture may be due to an overwhelming effect of stereopsis which maximised shape constancy and caused slant estimation to be close to veridical. The majority of the population can perceive disparities of at least 0.0278 degrees (Coutant & Westheimer, 1993), and even individuals who have minimal stereovision can perceive disparities of ~ 0.556 degrees as measured by the screening plates of the TNO stereotest (Fricke & Siderov, 1997). The relative disparity between the top and bottom of the slanted circular mask in the present study was very large – a difference of 4.322 degrees, meaning that all participants who were not stereoblind could effectively use binocular disparity as a cue to slant. This could also explain the absence of any effect of stereoacuity. Presentation of the stimuli on a computer screen would allow for much smaller amounts of disparity (and therefore disparity gradient) to be present, preventing the 'ceiling effect' seen here. This idea is supported by previous research which has used these types of digital stimuli, all of which found an additive effect of texture in adults even when disparity was present (Hillis et al., 2002, 2004;

Knill & Saunders, 2003; Nardini et al., 2010).

In contrast to the earlier findings of Taylor and Mitchell (1997), there was no main effect of or interactions involving prior knowledge of real shape in the current experiment. However, this finding is consistent with those of Thouless (1931a, 1931b, 1932), who concluded that shape constancy is not dependent on the subject's previous knowledge of the actual shape, instead being caused by presence of low-level cues to slant. Explanations for the absence of previously-observed effects notwithstanding, attention must be paid to the fact that the number of variables in the current experiment was much greater than in any previous work, with the presence of texture, disparity, and prior knowledge – as well as the shape of the mask – all being manipulated. The possible interference of the presence of any one of these variables in the replication of previous findings cannot be ruled out. Additionally, while the ratio of subjects to variables exceeded both the 5:1 rule-of-thumb proposed by Tabachnick and Fidell (2012) and the simulation-derived 2:1 ratio of P. C. Austin and Steyerberg (2015), the size of the sample falls drastically short of the $N > 50 + 8m$ (where m is the number of independent variables) recommended by S. B. Green (1991) for adequate statistical power.

These possibilities were addressed in the next experiment (by reducing the number of independent variables and increasing the number of participants), which aimed to explore the developmental trajectory of shape constancy.

3.3 Experiment 2: children

The aim of the second experiment was to measure the degree of shape constancy elicited by a variety of low- and high-level cues across childhood. In addition to the initial variables of interest set out in Section 3.2, I also wanted to explore if sensitivity to different low- and high-level cues to real shape changed with age with particular emphasis on whether there was a developmental trajectory of the effect of modulatory feedback induced by prior knowledge.

3.3.1 Methods

3.3.1.1 Participants

Sixty-one child participants were recruited from the University of Nottingham's 2013 Summer Scientist Week event. As for the adult version of this study, the child version of the study was approved by the University of Nottingham School of Psychology Ethics Committee. In addition to obtaining written parental consent for the child to take part in the study, verbal consent to participate was also given from the child themselves in line with the University of Nottingham's School of Psychology Ethics Committee Guidelines. See Table 3.2 for descriptives regarding the age and gender of the child participants.

Table 3.2: Child participant age breakdown

age band	mean age (years)	SD	n (female)
5	5.920		1 (1)
6	6.622	0.226	11 (6)
7	7.428	0.299	18 (11)
8	8.422	0.292	13 (7)
9	9.529	0.333	11 (6)
10	10.424	0.218	5 (1)
11	11.255	0.346	2 (1)

As previously, all participants had normal or corrected-to-normal visual acuity, but presence of stereopsis was not required. Sensitivity to stereopsis was measured using the TNO stereotest.

3.3.1.2 Stimuli

The stimuli used in this experiment were the same as those detailed in Section 3.2.1.3.

3.3.1.3 Design

The basic design of this experiment was the same as for Experiment 3.2, with three within-subject factors: binocular disparity, texture, and prior knowledge of real shape. Each of these within-subject factors had two levels consisting of 'present' and 'not-present'. However, in the child study the shape of the stimulus mask was circular for all experimental trials (see Section 3.3.1.4).

3.3.1.4 Procedure

The procedure was similar to that outlined in Section 3.2.1.5. It differed from the adult protocol in that only the slanted circular masks were used in the experimental trials when working with children, with 3 trials of each condition. To reduce the possibility of response bias, catch trials consisting of the four possible low-level cue configurations were replicated with the frontally-viewed elliptical mask in the first part of the experiment, with a single trial for each condition. This meant that for the child group, there were a total of 22 trials, including both experimental and catch trials. As for the adult experiment, steps were taken to hide manipulations[2].

3.3.2 Results

Stereoacuity (as measured by the TNO test) of the child sample ranged from 0.004 - 0.133 degrees, with a median value of 0.017 degrees. Unlike the adult sample, zero children qualified as 'stereoblind'.

The median height of the replicated shape was calculated for each child condition-wise. These values were then mean-aggregated. Outliers were identified as for the adult sample, and the data points identified using this method – 11 data points across 9 participants – were not retained in the subsequent analysis.

3.3.2.1 Prediction of degree of shape constancy using a linear mixed-effects model

Again, linear mixed-effects modelling was used to evaluate the extent to which stereoacuity, age, and low- and high-level cues to real shape (i.e. slant) predicted the amount of shape constancy elicited. Predictors included in the model were stereoscopic ability (log-transformed mean-centred TNO scores), age (mean-centered), squared age (mean-centered; this squared term was included to assess whether any developmental trajectory was linear or curvilinear), disparity (present, not-present), texture (present, not-present), and prior knowledge of real shape (present, not-present), while the criterion variable was the vertical height of the reproduced ellipse. Sum contrast coding was used for the categorical variables.

Using the `mixed` function of the R package `afex` (Singmann & Bolker, 2014), mixed-effects models were fitted which included the maximal random effects structure justified by the design, as recommended by Barr et al. (2013) – this comprised of random intercepts and fully-crossed random slopes for participants[3]. I report the standardised and unstandardised coefficient estimates, standard error, *t*-value, and Kenward-Roger approximated p-values (Halekoh & Højsgaard, 2014) in Table 3.3.

For the child data, only the disparity and texture predictors; two-way interactions between presence of disparity and texture, and age and texture, and age and prior knowledge; and three-way interactions between presence of disparity, squared/linear age and stereoscopic ability were statistically significant ($p < 0.05$)

[2]Children found the distraction game so engaging that they often thought it was the real object of study.

[3]Use of the maximal as opposed to parsimonious random effects structure (as was necessary for model convergence in the adult sample) did not change the pattern of results, so the maximal random effects were retained to increase the generalisability of the model.

Table 3.3: Linear mixed-model analysis of child participant characteristics and low- and high-level predictors that contribute to the perceived circularity of the viewed shape. Highlighted rows indicate main effects or interactions involving age that were no longer significant once the data from the two eldest children were removed.

	β	B	B Std. Error	t value	p
Intercept		5.500	0.141	39.070	NA
Disparity	0.989	0.390	0.077	5.086	**<0.001**
Texture	−1.107	−0.436	0.068	−6.378	**<0.001**
c.Age	0.086	0.034	0.163	0.209	0.836
sq.Age	−0.162	−0.064	0.067	−0.957	0.343
Stereo	−0.610	−0.240	0.430	−0.559	0.579
Prior	−0.338	−0.133	0.068	−1.962	0.056
Disparity:Texture	0.534	0.210	0.065	3.256	**0.002**
Disparity:c.Age	−0.103	−0.041	0.090	−0.453	0.652
Texture:c.Age	0.271	0.107	0.079	1.353	0.182
Disparity:sq.Age	−0.116	−0.046	0.036	−1.258	0.212
Texture:sq.Age	0.207	0.081	0.033	2.478	**0.017**
Disparity:Stereo	0.187	0.074	0.234	0.316	0.753
Texture:Stereo	0.876	0.345	0.210	1.644	0.107
c.Age:Stereo	1.656	0.653	0.498	1.310	0.196
sq.Age:Stereo	0.821	0.324	0.274	1.182	0.242
Disparity:Prior	0.310	0.122	0.065	1.878	0.064
c.Age:Prior	0.412	0.162	0.080	2.038	**0.047**
sq.Age:Prior	0.214	0.085	0.033	2.592	**0.013**
Stereo:Prior	0.158	0.062	0.208	0.299	0.766
Disparity:Texture:c.Age	0.061	0.024	0.075	0.320	0.750
Disparity:Texture:sq.Age	0.016	0.006	0.031	0.208	0.836
Disparity:Texture:Stereo	−0.214	−0.084	0.198	−0.425	0.673
Disparity:c.Age:Stereo	−0.722	−0.285	0.278	−1.024	0.310
Texture:c.Age:Stereo	−1.698	−0.670	0.253	−2.651	**0.011**
Disparity:sq.Age:Stereo	−0.346	−0.136	0.151	−0.906	0.368
Texture:sq.Age:Stereo	−1.042	−0.411	0.136	−3.027	**0.004**
Disparity:c.Age:Prior	0.020	0.008	0.076	0.106	0.916
Disparity:sq.Age:Prior	0.031	0.012	0.031	0.385	0.702
Disparity:Stereo:Prior	0.148	0.058	0.199	0.293	0.770
c.Age:Stereo:Prior	−0.682	−0.269	0.259	−1.037	0.308
sq.Age:Stereo:Prior	−0.216	−0.085	0.137	−0.624	0.537
Disparity:Texture:c.Age:Stereo	0.557	0.219	0.240	0.915	0.365
Disparity:Texture:sq.Age:Stereo	0.329	0.130	0.129	1.010	0.317
Disparity:c.Age:Stereo:Prior	0.547	0.216	0.250	0.862	0.394
Disparity:sq.Age:Stereo:Prior	0.138	0.054	0.131	0.414	0.681

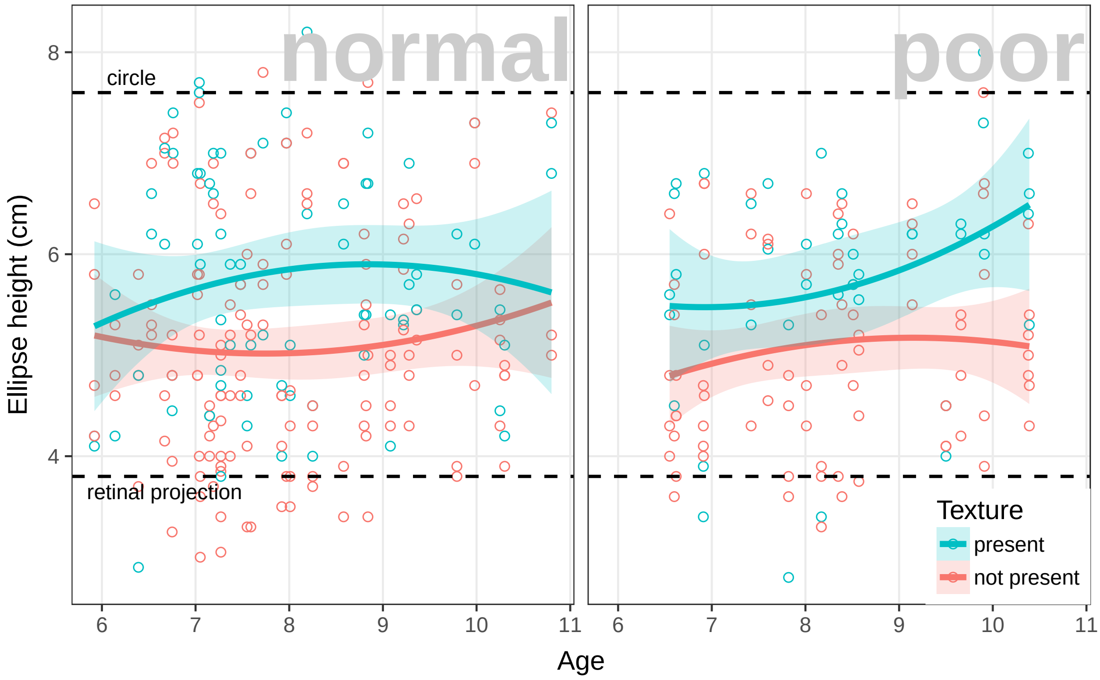


Figure 3.4: Curvilinear developmental trajectory (± 95% confidence interval) of retinal image reproduction with three-way interaction between presence of texture, squared age, and stereoscopic ability. Left panel depicts the relationship between age and texture for those with normal stereopsis, and the right panel does so for those with poor stereopsis.

3.3.2.2 Low-level cues to slant

As was seen in the adult data, presence of disparity (β = 0.989, p = <0.001) or texture (β = -1.107, p = <0.001) increased the circularity of the reproduced ellipse. There was an interaction between the texture and disparity cues (β = 0.534, p = 0.002), which mirrored the pattern present in the adult data with shape constancy only being induced to a significant degree by texture when disparity was not present.

3.3.2.3 The effect of age on perceived circularity

There were five interactions involving age for the child sample. However three of these – two-way interactions between squared age and either presence of texture or presence of prior knowledge, as well as an interaction been linear age and prior knowledge – did not remain significant when the data from the two 11-year-old children were removed (see Table A.1 in Appendix A.1.1). The two other interactions remained significant – these included an interaction between linear age, stereoscopic ability, and texture (β = -1.486, p = 0.012) and an interaction between squared age, stereoscopic ability, and texture (β = -0.868, p = 0.003). That the linear term is significant indicates that the extremum of the quadratic fit was not zero ; this makes sense, as both the linear age and squared age variables were mean-centered *around* zero. For this reason, only the interaction involving squared age will be discussed henceforth. Interactions involving two continuous variables are difficult to plot; I therefore split individuals into two groups based on TNO score to allow for easier depiction of this interaction. A curvilinear trajectory could be observed when texture was present for those with 'normal' (TNO score of $\leq$ 60 arc seconds) and 'poor' (TNO score of > 60 arc seconds) stereopsis. However, as can be seen in Figure 3.4, the trajectories were markedly different. For those with normal stereopsis, the amount of shape constancy elicited by texture first increased and then dropped as the children approached eleven years of age. This was not the case for those individuals with poor stereopsis, where the amount of shape constancy elicited by the texture cue continually increased as the children grew older.

3.3.3 Discussion

The findings in the child sample broadly reflected those of the adult sample, with the presence of disparity or texture increasing the circularity of the reproduced shape. Though the effects of these cues were not additive for the child sample, this is consistent with previous work which has observed that fusion of multiple cues to slant does not occur until age 12 (Nardini et al., 2010). The absence of an age-dependent effect of disparity is not surprising given that psychophysical thresholds in children 3 - 5 years of age are similar to those of adults (R. Fox, Patterson, & Francis, 1986), indicating that maturation of stereoscopic ability is nearly complete at this age.

The effect of texture followed a curvilinear developmental trajectory that differed depending on stereoscopic ability. That individual differences in stereopsis lead to divergent developmental trajectories is a novel and intriguing finding, but it remains to be seen if these differences even out by adulthood. Further work should investigate whether a reduction in ability to effectively utilise one cue affects the reliability weighting of individual cues and how this may change over the course of development.

3.4 Further analysis: adults vs. children

Thus far, the results of adult and child groups have been considered separately. Here, both age groups are brought together in a single model, to explore the possibility of more broad age-related differences.

3.4.1 Results

A two-tailed independent-groups t-test showed that log-transformed stereoacuity scores differed significantly between age groups; $t(30) = 2.464$, $p = 0.02$. Adults had a worse average stereoacuity of 0.064 degrees (SD = 0.004) whereas children had a better average stereoacuity of 0.023 degrees (SD = 0.004). This finding was likely driven by the relatively large proportion of the adult group who had no measurable stereoacuity (were 'stereoblind', with a TNO score of 2.8 degrees; 21.429%) compared to the child group, who had no individuals with nil stereoacuity. Upon removal of stereoblind individuals from the dataset (n = 6), log-transformed stereoacuity scores no longer differed between groups; $t(37) = -0.076$, $p = 0.94$. In the interest of maintaining equality between the age groups, the data from individuals who were stereoblind was discarded.

The median height of the replicated shape was calculated for each individual condition-wise (for adults, only the data for the circular stimulus mask was retained) and these values were mean-aggregated. Before the analysis was carried out, the data were screened for potential outliers on a per condition level using a criterion based on the Median Absolute Deviation (MAD; Leys et al., 2013). The threshold for rejection was set at 2.5·MAD (a moderately conservative value) based on the recommendations of Leys et al. (2013). The data points identified using this method – 14 [11 child] data points across 12 [9 child] participants – were not retained in the subsequent analysis.

3.4.1.1 Prediction of degree of shape constancy using a linear mixed-effects model

Linear mixed-effects modelling was used to evaluate the extent to which stereoacuity and low- and high-level cues to real shape (i.e. slant) predicted the amount of shape constancy elicited. For the final model, with the combined data of both age groups, predictors were stereoscopic ability (log-transformed mean-centred TNO scores), age group (adult, child), disparity (present, not-present), texture (present, not-present), and prior knowledge of real shape (present, not-present), while the criterion variable was the vertical height of the reproduced ellipse. Again, sum contrast coding was used for the categorical variables and the model included the maximal random effects structure.

I report the standardised and unstandardised coefficient estimates, standard error, *t*-value, and Kenward-Roger approximated p-values (Halekoh & Højsgaard, 2014) in Table 3.4. For the combined model, only the age group, disparity, and texture predictors; two-way interactions between presence of disparity and texture, presence of texture and age group, and presence of disparity and prior knowledge; and three-way interactions between presence of disparity, texture/prior knowledge and stereoscopic ability were statistically significant ($p < 0.05$).

3.4.1.2 Low-level cues to slant

In the aggregate model, presence of disparity (β = 0.235, p = <0.001) or texture (β = -0.166, p = <0.001) continued to increase percieved circularity. The same disparity-

Table 3.4: Linear mixed-model analysis of adult and child participant characteristics and low- and high-level predictors that contribute to the perceived circularity of the viewed shape.

	β	B	B Std. Error	t value	p
Intercept		5.229	0.093	56.068	NA
Disparity	0.235	0.359	0.047	7.569	**<0.001**
Texture	-0.166	-0.253	0.047	-5.358	**<0.001**
Group	-0.135	-0.206	0.093	-2.204	**0.030**
Stereo	0.046	0.070	0.287	0.242	0.809
Prior	0.026	0.040	0.047	0.852	0.397
Disparity:Texture	0.128	0.195	0.039	5.024	**<0.001**
Disparity:Group	0.046	0.070	0.047	1.475	0.143
Texture:Group	0.068	0.103	0.047	2.182	**0.032**
Disparity:Stereo	-0.146	-0.223	0.147	-1.517	0.132
Texture:Stereo	-0.137	-0.209	0.146	-1.433	0.156
Group:Stereo	-0.013	-0.019	0.287	-0.067	0.947
Disparity:Prior	0.069	0.105	0.039	2.698	**0.008**
Group:Prior	0.061	0.093	0.047	1.987	0.051
Stereo:Prior	-0.025	-0.038	0.144	-0.261	0.795
Disparity:Texture:Group	-0.024	-0.037	0.039	-0.959	0.339
Disparity:Texture:Stereo	0.186	0.283	0.120	2.367	**0.019**
Disparity:Group:Stereo	-0.131	-0.199	0.147	-1.356	0.178
Texture:Group:Stereo	-0.116	-0.177	0.146	-1.213	0.229
Disparity:Group:Prior	-0.039	-0.060	0.039	-1.530	0.128
Disparity:Stereo:Prior	0.213	0.325	0.121	2.682	**0.008**
Group:Stereo:Prior	-0.055	-0.085	0.144	-0.586	0.560
Disparity:Texture:Group:Stereo	0.143	0.218	0.120	1.819	0.071
Disparity:Group:Stereo:Prior	0.154	0.234	0.121	1.931	0.056

specific effect of texture as seen in both of the separate adult and child models was also observed (β = 0.128, p = <0.001).

3.4.1.3 Interaction of low- and high-level cues to slant

There was an absence of a main effect of prior knowledge of real shape. However, there was an interaction between the presence of disparity and prior knowledge (β = 0.069, p = 0.008). Pairwise comparison tests revealed that the nature of the relationship between presence of prior knowledge and amount of shape constancy depended upon whether the disparity cue was present. When prior knowledge and disparity were present, the perceived circularity of the viewed shape was reduced compared to when prior knowledge was not present (t(174.091) = 2.371, p = 0.019, least-squares mean difference = -0.288 [SE = 0.122]). However, when prior knowledge was the only cue to real shape, the perceived circularity of the viewed shape did not change (t(180.687) = -1.065, p = 0.288, least-squares mean difference = 0.129 [SE = 0.121]). In other words, prior knowledge caused the percept to shift *downwards*, towards the veridical

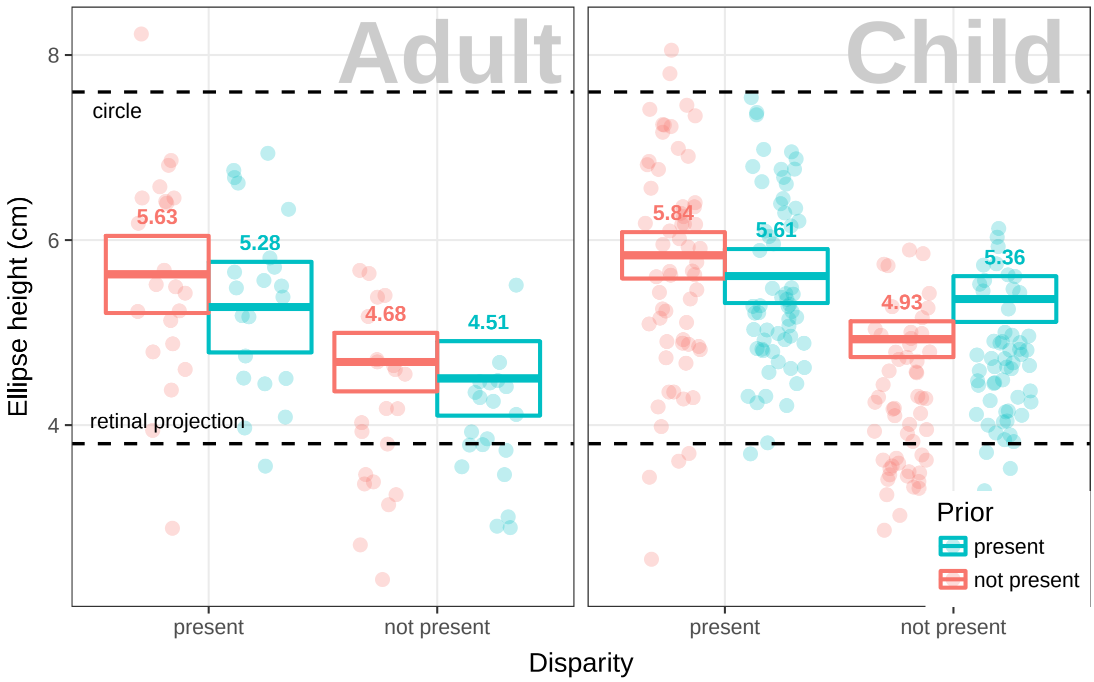


Figure 3.5: Mean height (± 95% confidence interval) of retinal image reproduction with a two-way interaction between viewing condition and availability of prior knowledge.

retinal projection, when disparity was present, but did not cause the percept to change when disparity was absent (Figure 3.5).

3.4.1.4 Participant characteristics and their effect on perceived circularity

A significant main effect of age group was observed (β = -0.135, p = 0.030); the reproduction of the retinal projection tended to be significantly closer to the veridical for the adult group compared to the child group. There was also an interaction between age group and presence of texture (β = 0.068, p = 0.032). When the texture cue was absent, there was no significant difference between adults and children in the height of the reproduced shape (t(69.513) = -1.179, p = 0.242, least-squares mean difference = 0.204 [SE = 0.173]). However, when the texture cue was present this induced shape constancy to a much larger degree in children compared to adults (t(78.119) = -2.578, p = 0.012, least-squares mean difference = 0.618 [SE = 0.24]), indicating that children appear to be more sensitive to monocular cues to slant than adults. This can be seen in Figure 3.6.

Although there was no main effect of stereoscopic ability in the model, it was involved in two interactions. For the first of these, an interaction between presence of disparity, texture and stereoscopic ability (β = 0.186, p = 0.019), it was found that individuals with worse stereoscopic ability (i.e. an increased TNO score) demonstrated a significantly increased effect of the texture cue when the disparity cue *was not present* compared to

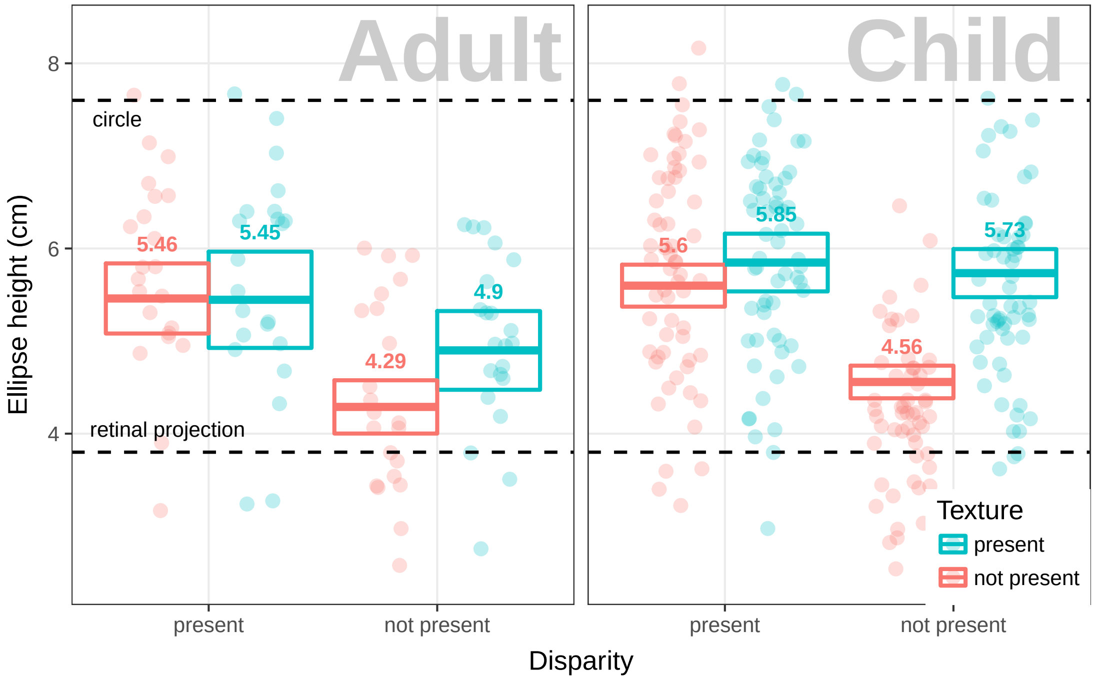


Figure 3.6: Mean height (± 95% confidence interval) of retinal image reproduction for adult and child groups with a two-way interaction between viewing condition and presence of texture gradient.

Table 3.5: Pair-wise comparisons of fitted slopes of three-way interaction between disparity, texture, and stereoscopic ability, using Tukey's HSD test with α = .05. *Note*. Slopes followed by the same letter are not significantly different to each other (Piepho, 2004).

Disparity	Texture	logTNO slope	SE	df	lower CL	upper CL	posthoc
not present	not present	-0.200	0.262	81.915	-0.721	0.321	a
	present	0.784	0.389	128.576	0.014	1.554	b
present	not present	-0.079	0.342	80.933	-0.759	0.601	a
	present	-0.227	0.471	106.107	-1.161	0.706	a

all other conditions. Table 3.5 shows descriptives and pair-wise comparisons at all levels of the disparity and texture cues. In the second interaction involving stereoscopic ability, I found an interaction between presence of disparity, prior knowledge and stereoscopic ability (β = 0.213, p = 0.008). Here, individuals with worse stereoscopic ability also demonstrated a significantly increased effect of the prior knowledge cue when the disparity cue *was not present* compared to all other conditions; see Table 3.6 for descriptives and pairwise comparisons.

3.4.2 Discussion

The aim of the present analysis, where the adult and child data sets were analysed together, was to ascertain if shape constancy changed with age, and whether the effect of

Table 3.6: Pair-wise comparisons of fitted slopes of three-way interaction between disparity, prior knowledge, and stereoscopic ability, using Tukey's HSD test with α = .05. *Note*. Slopes followed by the same letter are not significantly different.

Disparity	Prior	logTNO slope	SE	df	lower CL	upper CL	posthoc
not present	not present	-0.071	0.289	84.306	-0.645	0.503	a
	present	0.655	0.367	130.896	-0.072	1.382	b
present	not present	0.135	0.376	87.113	-0.613	0.882	a
	present	-0.441	0.446	103.763	-1.324	0.443	a

modulatory feedback, induced by prior knowledge of real shape, had an age-dependent impact on how a low-level cue to real shape was processed. I found that only the texture cue induced a larger amount of shape constancy for children compared to adults; for all other conditions there was no significant difference in responses between the adult and child groups. The data also showed that access to prior knowledge of real shape had a similar effect on children and adults. For both groups, prior knowledge of real shape interacted with binocular disparity causing a qualitative difference in perception. When disparity information was present, prior knowledge caused the reproduction to shift downwards, towards the retinal projection. Finally, the relative weighting of monocular cues to slant (texture and prior knowledge) was found to depend upon stereoacuity. I place these results within the context of models of cue combination and and discuss what they indicate about the maturation of feedback projections throughout the visual cortex.

3.4.2.1 Utilisation of single low-level cues in childhood and adulthood

Consistent with previous studies of shape perception, the presence of binocular disparity caused an increase in shape constancy for both adult and child participants (Hanada, 2005; Hibbard et al., 2012; Scarfe & Hibbard, 2013; Thouless, 1931b; Lim Lee & Saunders, 2011). The absence of an age-dependent effect of disparity is not surprising given that psychophysical thresholds in children 3 - 5 years of age are similar to those of adults (R. Fox et al., 1986), indicating that maturation of stereoscopic ability is nearly complete at this age. An increase in the size of the reproduced shape occurred alongside the presence of a texture gradient, but this effect was larger for children than for adults. I did not predict this age-dependent effect of texture; according to Osaka and Osaka (1983), the contribution of texture cues to shape constancy appears to develop as a linear function of age, not maturing until after 12 years. Similar results have been found for perception of texture-defined form (Parrish, Giaschi, Boden, & Dougherty, 2005; Bertone, Hanck, Guy, & Cornish, 2010). However, Nardini et al. (2010) reported that while older children placed a significantly higher weight on texture when it was a reliable cue to slant, younger children appeared to do so even when the texture cue was unreliable. This may mean that children re-weight monocular low-level cues to slant as they mature.

3.4.2.2 The effect of feedback induced by prior knowledge

Based on previous studies which used tasks involving linguistic judgement (Bitan et al., 2009) and target-directed visual attention (Hwang et al., 2010), I predicted that there would be an age-dependent effect of high-level information. No supporting evidence for this hypothesis was found in the current study – there was no significant difference between the adult and child age groups in the context of the prior knowledge cue. Instead, the modulatory feedback induced by this cue was the same across both age groups. When prior knowledge was not present, binocular disparity caused an increase in shape constancy. When the participant had prior knowledge of real shape, presence of binocular disparity caused a reduction in shape constancy (i.e. the height of the matched shape was closer to that of the retinal projection). It might be argued that this effect of prior knowledge occurred because the subjects initially found the instructions ambiguous until they were explicitly shown the difference between the retinal image and the inclined shape as part of the procedure for the second part of the experiment. However, if this were the case, it would be expected that the judgements of height would decrease for the monocular condition as well. Instead, when the low-level binocular cue was absent, introduction of prior knowledge did not cause a substantial shift in the reproduction, indicating that these findings were not due to simple misinterpretation of instructions or a general response bias. Therefore the presence of prior knowledge can be reasonably assumed to cause a change in the processing of low-level cues through feedback mechanisms regardless of an individual's stage of development.

Previous studies assessed feedback processes through asking participants to make perceptual judgements that required attentional involvement (for instance, inhibiting responses to conflicting stimuli; Bitan et al., 2009; Hwang et al., 2010). The data presented here go beyond this previous work by using a paradigm that was not dependant on attentional mechanisms. If all types of high-level information were dependent on the same underlying feedback mechanisms, the shape constancy induced by the disparity cue when prior knowledge was present would have decreased as the children aged and feedback connections became increasingly mature. However, for performance to be optimal in the task of the current study, participants needed to diminish the effect of low-level cues to shape constancy. This is directly opposed to the majority of other tasks which aim to quantify feedback, where introduction of a high-level cue *enhances* or increases likelihood of the response. That an age-dependent modulatory effect of high-level information (i.e. the interaction between prior knowledge and presence of the disparity cue did not differ with age) was not observed suggests that in the context of the current task feedback projections appear to show adult-like modulation by 5 years of age. However, this is a post-hoc observation and future examination of the developmental trajectory of feedback mechanisms using a variety of paradigms (such as attentional inhibition or facilitation) which require increased or reduced receptive field sensitivity would be valuable.

3.4.2.3 Shape constancy in children and adults

Although I did not find that shape constancy followed a overall developmental trajectory (see Section 3.3.2), it is interesting that the matched shape's height was closer to the real shape in the child group overall. One simple explanation is that perhaps the difference in judgements between the adult and child groups was not due a developmental change in shape constancy but rather to differences in the interpretation of the instructions (Howard et al., 2014). Participants in both groups generally understood that they were not simply being asked to generate a somewhat circular ellipse as their judgements closely approximated the projected shape in the no-cue-to-slant condition (no prior knowledge or texture, stimulus monocularly viewed). For all experimental conditions the real and projected shapes differed, possibly allowing for ambiguity over which was supposed to be reproduced (see Carlson, 1977; Lichte & Borresen, 1967; Howard et al., 2014). Perhaps the adult participants thought they were being asked to reproduce the retinal projection, while the child participants thought they were being asked to reproduce the real shape.

Upon inspection of the distribution of responses, it was found that only 1.515% of adult and 4.098% of child participant responses were 95% of the height of the circle or larger (humans are able to reliably detect deviations from circularity as small as 2% of aspect ratio; Regan & Hamstra, 1992). The distribution of responses for the adult and child groups both showed some degree of skewness (0.055 and 0.19 respectively), but these values were below the value considered 'substantial' (> 2; H.-Y. Kim, 2013). Additionally, if the child participants thought the task to involve reproduction of real shape, a negative skewness would have been expected. The pooled distributions were shown to be uni-modal according to Hartigan's dip test of uni-modality (Hartigan & Hartigan, 1985), indicating that the majority of participants interpreted the instructions similarly regardless of age. This suggests that the main effect of age group demonstrated above is genuine.

3.4.2.4 Participant characteristics

In this study, I obtained a measure of sensitivity to binocular disparity (stereoacuity) for each participant. While stereoacuity did not appear to directly affect sensitivity to either texture or prior knowledge in either the adult or child samples (though the latter group displayed an effect of texture that followed differing curvilinear developmental trajectories dependent on stereoacuity), the increase in power afforded by combining the data from both samples showed that stereoacuity moderated sensitivity to both low- (texture) and high-level (prior knowledge) monocular cues, as participants with worse stereoacuity demonstrated a significantly increased effect of shape constancy when these cues were present.

These data support suggestions by previous research that the weighting of different cues is largely observer-dependent (Zalevski, Henning, & Hill, 2007; Nefs, O'Hare, & Harris, 2010). Despite there being some interest in the role of the individual differences in depth cue utilisation and combination, the ramifications of variability in stereoacuity have not yet been explored (though it has been hypothesised that those with poor binocular vision may favour (or over-weight) monocular depth cues; Hahn et al., 2010; Hildreth & Royden, 2011. The presence of these individual differences indicates that current models of depth cue integration may not be applicable to the majority of the population, as subjects recruited in studies of cue combination typically have stereoacuity equal to or smaller than 40 arc seconds (Heron & Lages, 2012), whereas only ~ 80% of the general population are able to detect horizontal disparities of 40 arc seconds or less (Coutant & Westheimer, 1993; Zaroff et al., 2003; Bohr & Read, 2013; Bosten et al., 2015). Further work should investigate whether depth cue integration is optimal in observers with reduced stereopsis, and whether it affects the reliability weighting of individual cues.

3.5 Conclusions

Unlike previous work, the present study demonstrates that shape constancy does not follow a universal developmental trajectory; for certain cues to real shape a curvilinear trajectory is present, whereas sensitivity for others does not change with age. There was no difference in the effect of modulatory feedback upon low-level visual cues between adults and children. Finally, the (in)ability to utilise certain cues appears to re-distribute cue weightings towards favouring other, more reliable cues, regardless of age. The next chapter in this thesis will use a shape-constancy paradigm to investigate perception in participants with ASD, who are believed to be (a) unable to integrate high-level cues into their overall percept and (b) less sensitive to binocular disparity information.

CHAPTER 4

The influence of low- and high-level perceptual cues on shape constancy in typical and autistic individuals

Previous literature has suggested that individuals with autism fail to incorporate either low-level (perceptual) or high-level (conceptual) information when processing stimuli. However, individuals with autism are more likely to have difficulty utilising certain low-level cues to depth. A shape-constancy paradigm was used to measure the effect of prior knowledge of real shape and low-level depth cues (binocular disparity and texture gradient) and their integration upon shape judgement in 34 children with an ASD and 39 TD children. Both low-level cues induced shape constancy, and when presented together increased the apparent circularity of the viewed shape above that generated by either single cue. Prior knowledge effects depended upon the presence of binocular disparity; the reproduced shape was closer to the retinal projection when both cues were available. Individuals with ASD experienced less shape constancy overall but a group-wide reduction in ability to use the disparity cue was not responsible for this finding, indicating that the main effect of diagnostic group appears to be due to underlying neurological differences between the groups. This suggests that there is a need for more nuanced accounts of atypical perception in ASD, where both top-down and bottom-up strengths and deficits, as well as feedback mechanisms, are taken into consideration.

4.1 Introduction

INDIVIDUALS with ASD appear to perceive visual information differently to TD individuals, with reports of enhanced performance in tasks benefiting from a local processing style. This localised processing style has been the focus of three theories of autism, the weak central coherence theory (WCC; Happé & Frith, 2006; Happé & Booth, 2008), the enhanced perceptual functioning hypothesis (EPF; Mottron & Burack, 2001; Mottron et al., 2006) and the Bayesian hypo-prior theory (BHP; Pellicano & Burr, 2012). WCC tries to explain autistic perception using a top-down approach, proposing that people with ASD experience difficulties in the integration of information and context causing a bias towards using local-type lower-level information. EPF instead focuses on the enhanced low-level processing abilities of those with ASD and proposes that global processing is optional for this group and that individuals with autism are less likely to integrate low-level visual cues. BHP incorporates elements of both WCC and EPF, by suggesting that people with autism have enhanced local processing due to an attenuated effect of top-down input. BHP proposes that people with autism may perceive the world differently due to atypical priors. Priors are a bias towards perceptual attributes that are most prevalent (or 'likely') under normal viewing conditions. In general, priors act as a source of top-down information, improving the efficiency of neural computations by acting as constraints and reducing overall noise or error. However, priors can sacrifice accuracy (closeness to physical reality) for improved precision or reliability, causing perception to become biased towards the prior, away from the maximum likelihood based on only sensory information. It is thought that autistic perception may be more accurate due to 'hypo-priors' that result in fewer internal constraints on perception.

In line with the mechanisms of atypical autistic perception proposed by the two most prominent theories, WCC and EPF, much of the literature on this topic makes a distinction between top-down and bottom-up processes. Bottom-up processes are stimulus-driven, passive, or reflexive, rely primarily on sensory information and are generally framed as proceeding in a feed-forward manner from the retina to the visual cortex, with more complex analysis of input occurring at each stage of the visual pathway. Top-down processing is the information processing guided by higher-level processes, such as when we construct perceptions drawing on our experiences and expectations. Thus far, research on visual perception in ASD has largely investigated low-level (bottom-up) visual processing and the effect of high-level (top-down) influences in relative isolation from one another, searching for paradigms that demonstrate deficits in top-down processing or enhanced low-level perception.

One such example is a study by Ropar and Mitchell (2002), where they used a shape constancy paradigm to examine the ability of individuals with ASD to integrate top-down contextual information in the form of prior knowledge. In Ropar and Mitchell's study, participants were asked to reproduce the retinal projection of a shape under three different conditions – one where they viewed a frontally-oriented ellipse, and two where they viewed an inclined circle and had prior knowledge about the 'real' viewed shape. In one of the 'prior knowledge' conditions, an additional perspective cue was present in the form of vertically-oriented grating. Ropar and Mitchell (2002) found that when participants knew the 'real' shape, both ASD and TD participants increased the circularity of their reproduced shape, as predicted by shape constancy. However, in the ASD group this increase was significantly smaller. They concluded that perception in autism appeared less influenced by prior knowledge and was therefore less 'top down' or conceptually driven. It is important to note that Ropar and Mitchell (2002) did not include a condition where a circle was viewed obliquely in the absence of prior knowledge about the 'real' viewed shape.

Shape constancy can be elicited by both low-level visual cues and high level information. Unlike previous studies on the effect of prior knowledge on shape constancy (Mitchell & Taylor, 1999; Taylor & Mitchell, 1997; Thouless, 1931a), Ropar and Mitchell (2002) allowed binocular viewing of the stimulus. Due to the eyes' horizontal separation, binocular viewing introduces a difference (or absolute disparity) in image location of an object seen by the left and right eyes. For a slanted object, absolute disparity increases across the surface and can be characterised as a disparity gradient. Though Ropar and Mitchell (2002) took precautions in the prior knowledge only condition to remove monocular perspective cues which may have indicated the 'real' shape, it has been demonstrated that – for sparse stimuli – low-level cues to slant such as binocular disparity (Hanada, 2005; Hibbard et al., 2012; Thouless, 1931b) can induce shape constancy, even when a participant does not explicitly know the 'real' shape of the object. By allowing shape constancy to be elicited by both low- and high-level cues, Ropar and Mitchell (2002) cannot readily state that perception in autism is less-influenced by top-down information.

This leads to a second possible explanation of Ropar and Mitchell's findings; individuals with ASD may be less able to utilise binocular cues. Individuals with ASD show an increase in prevalence of a number of disorders that prevent binocular fusion. For instance, there is a 5 - 50% increased incidence of strabismus in people with ASD compared to the general population (Scharre & Creedon, 1992; Denis et al., 1997; Kaplan et al., 1999; Milne et al., 2009). Other visual deficits such as convergence insufficiency (Milne et al., 2009), and behaviours such as lateral vision (Coulter, 2009) are also more common in ASD populations. Strabismus, convergence insufficiency, and lateral vision all prevent binocular fusion, a necessary precursor of stereopsis or depth from disparity. Screening studies have also shown that ASD populations exhibit worse stereoacuity (the smallest amount of retinal disparity that results in stereopsis) compared to typical controls (Scharre & Creedon, 1992; Milne et al., 2009; Adams et al., 2010; Anketell et al., 2013; Coulter et al., 2013). Theoretically, if observers were unable to use binocular cues, shape constancy for sparse stimuli would diminish due to the lack of cues to slant. The findings of Ropar and Mitchell (2002), especially that shape constancy was reduced in those with ASD when prior knowledge was the only cue to slant, may be explained by the inability of this population to use binocular cues to slant rather than an inability to utilise contextual information in the form of prior knowledge. In such circumstances, the reproduced shape would be closer to the retinal projection. If poor binocular vision was the only reason for the reduced shape constancy in ASD found by Ropar and Mitchell (2002), introduction of a monocular cue to slant should theoretically increase the amount of shape constancy elicited (which was the case in Ropar and Mitchell's 'prior knowledge + perspective' condition).

A final possibility is that of atypical feedback connections in the autistic brain. As mentioned previously, the most prominent (neuro)cognitive theories of autism place a strong emphasis on ether reduced high-level (Happé & Frith, 2006; Happé & Booth, 2008; Loth, Gómez, & Happé, 2010; Mitchell, Mottron, Soulières, & Ropar, 2010) or increased low-level processing (Mottron & Burack, 2001; Mottron et al., 2006), an emphasis which is reflected in the research literature. However, low- and high-level processes are not easily dissociable; neurons in the visual cortex receive feed-forward information (from the retina), feedback (from higher cortical areas) and have inputs from lateral connections. Although there does seem to be a pervasive difference in modulatory feedback in ASD, the exact nature of this atypicality is yet to be determined as it has been reported to be both enhanced (Vandenbroucke, Scholte, van Engeland, Lamme, & Kemner, 2009), and reduced (Loth et al., 2010; Jachim, Warren, McLoughlin, & Gowen, 2015). Additionally, it has been observed that brain connectivity appears disrupted in ASD, with a deficit of long-range connections and an excess of short-range connections (Barttfeld et al., 2011; Samson, Mottron, Soulières, & Zeffiro, 2011; Wass, 2011). A lack of long-range connections between different visual areas could mean the integration of high- and low-level sources of information is less-developed, leading to differences between TD and ASD populations in the performance of some visual tasks. Within the context of shape constancy, feedback connections could have caused prior knowledge of true shape to produce a qualitative change in perception by adjusting receptive field size and sensitivity to disparity information. In the Ropar and Mitchell (2002) paper, it may have been the case that people with autism *are* influenced by prior knowledge but its modulatory effect is different for ASD and TD groups – for instance, prior knowledge may cause a decrease in shape constancy elicited by binocular disparity for participants with ASD but actually increase the efficacy of binocular disparity for the TD group.

The purpose of the current study was to examine the contribution of both top-down (such as prior knowledge) and bottom-up (binocular and monocular cues to slant) mechanisms to shape constancy in children who are TD or have an ASD. I was particularly interested in whether people with autism show more ‘accurate’ perception due to the lesser influence of top-down mechanisms or if the failure of shape constancy in this population was due to either an inability to utilise binocular cues to slant or to atypical modulatory feedback between high- and low-level information in the autistic brain. The monocular cue to slant used in this study was the same used by classic studies of depth cue combination - a texture gradient composed of Voroni cells (Hillis et al., 2004). In order to assess the impact of a stereoscopic cue to slant on shape constancy, two measures were taken. First, all binocular conditions were also performed monocularly. Second, the group of typically-developing controls included individuals with a range of stereoscopic ability.

4.2 Methods

4.2.1 Participants

Thirty-four children with an ASD (M_{age} = 13.909, 5 females) and 39 TD children (M_{age} = 13.825, 4 females) were recruited from schools and community contacts. Participant demographics are reported in Table 4.1. Parents or guardians of the children involved all gave informed written consent and the children themselves gave informed verbal consent. The study was approved by the University of Nottingham School of Psychology Ethics Committee.

Children with ASD had previously received an independent diagnosis of autism, autism spectrum condition or Asperger's syndrome from an clinician or paediatrician. This diagnosis was confirmed using parent reports of the Social Responsiveness Scale (SRS; Constantino & Gruber, 2005) and SAS (Social Aptitudes Scale; Liddle, Batty, & Goodman, 2008) in 28 participants. One scored just below the recommended cut off for autism on the Social Responsiveness Scale (SRS) (a T-score of 60; Constantino & Gruber, 2005) and six failed to complete it. These participants were all recruited through specialist schools for autism or through an autism unit at a mainstream school, both of which require a clinical diagnosis as part of their Statement of Educational Needs. On this basis I included these children in later analyses, despite the lack of diagnosis confirmation using the SRS or Social Aptitudes Scale (SAS). Parents of typically-developing children reported no developmental disorder in their children.

The children with ASD and TD children were matched in terms of chronological age ($t(52) = 0.241$, $p = 0.811$), verbal ability ($t(40) = -1.704$, $p = 0.096$) and nonverbal ability ($t(60) = -0.708$, $p = 0.481$).

All participants had normal or corrected-to-normal vision, but presence of stereopsis was not required. Stereoacuity was measured using the TNO stereotest detailed in Chapter 3, subsection 3.2.1.2.

4.2.2 Stimuli

The stimuli used in this experiment were the same as those used in Chapter 3.

4.2.3 Design

The basic design of the study was identical to that of Chapter 3. There was a single between-subjects factor, diagnostic group – this factor had two levels, 'ASD ' and 'TD'.

Table 4.1: Participant characteristics of the autism spectrum disorder (ASD) and typically-developing (TD) groups, including scores on the British Picture Vocabulary Scale, Second Edition (BPVS-2) and Ravens Standard Progressive Matrices (Ravens SPM) for both groups, and the Social Responsiveness Scale (SRS) and Social Aptitudes Scale (SAS) for the ASD group.

Measures	ASD	TD
N	34	39
Gender (*n* males : *n* females)	29:5	34:4
Age (years)		
Mean (SD)	13.909 (1.741)	13.825 (1.09)
Range	11.167 - 18.167	11.333 - 16.167
BPVS raw		
Mean (SD)	128.235 (27.778)	136.769 (9.672)
Range	75 - 165	109 - 155
Ravens SPM raw		
Mean (SD)	37.788 (9.34)	39.211 (7.268)
Range	16 - 51	23 - 51
SRS T-score		
Mean (SD)	90.643 (15.295)	
Range	56 - 117	
SAS score		
Mean (SD)	7.367 (5.696)	
Range	0 - 23	

4.2.4 Procedure

The procedure was identical to that outlined in Chapter 3 for the typical children (Section 3.3). This means that there were a total of 22 trials, including both experimental and catch trials.

4.3 Results

The projected shape was an ellipse with an aspect ratio of 2:1 along the horizontal axis. The median height of the replicated shape was calculated for each individual condition-wise and these values were aggregated. Before the analysis was carried out, the data were screened for potential outliers on a per condition level using a criterion based on the median absolute deviation (MAD; Leys et al., 2013). The threshold for rejection was set at 2.5·MAD (a moderately conservative value) based on the recommendations of Leys et al. (2013). The data points identified using this method – 15 [9 ASD] data points across 10 participants [5 ASD] – were not retained in the subsequent analysis.

Stereoacuity (as measured by the TNO test) ranged from 0.004 - 2.778 degrees, with a median value of 0.033 degrees. Twelve (8 ASD) were unable to pass the screening plates of the TNO test. These participants were deemed 'stereoblind' and a stereoacuity threshold of 2.8 degrees was recorded. A one-tailed independent-groups t-test showed that log-transformed stereoacuity scores differed significantly between groups; $t(63) = -1.786$, $p = 0.039$. Participants with ASD had an worse average stereoacuity of 0.074 degrees (SD = 0.008) whereas TD individuals had a better average stereoacuity of 0.032 degrees (SD = 0.006).

4.3.1 Prediction of degree of shape constancy using a linear mixed-effects model

Linear mixed-effects modelling was used to evaluate the extent to which participant characteristics and low- and high-level cues to real shape (i.e. slant) predicted the amount of shape constancy elicited. The predictors were stereoscopic ability (log-transformed mean-centered TNO scores), diagnostic group (ASD, TD), disparity (present, not-present), texture (present, not-present), and prior knowledge of real shape (present, not-present), while the criterion variable was the vertical height of the reproduced ellipse. Sum contrast coding was used for the categorical variables.

Using the `mixed` function of the R package `afex` (Singmann & Bolker, 2014), I fitted a mixed-effects model which included the maximal random effects structure justified by the design, as recommended by Barr et al. (2013) – this comprised of random intercepts and fully-crossed random slopes for participants. I report the standardised and unstandardised coefficient estimates, standard error, *t*-value, and Kenward-Roger approximated p-values (Halekoh & Højsgaard, 2014) in Table 4.2. Only the diagnostic group, disparity and texture predictors, and interactions between presence of disparity and texture, and presence of disparity and prior knowledge, were statistically significant ($p < 0.001$ in all cases but one, where $p < 0.05$).

4.3.2 Low-level cues to slant

In terms of the low-level cues to slant, presence of disparity (β = -0.249, p = <0.001) or texture (β = -0.327, p = <0.001) accounted for a significant proportion of variance; when either of these low-level cues were present, the effect of shape constancy increased and participants created a more circular ellipse. There was an interaction between presence of disparity and texture (β = -0.11, p = <0.001). Pairwise comparisons were made with *p* values adjusted using the Tukey method (Tukey, 1977), using the R package `lsmeans` (Lenth, 2014).

Both pairwise comparison tests revealed a significant positive association between presence of texture and perceived circularity of the viewed shape, but this relationship was

Table 4.2: Linear mixed-model analysis of TD and ASD participant characteristics and low- and high-level predictors that contribute to the perceived circularity of the viewed shape.

	β	B	B Std. Error	t value	p
Intercept		4.842	0.094	51.243	NA
Disparity	-0.249	-0.341	0.055	-6.241	**<0.001**
Texture	-0.327	-0.447	0.046	-9.659	**<0.001**
Group	0.144	0.197	0.094	2.087	**0.041**
Stereo	-0.133	-0.181	0.111	-1.631	0.108
Prior	0.023	0.032	0.042	0.754	0.454
Disparity:Texture	-0.110	-0.150	0.038	-3.925	**<0.001**
Disparity:Group	-0.023	-0.031	0.055	-0.570	0.570
Texture:Group	-0.030	-0.041	0.046	-0.887	0.378
Disparity:Stereo	0.026	0.036	0.065	0.557	0.580
Texture:Stereo	-0.015	-0.021	0.055	-0.374	0.710
Group:Stereo	0.022	0.029	0.111	0.265	0.792
Disparity:Prior	-0.168	-0.230	0.039	-5.967	**<0.001**
Group:Prior	-0.030	-0.042	0.042	-0.997	0.323
Stereo:Prior	-0.034	-0.046	0.050	-0.928	0.358
Disparity:Texture:Group	-0.029	-0.039	0.038	-1.026	0.307
Disparity:Texture:Stereo	0.065	0.089	0.046	1.925	0.057
Disparity:Group:Stereo	0.021	0.028	0.065	0.435	0.665
Texture:Group:Stereo	0.032	0.044	0.055	0.792	0.432
Disparity:Group:Prior	-0.005	-0.006	0.039	-0.168	0.867
Disparity:Stereo:Prior	0.025	0.034	0.046	0.734	0.465
Group:Stereo:Prior	-0.021	-0.028	0.050	-0.567	0.574
Disparity:Texture:Group:Stereo	-0.022	-0.030	0.046	-0.659	0.512
Disparity:Group:Stereo:Prior	0.000	0.000	0.046	0.005	0.996

stronger when the disparity cue was not present (t(164.242) = -9.882, p = <0.001, least-squares mean difference = -1.198 [standard error of the mean (SE) = 0.121]), compared to when the disparity cue was present (t(157.539) = -4.949, p = <0.001, least-squares mean difference = -0.587 [SE = 0.119]). That both pairwise comparison tests were significant indicates that texture still significantly contributed to the perceived circularity of the viewed shape when binocular disparity was present (i.e. there was an additive effect; Figure 4.1).

4.3.3 Interaction of low- and high-level cues to slant

I found no main effect of the high-level cue, prior knowledge of real shape. However, there was an interaction between the presence of disparity and prior knowledge (β = -0.168, p = <0.001). Pairwise comparison tests revealed that the nature of the relationship between presence of prior knowledge and amount of shape constancy elicited depended upon whether the disparity cue was present. When prior knowledge and disparity were present, the perceived circularity of the viewed shape was reduced compared to

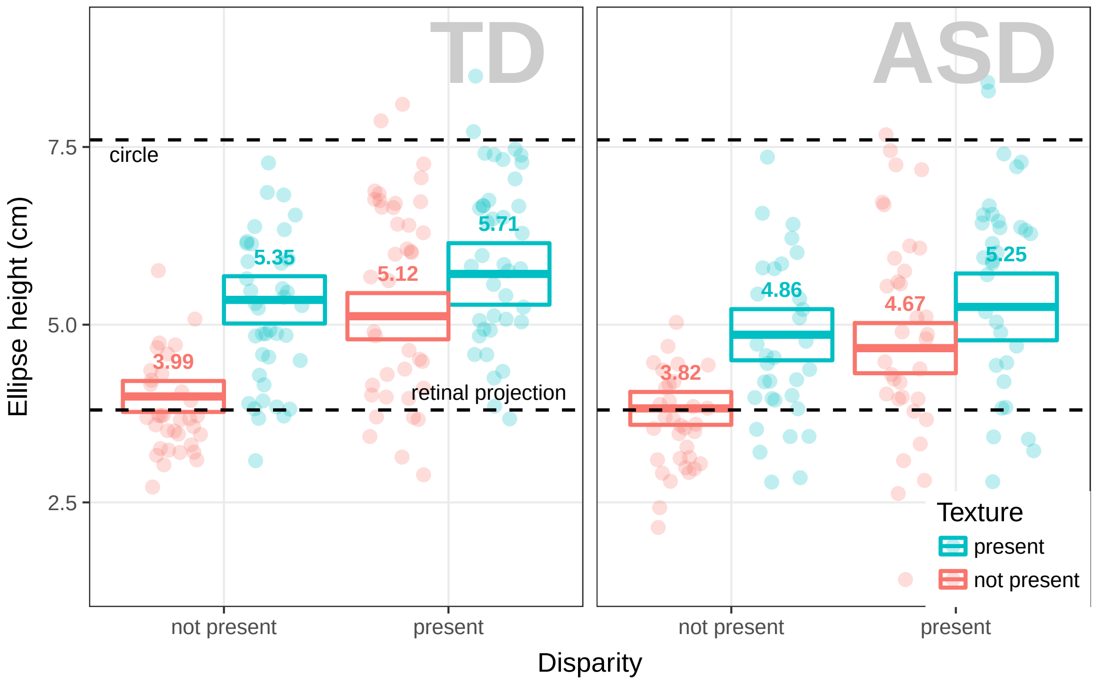


Figure 4.1: Mean height (± 95% confidence interval) of retinal image reproduction for typically-developing (TD) and autism spectrum disorder (ASD) groups with a two-way interaction between viewing condition and presence of texture gradient. Thick bars and number annotations are mean values, bounding box is 95% confidence interval, and points are the scores of individual participants.

when prior knowledge was not present (t(176.682) = 4.693, p = <0.001, least-squares mean difference = -0.527 [SE = 0.112]). However, when prior knowledge was the only cue to real shape, the percieved circularity of the viewed shape increased (t(182.845) = -3.455, p = <0.001, least-squares mean difference = 0.396 [SE = 0.115]). In other words, prior knowledge caused the percept to shift *downwards*, towards the veridical retinal projection, when disparity was present, but caused the percept to shift *upwards*, towards that of the real shape, when disparity was absent (Figure 4.2).

4.3.4 Participant characteristics and their effect on perceived circularity

There was a significant main effect of diagnostic group (β = 0.144, p = 0.041); the reproduction of the retinal projection tended to be significantly closer to the veridical for participants with ASD compared to those who were TD. This can be seen in Figures 4.1 and 4.2, where although the same pattern of results is seen across both diagnostic groups, the vertical height of the reproduced ellipse is reduced across all conditions for participants who had ASD. There was no main effect or interaction involving stereoscopic ability.

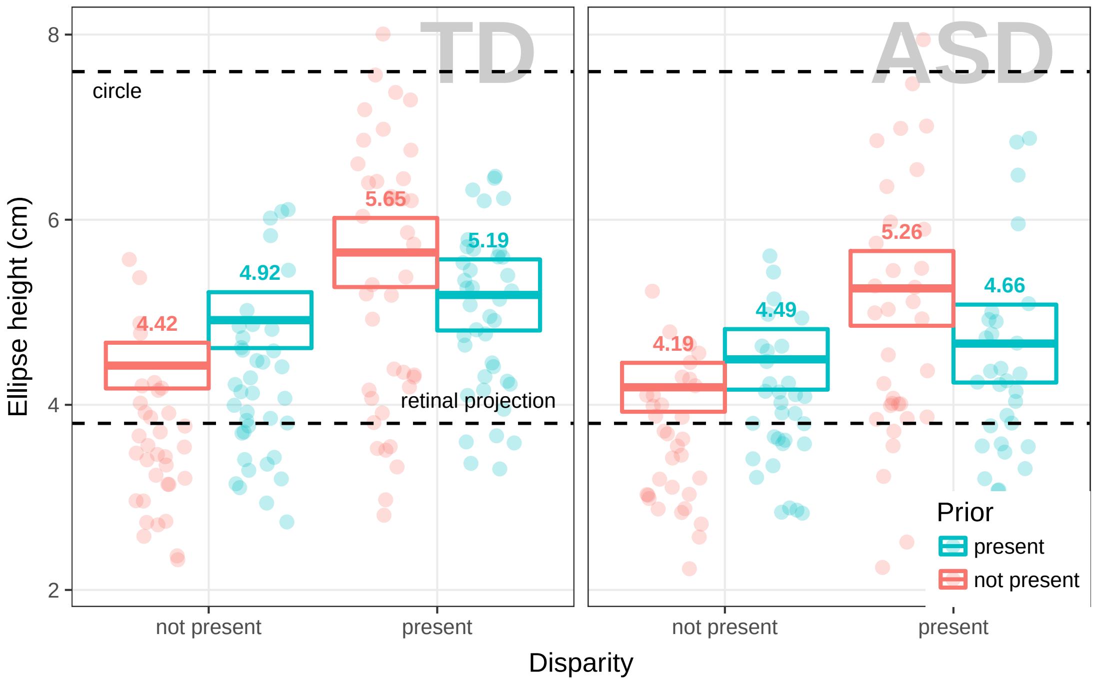


Figure 4.2: Mean height (± 95% confidence interval) of retinal image reproduction with a two-way interaction between viewing condition and availability of prior knowledge.

4.4 Discussion

This study investigated the contribution of top-down and bottom-up mechanisms to shape constancy in children with ASD and ability-matched TD children. A main effect of diagnosis was found – children with ASD tended to bias their responses downward, toward the retinal projection. There was no interaction between diagnosis and any other variable. I did not observe a main effect of, or any interactions involving, stereoscopic ability. I found that both low-level cues to slant (texture and binocular disparity) contributed to shape constancy. Finally, a main effect of prior knowledge of true shape was not found; instead, prior knowledge interacted with the presence of binocular disparity causing a qualitative difference in perception.

Consistent with previous studies of shape perception (Hanada, 2005; Hibbard et al., 2012; Thouless, 1931b; Lim Lee & Saunders, 2011), the presence of binocular disparity caused an increase in shape constancy. Texture increased shape constancy to a larger degree when the stimulus was viewed monocularly, but it still contributed to the perceived circularity when binocular disparity was present. This latter finding is consistent with theories of cue combination, which predict that slant estimation becomes closer to veridical when multiple depth cues (i.e. cues to slant) are available (Hillis et al., 2004). If an observer's perception of slant were close to veridical, shape constancy could reasonably be expected to increase due to the resolution of shape ambiguity, which is characterised by the failure to discriminate shapes of objects which result in identical retinal images despite differences in orientation (i.e. 'Is this shape an upright ellipse or a slanted circle?'). Similar to my findings, Lim Lee and Saunders (2011) observed that introduction of a stereoscopic cue improved three-dimensional shape discrimination even when rich monocular cues were available.

The presence of prior knowledge appeared to modulate the effect of the binocular disparity cue. When prior knowledge was not present, binocular disparity caused an increase in shape constancy. When the participant had prior knowledge of real shape, presence of binocular disparity caused a *reduction* in shape constancy (i.e. the height of the matched shape was closer to that of the retinal projection). It might be argued that this effect of prior knowledge occurred because the subjects initially found the instructions ambiguous until they were explicitly shown the difference between the retinal image and the inclined shape as part of the procedure for the second part of the experiment. However, if this were the case, it would be expected that the judgements of height would decrease for the monocular condition as well. Instead, judgements of height *increased* in this condition, indicating that these findings were not due to simple misinterpretation of instructions or a general response bias. This dichotomous effect of prior knowledge provides direct support for the notion that feedback connections in the visual area of the brain allow top-down information to influence the ongoing computation of a low-level visual feature, producing a qualitative change in perception. This interaction reflects the importance of considering both top-down and bottom-up mechanisms of visual processing.

I was particularly interested whether people with autism show more 'accurate' perception (and therefore less shape constancy) due to a reduced influence of high-level top-down cues to shape, or if the failure of shape constancy in this population was due to an inability to utilise binocular cues to slant. Unexpectedly, although the matched shape ratios of individuals with ASD tended to be closer to the retinal projection than for those who were TD, there were no interactions involving diagnosis. Perception in autism appears to be influenced by low- and high-level cues in the same manner, and to the same degree, as for typical participants.

In the only previously published study of the effect of prior knowledge upon shape constancy in autism, Ropar and Mitchell (2002) reported that although children with autism showed a substantial shape constancy effect due to a low-level perceptual cue, they exhibited a smaller increase in shape constancy due to prior knowledge compared to TD children. Based on the findings of the current study, it would appear that the apparent reduced effect of prior knowledge for the ASD group in Ropar and Mitchell (2002) may have been driven by an inability to use binocular disparity rather than a disinclination to integrate prior knowledge into the final percept. Although there was no interaction between stereoacuity or diagnosis and prior knowledge in my analyses, that participants with ASD had significantly worse stereoacuity than the TD group suggests that a reduced ability to utilise binocular cues in people with ASD could be responsible for the findings of Ropar and Mitchell (2002). The importance of considering the possibility of deficits in both top-down and bottom-up processing must be reiterated, especially when testing clinical populations that exhibit deficits in one or both processing mechanisms.

Overall, the current results suggest that the processing and integration of cues to slant is unimpaired in children with ASD. This finding is contrary to predictions from both the 'Weak Central Coherence' (Happé & Frith, 2006; Happé & Booth, 2008) and the 'Enhanced Perceptual Functioning' hypotheses (Mottron & Burack, 2001; Mottron et al., 2006), which predict that either people with autism will show a reduced effect of high-level cues such as prior knowledge of real shape, or will fail to integrate multiple low-level cues. My findings suggest that young people with ASD involuntarily integrate task-irrelevant low-level visual information, as well as high-level contextual information, and have intact feedback projections within the visual areas of the brain.

It is interesting that the matched shape's height was biased towards that of the veridical retinal projection in the ASD group. One simple explanation is that perhaps the difference in judgements between those with and without autism was not due to how the stimulus was perceived but rather to differences in the interpretation of the instructions (Howard et al., 2014). Evidently, participants in all groups generally understood that they were not simply being asked to generate a somewhat circular ellipse as their judgements closely approximated the projected shape in the no-cue-to-slant condition (no prior knowledge or texture, stimulus monocularly viewed). For all experimental conditions the real and projected shapes differed, possibly allowing for ambiguity over which was supposed to be reproduced (see Carlson, 1977; Lichte & Borresen, 1967; Howard et al., 2014). Perhaps participants with autism thought they were being asked to reproduce the retinal projection, while those without autism thought they were being asked to reproduce the real shape. Upon inspection of the distribution of responses, it was found that only 2.451% of ASD and 3.419% of TD participant responses were 95% of the height of the circle or larger (humans are able to detect deviations from circularity as small as 2% of aspect ratio; Regan & Hamstra, 1992). The distribution of responses for the ASD and typical groups both showed some degree of skewness (0.668 and 0.409 respectively), but these values were below the value considered 'substantial' (> 2; H.-Y. Kim, 2013). Additionally, if the TD participants thought the task to involve reproduction of real shape, a negative skewness would have been expected. The pooled distributions were shown to be uni-modal according to Hartigan's dip test of unimodality (Hartigan & Hartigan, 1985), indicating that the majority of participants interpreted the instructions similarly regardless of diagnostic group.

If people with ASD showed more accurate perception due solely to an inability to utilise binocular cues to slant, there would have been interactions involving stereoacuity and diagnostic group. The absence of interactions involving these two factors suggests that the overall reduction in shape constancy in the ASD group can not be attributed to poor stereopsis. It is likely that the main effect of group is due to the underlying neurological differences in autism, as opposed to a secondary cause. BHP proposes that people with ASD may perceive the world differently due to reduced, or attenuated, priors (Pellicano & Burr, 2012) that result in fewer internal constraints on perception. If this is the case, sensory signals in autism would be less biased towards what is suggested by visual or contextual cues and closer to physical reality (i.e. the 'sensory input'; Lawson, Rees, & Friston, 2014; Van de Cruys et al., 2014). This is exactly what the findings of the current study suggest – although autistic perception was influenced somewhat by both low- and high-level cues to slant, shape judgements were much closer to the retinal projection than the phenomenon of shape constancy would predict.

The current findings have important implications for studies addressing visual perception in ASD. As stated previously, research in this domain has tended to view low-level (bottom-up) vision and top-down influences on perception as separate entities. Often, experimental designs explicitly test one or the other of these domains in such a way that assesses the validity of one or both of the most established perceptual theories of autism (WCC and EPF). These theories lend themselves to conceptualising the lower and higher levels of vision as separate entities, constraining the number and scope of possible hypotheses. However, both empirical research and theories of autism are moving towards exploring whether people with ASD have intact feedback mechanisms or if they show overall reduced top-down modulation of low-level visual processes (Loth et al., 2010; Van Eylen, De Graef, Steyaert, Wagemans, & Noens, 2013; Jachim et al., 2015). My findings indicate that the feedback mechanisms involving the modulation of low-level input by high-level information are present, but that perceptual priors appear to be attenuated in individuals with ASD. As shown by the failure to replicate Ropar and Mitchell (2002), it is important to consider the possibility of engaging feedback mechanisms when designing experiments and formulating explanations of results.

4.4.1 Conclusions

To conclude, I have established that children with ASD are equally sensitive to low- and high-level cues to slant as typical children. Children with ASD showed an overall reduction in shape constancy, but diagnosis did not interact with any other factor. These results cannot be explained by the weak central coherence or enhanced perceptual functioning hypotheses, which both predict that people with autism will show a reduced effect of high-level cues such as prior knowledge of real shape. Instead, my results appear to be in line with Bayesian hypo-prior theory, which predict that overall the perception of people with ASD will be closer to physical reality. The findings of the current study suggest the need for more nuanced accounts of atypical perception in ASD, where both top-down and bottom-up strengths and deficits, as well as feedback mechanisms, are taken into consideration.

CHAPTER 5

Integration of metric and ordinal depth cues is automatic in individuals with autism spectrum disorder

Traditionally, research on depth cue integration has focused on the 'ideal observer', not taking into account the large degree of individual differences in sensitivity to stereopsis and relative cue-weighting. Studies which have explored cue integration in populations with developmental disorders have also failed to take into account these individual differences, even though there is commonly increased heterogeneity within such groups. In ASD in particular, it has been suggested that abnormal cue integration may be due to flattened perceptual priors or selective fusion. The present study assesses within-modality integration of ordinal (occlusion) and metric (disparity) depth cues in typical and autistic adults, while accounting for sensitivity to stereoscopic information. Results indicated that cue integration did not depend upon level of stereoacuity or autism diagnosis. Unlike previous work, people with ASD were found to automatically integrate conflicting depth cues, lending support to the idea that priors are intact in ASD and, furthermore, that cue integration is automatic in this population. It is concluded that while Bayesian priors may remain intact in ASD, there may be differences in the decision-making aspect of the 2AFC task used to measure cue combination.

5.1 Introduction

DESPITE the fact that the images projected onto the retinae are two dimensional, we experience the world as having three-dimensional structure. This is because these images contain a multitude of cues to depth, which, as summarised in Chapter 1 may be classified into two types; binocular cues, which require input from both eyes and monocular cues, which require input from only one eye. The integration of these cues is an important function of the visual system and by combining information from multiple different cues to depth, a single perceptual judgement can be made with less variability than if estimates were based upon single cues (Landy et al., 1995; Knill & Saunders, 2003; Hillis et al., 2004), resulting in an overall reduction of uncertainty and subsequent decrease in reaction time (RT) needed to make said judgement (Mather & Smith, 2004). Past research has suggested that the integration of different cues in modulated by the relative reliability of each cue, with more reliable cues exerting a greater influence over the combined estimates (Knill & Saunders, 2003; Alais & Burr, 2004). When cues are in direct conflict with one another (i.e. specify inconsistent depths), typical adults cannot help but average the cues, even in cases where this makes them worse at the task than relying on a single cue. This reduction in precision can be attributed to the effect of 'mandatory fusion' (Hillis et al., 2002). Children do not experience mandatory fusion and do not show the deleterious effect of incongruent cues – but subsequently they do not have increased accuracy in the presence of congruent cues (Nardini et al., 2010).

In autism, cue combination is typically assessed *across* sensory modalities, and cross modal integration appears reduced in ASD for social stimuli (see Marco, Hinkley, Hill, & Nagarajan, 2011 and Martínez-Sanchis, 2014 for a review of the literature). A single study has assessed uni-modal integration in autism, using a classic depth cue integration paradigm involving estimation of slant. Bedford, Pellicano, Mareschal, and Nardini (2016) investigated how young people with autism or who were typically-developing integrated binocular disparity and texture gradient information. They did this by asking them to judge whether two surfaces had the same or different degree of slant. The cues to depth-defined slant were presented either alone or together; when both cues were available they could be either congruent (in agreement, specifying the same amount of slant) or conflicting (specifying different amounts of slant). The paradigm used was identical to that used by Hillis et al. (2004) and Nardini et al. (2010), and is more thoroughly described in Chapter 3. Bedford et al. (2016) found that typically-developing adolescents' ability to judge slant was improved when both cues were available and they were congruent, compared to judgement of depth-defined slant using either cue alone. This benefit of combining sensory estimates is thought to be due to a reduction in uncertainty due to averaging (Hillis et al., 2002, 2004). When the cues were again presented together but conflicted and signalled different slants, this reduced the typically-developing adolescents' precision due to 'mandatory fusion' or averaging of the two cues. Those with an ASD were able to integrate disparity and texture cues when congruent (showing increased judgement precision), but unlike their typical peers, they did not show the effects of mandatory fusion. That is, when cues were conflicting, the thresholds of those with ASD were identical to those obtained for their single best cue. Bedford et al. (2016) termed this 'selective fusion' and concluded that the perception of individuals with ASD was more flexible and less governed by top-down feedback (see Chapter 4 and Smith, Ropar, and Allen (2015) for a discussion of the role of top-down processing in autistic perception).

Both Bedford et al. (2016) and studies of typical depth cue integration (see above) either explicitly state that their observers passed a clinical stereotest or state more generally that participants had no known stereo-vision problems/performed sufficiently on experimental tasks involving the use of stereo-vision for depth judgements[1]. However, individual differences are abundant in depth perception research (Hillis et al., 2002; Knill & Saunders, 2003; McKee, 1983), and it has been suggested that the combination and relative weighting of cues may be largely observer-dependent (Zalevski et al., 2007; Nefs et al., 2010). As mentioned in Chapter 1, one of the most poorly represented individual differences in depth perception research is the ability to perceive depth from disparity (stereopsis). Observers in depth cue combination studies typically have stereoacuity ≤ 40 arc seconds (Greenwald & Knill, 2009; Keefe, Hibbard, & Watt, 2011; Louw, Smeets, & Brenner, 2007; van Beers, van Mierlo, Smeets, & Brenner, 2011), or are said to have good/normal stereoacuity (Hillis et al., 2004; Knill, 2005; Lim Lee & Saunders, 2011; Welchman et al., 2005), whereas only ~80% of the general population have this level of stereoacuity (Coutant & Westheimer, 1993; Zaroff et al., 2003; Bohr & Read, 2013; Bosten et al., 2015). Though there is an emerging interest in the role of such individual differences in how depth cues are utilised and combined (Wilmer, 2008), the ramifications of differences in stereoacuity have not yet been explored (though it has been hypothesised that those with poor stereopsis may over-weight monocular depth cues; Hahn et al., 2010).

This is especially important in the case of developmental disorders, where an underlying cause shared between different developmental disorders must be differentiated from an effect stemming from a singular disorder. As pointed out in Chapter 1, individuals with autism are more likely to have poor binocular fusion and worse stereoacuity due to an increase in prevalence of a number of vision disorders. It may be that the ‘selective fusion’ observed in ASD is a ramification of limited stereopsis (which occurs in a number of developmental disorders; Atkinson et al., 2001; Langaas et al., 2010) rather than a consequence of diagnosis, meaning that this pattern of results may be seen more generally in those with poor stereoacuity. Bedford et al.’s (2016) results lend support to this idea; participants with ASD appeared to have different cue weighting compared to TD, whereas those with ASD were less sensitive to disparity and appeared to utilise the texture cue to a greater extent. This mirrors the findings detailed in Chapter 3, where an inability to use binocular information appeared to cause re-distribution of cue weightings towards monocular cues in TD children and adults.

Typically, studies of depth cue integration assess depth thresholds and/or sensitivity for both single and multiple cues in order to assess the degree to which cue combination increases precision. To this end, it is assumed that different cues to depth must be in the same units for meaningful combination to take place (Landy et al., 1995) and the majority of research reflects this, focusing upon the combination of binocular disparity and a metric monocular cue such as texture (Hillis et al., 2004; Knill, 2005; Zalevski et al., 2007; Nardini et al., 2010; Bedford et al., 2016), or motion parallax (Hildreth

[1]Under-reporting of visual- and stereo-abilities in studies of binocular vision is a known issue, with only 21% of studies reporting stereo-screening through means of a standard stereo test (Heron & Lages, 2012).

Figure 5.1: An example of occlusion. The interposition of the tree trunk and elephant make it clear even without stereoscopic cues that the elephant is behind the tree. Picture reproduced with permission (Hinton, 2014).

& Royden, 2011). However, ordinal cues are also well-suited to assessing how multiple cues are integrated into the final percept.

One such example is that of occlusion or interposition, which occurs when one object fully or partially hides another from view (see Figure 5.1 for an example). It is arguably one of the most reliable cues to depth, since it has an efficacy which does not attenuate with distance (Cutting & Vishton, 1995). Presence of occlusion has been demonstrated to hasten the processing of disparity and improve accuracy of depth judgements (Gillam & Borsting, 1988); it is though that this is due to monocular regions, occurring at the boundaries of opaque objects, which are unable to be binocularly matched and are therefore highly reliably signatures of depth discontinuities. Such monocular regions can be used to estimate both the sign and magnitude of the depth of the occluding surface (Tsirlin, Wilcox, & Allison, 2010). Moreover, when occlusion conflicts with other depth cues there is reduced reliance on disparity (Braunstein, Andersen, Rouse, & Tittle, 1986), and can interfere with perception of depth overall (Schriever, 1924; Stevenson & Körding, 2009). The importance of the structural inference that occlusion affords have been noted previously (Nakayama & Shimojo, 1990; Tsai & Victor, 2000; Harris & Wilcox, 2009); it is thought to aid in the perception of depth by providing hard constraints, where certain depth configurations are ruled out (Nakayama & Shimojo, 1992).

As well as allowing us to examine the consequences of individual differences in stereoacuity, use of an ordinal cue also is also useful in probing the use of learned information. While an ability to process occlusion has been demonstrated in children as young as three months of age (Baillargeon & DeVos, 1991), it is thought that *understanding* of occlusion and subsequently depth order can only occur once the child has internalised this relationship as a perceptual prior (which occurs at around 8 – 9 months of age; Bremner, Slater, & Johnson, 2014). This occlusion-as-a-perceptual-prior has been related to cue combination by Gillam, Anderson, and Rizwi (2009), who suggests that the influence of ordinal depth cues upon the perception of metric depth are learned and act as priors within the visual system, allowing possible depth percepts to be constrained.

Given the paucity of research regarding uni-modal cue combination in autism, a paradigm involving occlusion would be particularly useful in probing the shape of the perceptual prior in ASD, especially considering the strength and relative reliability of this cue. In Chapter 4, it was proposed that the pattern of results may be explained by individuals with ASD having hypo-priors, where the perceptual priors which modulate perception away from the raw sensory input are flattened (Pellicano & Burr, 2012), causing persons with ASD to perceive the world around them as closer to the raw sensory input. If there is indeed a weaker influence of priors upon overall percept, those with ASD would be expected to experience an attenuated affect of occlusion. This notion is substantiated by the observation that the effective depiction of occlusion is protracted in ASD (Hodgson & McGonigle-Chalmers, 2011).

However, it has previously been shown that reliance on occlusion is especially strong in those with poor stereopsis (Braunstein et al., 1986). If the reliance upon monocular cues in individuals with ASD is indeed due to a reduction in stereopsis rather than ASD itself, it would be expected that thresholds would be increased to a greater degree for all individuals with poor stereopsis (not just those with ASD) compared to those with intact stereopsis in cases where the occlusion cue conflicts with disparity information.

Yet, if we attempt to disentangle the root cause for abnormal cue utilisation and integration in ASD, it must be considered that an occluded area can also be used as a reference plane. Perception of depth from disparity is largely dependent upon the relative disparities in a stimulus. The presence of a reference plane could provide extra sources of relative disparity (Petrov & Glennerster, 2006; Andrews, Glennerster, & Parker, 2001) and previous studies have shown that relative disparity cues can influence a number of different aspects of binocular processing such as perceived depth and threshold, even in cases where the relative disparity information was irrelevant to the task (Mitchison & Westheimer, 1984; Mitchison & McKee, 1987). Therefore in the current study, in order to disambiguate the use of occlusion as a perceptual prior and as reference figure, I included a control condition where a *non occluded* reference figure was present. If individuals with ASD were able to utilise the occlusion prior, the thresholds would be expected to be lower for the congruent-occlusion-present compared to the reference-present condition, whereas if they were simply using a reference-plane strategy the thresholds of the congruent occlusion vs. reference conditions would be expected not to differ.

Finally, previous research has demonstrated that there are at least two mechanisms underlying the processing of disparity; one for ‘crossed’ disparities lying nearer than the fixation point, and another for ‘uncrossed’ disparities which lie further from fixation (van Ee & Richards, 2002). In spite of this, there is very little published data on the role of the *sign* of stereoscopic information in cue combination. Using luminance and disparity cues, it has been demonstrated that when the depth sign of these cues conflict (i.e. the luminance and disparity cues do not specify the same depth), any percept of depth is essentially nullified (Likova & Tyler, 2003). However, Kerrigan and Adams (2013) observed that when the disparity sign of two cues conflict, it is deleterious only for certain cue configurations (in their example, the disparity sign of highlights is important for gloss perception for concave objects, but does not appear important in the case of convex stimuli). As mentioned above, the vast majority of research on depth cue combination uses paradigms involving surface slant induced by binocular disparity and a monocular cue such as texture. Commonly depicted at a fronto-parallel slant, stimulus configurations have included the mid-line of the slanted surface being at the horopter (i.e. slanting about the axis of the CRT screen or other viewing surface upon which it is displayed, causing the surface to exhibit both crossed and uncrossed disparities; Hillis et al., 2002, 2004; Murphy, Ban, & Welchman, 2013) and the surface being presented behind the horopter (i.e. at uncrossed disparities which appear "as if they were behind the monitor"; Nardini et al., 2010, supplementary information Materials and Methods, p. 1; Bedford et al., 2016). Therefore, the majority of depth cue combination studies are unable to, or simply have not, investigate(d) the role disparity sign might play in the utility of other cues to depth.

In the present study, I assess the effect of occlusion information, which is conflicting or congruent with disparity information, on the precision of relative disparity threshold in adolescents and adults who are TD or have an ASD. In order to disambiguate whether any observed effects are due to occlusion, or simply use of the occluded figure as another source of relative disparity, configurations were also used that contained a non-occluded reference figure. In addition to impact of diagnosis, I was also interested in the modulatory affect of both stereoacuity and disparity sign and whether these would cause differences in the utilisation of the occlusion cue. For this reason, participants across both groups were chosen such that they presented with a range of stereoscopic ability (no specific stereo-threshold was necessary for inclusion in the study, unlike most other cue combination research). In order to assess the effect of disparity sign, both crossed and uncrossed disparity threshold were estimated for all conditions. There are three possible patterns of performance that could be shown by the ASD group (1) occlusion is used as a prior, disparity thresholds and reaction times are reduced when occlusion is congruent and increase when it is conflicting; (2) occluded object is used as a reference plane, threshold and reaction time is reduced whenever figure is present compared to TD participants, who will only show lower thresholds in conditions involving no cue conflict (3) inclusion of an occluded or reference figure has no effect on thresholds or reaction time. It is also predicted that, regardless of diagnostic group, presence of congruent occlusion will decrease threshold and reaction time for those with poorer stereoacuity.

5.2 Method

5.2.1 Participants

Twenty-seven adults and adolescents with ASD and 27 TD participants were recruited from colleges, autism provisions, and community contacts in the greater Nottinghamshire area. Individuals with an ASD had previously received an independent clinical diagnosis of autism or Asperger's syndrome according to the criteria set out in the International Classification of Diseases-10 (WHO, 2010). TD participants reported no diagnosed developmental conditions. All participants completed the Adult Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) and those in the ASD group were administered the Autism Diagnostic Observation Schedule – Module 4 (ADOS; Lord et al., 2000).

All participants in the ASD group who took part in this study scored above threshold on at least one of these measures, with the exception of one individual whose data was not included in the analysis (this participant was also unable to perform the baseline task, see below). All participants with ASD except for two met the cut-off score on the ADOS, with 12 participants obtaining the 'autism spectrum' classification and a further 13 obtaining the more severe 'autism' classification. Of the ASD group, thirteen individuals did not reach the 32-point criterion on the AQ (as recommended by Baron-Cohen et al., 2001), but this number was reduced to 7 when using the 26-point threshold suggested by Woodbury-Smith, Robinson, Wheelwright, and Baron-Cohen (2005). Four TD adults were removed from the dataset as their AQ scores surpassed the 32-point threshold. Finally, data from five ASD participants was not included in the analysis as these individuals were unable to perform the baseline task, see Section 5.2.5.

Twenty-two ASD and 23 TD participants were therefore included in the final dataset. Participant demographics are reported in Table 5.1. All participants had normal or corrected-to-normal vision, but presence of stereopsis was not required. An initial measure of crossed stereoacuity was obtained using the TNO stereotest - see Chapter 3, subsection 3.2.1.2 for more detail.

5.2.2 Apparatus

The stimuli were generated and presented using MATLAB, with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007) and Palamedes (Prins & Kingdon, 2009) software packages. Stimuli were displayed on a Sony Viewsonic P225f CRT monitor that had been previously calibrated using a PR655 spectro-photometer (Photo Research, Chatsworth, CA, USA), so there was a linear relationship between voltage and luminance. A pair of 3DPixx liquid-crystal shutter glasses controlled by a

Table 5.1: Participant characteristics of final dataset

Measures	ASD	TD
N	22	23
Gender (*n* males : *n* females)	16:5	11:12
Age (years)		
Mean (SD)	21.773 (4.81)	23.609 (6.985)
Range	16 - 34	16 - 40
WASI Verbal Subscale (standardised)		
Mean (SD)	98.273 (22.252)	106 (13.26)
Range	61 - 131	87 - 130
WASI Performance Subscale (standardised)		
Mean (SD)	108.091 (17.353)	114.174 (14.064)
Range	63 - 132	90 - 139
WASI Full Scale (standardised)		
Mean (SD)	103.5 (19.892)	110.957 (9.655)
Range	65 - 125	92 - 133
AQ		
Mean (SD)	31 (8.331)	19.136 (6.01)
Range	10 - 45	10 - 30
ADOS Communication		
Mean (SD)	3.091 (1.109)	–
Range	2 - 6	–
ADOS Social Interaction		
Mean (SD)	6.909 (1.95)	–
Range	3 - 11	–

DataPixx (VPixx Technologies Inc; Saint-Bruno, QC, Canada) allowed for stereoscopic viewing. The monitor had a frame rate of 120Hz – use of the shutter glasses meant that the effective viewed frame rate was 60Hz. The refresh rate of both the screen and the shutter glasses was confirmed using a photodiode and a Tektronix 2115 60MHz oscilloscope. Viewing distance was 928 cm; in this configuration, one pixel subtended ~ 0.00231 degrees of visual angle (8.32 arc seconds).

5.2.3 Stimuli and design

The task was to indicate via a button-press which of two circles appeared closer in depth to the participant. For all trials, the targets (i.e. parts of the scene to be discriminated in depth) were white circles (luminance 12.05 cd/m^2) with a diameter of 0.4 degrees, positioned on a grey background (luminance 3.15 cd/m^2). Only the red gun of the CRT monitor was used to display the stimuli, because the red phosphor has the fastest decay time and allows the best stereo separation. Disparity was induced by symmetrically

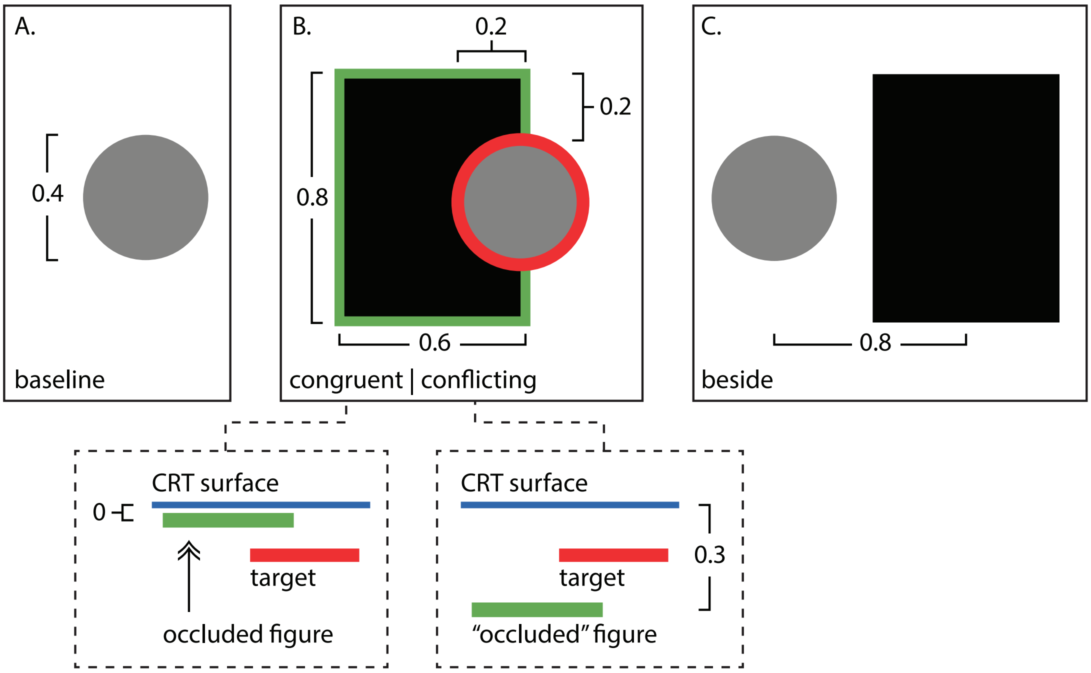


Figure 5.2: Examples of the different occlusion configurations. All measurements are in degrees. Panel A. The baseline condition which aimed to capture a control measure of disparity threshold. Though a single circle is shown here, the task involved discriminating which of two circle stimuli – presented one above the other – were closer to the participant. Panel B. Conditions which contained occlusion. Whether congruent or conflicting, in all displays the circle(s) intruded temporally (with respect to direction in the visual field) upon a rectangular figure. In the congruent condition, the figure had zero disparity and always appeared to be behind the circle(s) in depth. However, for the conflict condition, the figure had a disparity of 0.3 degrees and therefore appeared in front of the circle in depth, though the circle still occluded the figure. Note that the bird-eye view shown in the inset panels depicts the crossed disparity cases; in the case of uncrossed disparities the stimuli all appeared 'inside' or 'behind' the CRT screen, and the disparities of the congruent and conflict figures were swapped. Panel C. In the beside condition, the circle was presented to the left of a rectangular figure, thus acting as a control measure to check if participants were using occluded figures as additional reference points (see main text). The figure was presented at zero disparity for the crossed condition, and at 0.3 degrees of disparity for the uncrossed condition.

varying the lateral positions of the left and right eyes' images.

The targets could be presented in four different occlusion configurations; baseline, congruent occlusion, conflicting occlusion, and figure-present-but-nonoccluding or 'beside'; examples of all configurations can be seen in Figure 5.2. The baseline condition consisted of only the aforementioned circle stimuli (two circles were presented, one above the other - a reference circle of fixed disparity [0.16 degrees] and a comparison circle, where the disparity was changed each trial). In the conditions containing a rectangular figure (all but the baseline condition), this consisted of a black rectangle (luminance 1.07 cd/m^2) with dimensions 0.8×0.6 degrees which, unless otherwise stated, was presented with zero disparity for crossed conditions, and 0.3 degrees of disparity for uncrossed conditions. In the congruent occlusion condition, the comparison and reference circles each occluded a rectangular figure. In the conflict condition, again the comparison and reference circles each occluded a rectangular figure. However, the disparity information provided by the figure indicated that the figure was in front of the circles (for crossed conditions, the figure was presented at a disparity of 0.3 degrees, and at zero disparity for uncrossed conditions), information that conflicted with the occlusion cue. Finally, in the figure-present-but-nonoccluding or 'beside' condition, both the comparison and reference circles were presented beside a figure.

All occlusion configurations were presented in blocks containing either crossed or uncrossed disparities. For crossed disparities, which appeared to be floating in front of the surface of the CRT screen, the stimulus viewed by the right eye was located further to the left, and vice versa for the left eye. In the case of uncrossed disparities, which appeared to be floating behind or inside the CRT screen, the stimulus viewed by the right eye was further to the right and vice versa for the left eye.

5.2.4 Procedure

The procedure was approved by the University of Nottingham's School of Psychology Ethics Committee. Participants gave their informed consent, and were seen within the School of Psychology in two or three sessions, each lasting between 60 to 90 minutes. The experimental conditions (of which there were eight; 4 types of occlusion configuration, each with 2 possible signs of disparity) were presented in separate blocks, with each block consisting of one condition. The order of presentation of conditions was counterbalanced between participants. The Weschler Abbreviated Scales of Intelligence (WASI) and Autism Diagnostic Observation Schedule (ADOS) were administered in sessions which were separate to those in which the experimental task took place.

In the experimental task, participants completed a relative-depth discrimination task where they had to choose which of two circles appeared closer to them. A trial consisted of a pair of stimuli (reference and comparison circles) presented one above the other for an unlimited amount of time until a response was made. Trials were separated by a random temporal jitter ranging between 0.5 and 1 seconds. A fixation cross with zero disparity remained in the centre of the screen at all times and participants were instructed to fixate on this cross throughout stimulus presentation. The task was composed of three stages: a combined demonstration and practice phase, a threshold estimation phase and a psychometric function estimation phase.

5.2.4.1 On the use of adaptive and method-of-constant-stimuli threshold estimation methods

The behavioural response of observers to stimuli of different magnitudes can be used to characterise a psychometric function which depicts the quantitative relationship between physical stimuli and the observer's perceptual experience. In the current experiment, the psychophysical data are expressed as the probability of the comparison circle appearing in front of the reference circle as the function of changes in the disparity of the comparison circle. Psychometric functions are typically well-described by a curve that has a sigmoidal shape; the four degrees of freedom in these functions are discussed in Figure 5.3.

In current experiment, the comparison stimulus was displayed with varying degrees of disparity relative to the disparity of the reference. A two-interval forced choice procedure was used, where the reference (with a fixed disparity level) and comparison circles were spatially separated by presenting one above and another below fixation (both horizontal and vertical positioning were randomised, see below); the participant then had to chose which circle appeared closer to them by pressing a button.

The point at which the observer identifies the correct stimulus a certain percentage of the time is termed the *threshold*. In forced-choice procedures, the question arises as to how to present the different magnitudes of a stimulus during an experimental session. One popular solution is the method of constant stimuli. In this method, the stimulus magnitude on each trial is randomly selected from a predefined set which is usually the same for all observers.

However, this can be an issue for psychophysical phenomena in which the general population shows a large variation (such as disparity; Bosten et al., 2015), as the same stimulus set often does not provide an acceptable estimation of the psychometric function for all participants. Adaptive methods avoid this issue by efficiently zeroing in on the threshold, and this is reflected in their relative popularity (Klein, 2001). They do so by determining the next stimulus level in relation to the results of previous trials. In the simplest case of a one-up one-down staircase, a correct response on the previous trial results in the next trial being tested with a lower stimulus magnitude (i.e. making the task more difficult), while an incorrect response results in the next trial being

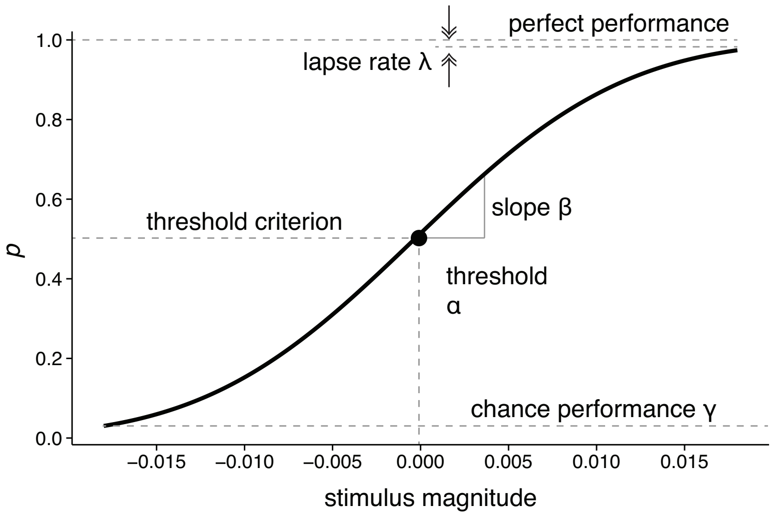


Figure 5.3: The psychometric function (reproduced from Figure 1 in Strasburger, 2001). Definition of terms: abscissa, stimulus level or magnitude; ordinate, subject performance, here as proportion p of responses indicating a certain appearance of the comparison relative to the reference (i.e. brighter, smaller, nearer).The two parameters which describe properties of the underlying sensory mechanism (in the current study, sensitivity to horizontal disparity) can only be estimated by iteratively searching through a range of possible values, α (alpha) and β (beta). The α parameter determines the position of the curve along the abscissa, or horizontal axis. The β parameter determines the slope or gradient of the curve. Two other parameters are needed to fully specify the psychometric function, γ (gamma) and λ (lambda). These parameters do not correspond to properties of the underlying sensory mechanism, but rather describe chance- or floor-level performance and lapsing, respectively. In a typical performance-based task, γ is assumed to equal the reciprocal of the number of alternatives in the forced-choice task, or $1/m$ in an M-AFC task (thus, for a 2AFC γ is 1/2 or 0.5). However, since the current experiment involves an *appearance-based* task (see Chapters 2-4 in Kingdom & Prins, 2010 for an excellent discussion of appearance versus performance-based tasks), γ represents the lower asymptote or floor-level performance which is typically constrained to zero. The fourth and final parameter associated with the psychometric function is λ, otherwise known as the lapse rate. On a small proportion of trials, observers will respond independently of stimulus level. For example, observers may have missed the presentation of the stimulus, perhaps due to a momentary lapse of attention. On such trials, observers may produce an incorrect response even if the stimulus level was so high that they would normally have produced a correct response. As a result of these lapses, the upper asymptote of the psychometric function will correspond to $1 - \lambda$. Researchers will usually allow only α and β to vary during the fitting procedure, and assume fixed values for γ and λ. Parameters that are allowed to vary during fitting are referred to as 'free parameters', those that are not allowed to vary are referred to as 'fixed parameters'. The chance- or floor-level in an M-AFC task can in most cases safely be assumed to equal $1/m$ or zero, depending on the nature of the task. However, it is debatable whether it is reasonable to assume any fixed value for the lapse rate. Researchers often implicitly assume the lapse rate to equal 0, but even the most experienced and vigilant observer will occasionally respond independently of stimulus level ("anybody who has ever participated in psychophysical experiments will recognize that sometimes our thumbs seem to have a mind of their own" [Kingdom & Prins, 2010, p. 76]). When it is assumed that lapse rate equals 0, but lapses do in fact occur, this may produce a significant bias on the threshold and slope parameters (Prins, 2012). The bias can be largely avoided by using one of two methods: assuming the lapse rate to have a fixed small value, such as 0.01, or – as was done in the current study – leaving it as a free parameter to be estimated in the psychometric function fitting procedure. See text for details of how the psychometric function was estimated in the current study.

tested with a higher stimulus magnitude. As this continues, stimulus magnitude and performance converge asymptotically upon the threshold determined by the parameters of the staircase.

However, many psychophysical techniques – adaptive methods in particular – presuppose a homogeneous cohort of highly attentive observers (a lapse rate > 6% is often taken to imply “that the experiment was not performed properly and that the data are invalid”; Wichmann & Hill, 2001, p.1295). Clinical populations, including those with ASD, are known to have increased lapse rates (Koldewyn et al., 2010), and this can cause difficulty when attempting to estimate threshold using purely adaptive methods. Therefore, in the currently study, a rough initial estimate of threshold was first gained by use of a staircase paradigm. This first measure of threshold was used to generate an appropriate stimulus set for each participant, which could be used with the method of constant stimuli to fit a full psychometric function. This combined use of adaptive and constant methods allowed for efficient estimation of both threshold and slope parameter with relatively few trials.

5.2.4.2 Demonstration and practice phase

The experimenter explained the task to the participants within the context of four demonstration trials, with each trial showing the stimuli for one of the possible occlusion configurations. In all of these trials, the disparity of the comparison stimulus was set to 0.3 degrees. Next, participants were presented with 20 practice trials, where the disparity of the stimulus was set adaptively, using a 2-down 1-up staircase (the parameters of which are described in the next section; however, for the practice phase the starting value of the comparison stimulus was set at ±0.148 degrees relative to the disparity of the reference stimulus). Participants indicated which stimulus appeared closer to them by pressing a key.

5.2.4.3 Threshold estimation phase

After the participant was comfortable with the task, I used a 2-down 1-up staircase with a 40-trial termination criterion, where the comparison circle had a starting disparity value of ±0.074 degrees relative to the disparity of the reference stimulus, to gain an initial estimate of threshold (i.e. the relative disparity at which the participant correctly identified the stimulus which was closer to them 83.25% of the time) using the mean stimulus intensity of the last 4 reversals. The ratio of down stepsize and up stepsize (Δ^-/Δ^+) was set at 0.5488 as recommended by García-Pérez (1998) in order to be able to accurately estimate threshold. No feedback was given regarding performance and a separate estimate of threshold was generated for each unique condition (of which there were eight in total). The relative position of the reference and comparison stimuli (above or below the fixation cross) was randomised on each trial. A random amount of horizontal jitter was added to each stimulus to ensure that the task could not be completed monocularly.

5.2.4.4 Psychometric function estimation phase

A series of fixed disparity levels were then generated around the threshold obtained in the prior phase, to be used with the method of constant stimuli. Summary statistics of the generated disparity levels are reported in Table 5.2. The threshold was used as an anchor for generating 5 levels of disparity - one at the same level as the reference stimulus, 2 at the threshold level (one of which appeared in front of and one behind the reference stimulus) and 2 that were 2.5 times larger than the threshold (again, one that would appear in front of and one behind the reference stimulus). This phase involved presenting each test disparity for 30 trials, yielding a total of 150 trials per block and a total of 1000 trials over the entire experiment. As in the previous phase, the relative vertical and horizontal position of the reference and comparison stimuli was randomised on each trial. Additionally, the presentation order of the the comparison stimulus disparities was randomly shuffled before each block began.

Table 5.2: Summary statistics for the disparity levels relative to the reference generated for the method of constant stimuli (minus the levels which were the same as the reference stimulus). All values are in degrees.

mean	median	mode	SD	range
0.0492	0.028	0.009	0.0479	0.005 – 0.148

5.2.5 Data analysis

All data were processed and analysed using `R 3.3.2`. The proportion of incorrect responses for trials where the disparity was set at $2.5 \cdot$ threshold was calculated for each participant condition-wise. Five ASD participants were excluded from the analysis as they did not perform significantly above chance in the trials where disparity was set at $2.5 \cdot$ threshold in at least one condition.

5.2.5.1 Psychometric parameters

For the remaining participants, the ratio of 'target in front' responses was calculated for each disparity level. These data were then fit for each participant condition-wise with a Gaussian cumulative density function using 'maximum likelihood estimation' via `R`'s `glm` function (Knoblauch & Maloney, 2012, p. 121-123). An estimate of the point at which a participant specified the target as being in front of the reference 83.25% of the time ('threshold'), and the slope of the psychometric function at this point ('slope'; both measures referred to as 'psychometric parameters' hereafter) was calculated using the `threshold_slope` function within the `modelfree` package. Threshold values obtained using this method may be defined as the minimum amount of relative disparity required between two stimuli so that they are reliably perceived as having different depths. Similarly, slope may be defined as a quantification of the precision or reliability of an observer's judgements (as since the slope of the psychometric function is inversely proportional to the standard deviation parameter of the function used to fit the data). Both provide useful information in the context of the current study, as different occlusion configurations may not cause a change in the amount of disparity needed to perceive a difference in depth (threshold), but might cause judgements to become more or less precise (slope; or vice-versa).

An example fit for a single participant's data for the crossed baseline condition can be seen in Figure 5.3, though it should be noted that the threshold and slope were estimated when $p = .8325$, not .5 as depicted in the figure. The thresholds for the baseline or no-occlusion condition were used as covariates to assess the impact of stereoacuity, meaning that the occlusion configuration factor in the final analyses had, de facto, three levels: congruent occlusion, conflicting occlusion and circle beside figure. The threshold covariates and dependent variable were log-transformed, justified by previous research which has reported that neural activity is approximately linear with respect to the logarithm of disparity (Wesemann, Klingenberger, & Rassow, 1987). Additionally, such transformation serves to minimise the effects of skewness and kurtosis, bringing the distributions closer to normality (the Q-Q plots for both the raw and log-transformed data can be seen in Figure B.1 in Appendix B.1).

5.2.5.2 Reaction times

Two RT outcome measures were calculated – median response speed (the reciprocal of RT), and the standard deviation of response speed (hereafter referred to as *response speed variability*). While the utility of central tendency parameters of RT distributions is obvious, measures of response dispersion (such as standard deviation) are given less recognition in the literature (Jensen, 1992). Such *interindividual variability* in RT is thought to reflect impairments in information processing and dysfunction associated with a failure to maintain attentional control (Bellgrove, Hester, & Garavan, 2004). In the context of the current study, this can be used to explore the behavioural effect of different occlusion conditions. For instance, when the occlusion cue conflicts with disparity information, an observer may take a similar amount of time to make a judgement compared to when the occlusion cue is congruent. However, the variability of time taken to respond may be increased, reflecting occurrence of perceptual instability or uncertainty. All RT measures were calculated separately for each combination of participant, condition, and disparity level. For both the median response speed and its standard deviation, the raw RT data were first trimmed so values fell between 250ms and $+2 \cdot$ standard deviations from the mean. The raw RT data were then transformed to speed by taking the reciprocal, bringing the typically heavily-skewed RT distribution closer to normality. Use of cut-offs and transformation when dealing with RT data is known to ameliorate the effect of slow outliers and thereby preserves power (Ratcliff, 1993; Whelan, 2008). However, transformation does not completely normalise the distribution, hence the reporting of the more robust median response speed as a central tendency parameter.

5.2.5.3 Outlier removal

Finally, both the psychometric parameters and RT outcome measures were screened for potential outliers on a per condition level using a criterion based on the median absolute deviation (MAD; Leys et al., 2013). The threshold for rejection was set at $2.5 \cdot$ MAD (a moderately conservative value) based on the recommendations of Leys et al. (2013). The data points identified using this method – a breakdown of which can be seen in Table 5.3 – were not retained in the subsequent analysis.

Table 5.3: Outlier breakdown

Measure	Data points removed (ASD)		Across *n* ppts (ASD)
	n	%	
threshold	8 (5)	2.97 (3.82)	6 (4)
slope	28 (8)	10.41 (6.11)	18 (6)
median response speed	27 (19)	2.01 (2.9)	11 (7)
response speed SD	42 (31)	3.13 (4.73)	12 (6)

5.3 Results

Twenty-two ASD and 23 TD participants were included in the final analysis, following the data screening procedures described above (Sections 5.2.1 and 5.2.5). The TD and ASD groups in this subset were matched in terms of chronological age ($t(39.141) = -1.031$, $p = 0.309$), raw verbal ($t(29.722) = -1.565$, $p = 0.128$) and performance ($t(35.387) = -1.138$, $p = 0.263$) WASI sub-scale scores, and WASI raw full-scale score ($t(27.517) = -1.543$, $p = 0.134$).

Three initial measures of stereoacuity (disparity threshold) were obtained; one via the TNO test, and the others by calculating the disparity threshold for the crossed and uncrossed baseline experimental conditions. Stereoacuity (across all three measures)

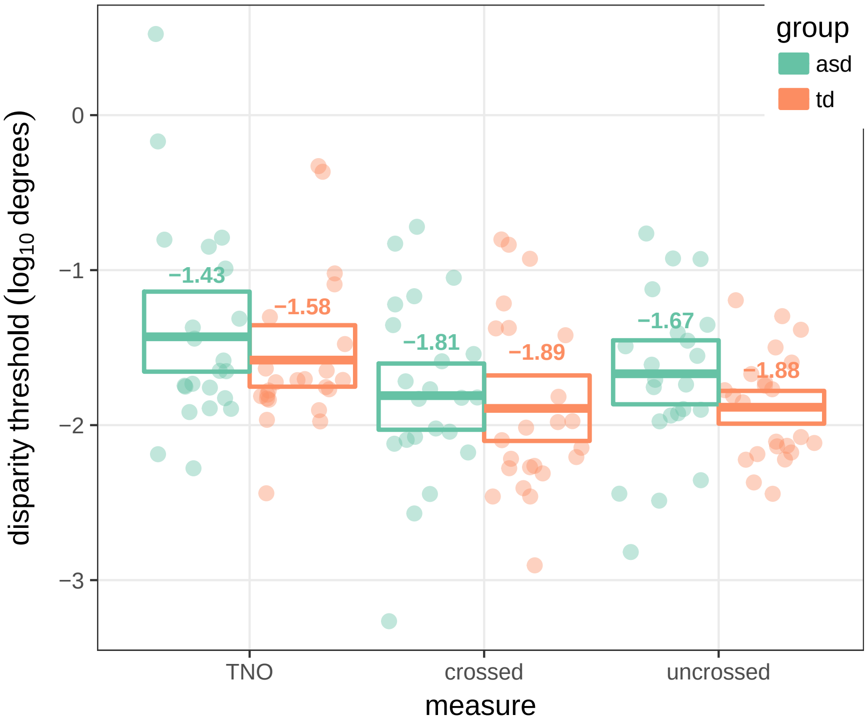


Figure 5.4: Mean (± 95% confidence interval) stereoacuity score in log-disparity units for both ASD and TD group across all initial measures of stereoacuity (the TNO, crossed and uncrossed baseline threshold; see main text for more information). Thick bars and number annotations are mean values, bounding box is 95% confidence interval, and points are the scores of individual participants.

ranged from 0.001 - 2.778 degrees, with a median value of 0.017 degrees. Examination of Figure 5.4 suggests that the stereoacuity scores of the ASD and TD groups may differ on a subset of the measures. Bonferroni-corrected one-tailed t-tests showed that log-transformed stereoacuity scores differed significantly between groups for the *uncrossed* experimental baseline measure only; $t(31.169) = -1.754$, $p = 0.045$. Participants with ASD exhibited a worse average stereoacuity of -1.668 $\log_{10}$ degrees [SD = 0.516], whereas TD individuals had a better average stereoacuity of -1.885 $\log_{10}$ degrees [SD = 0.267].

5.3.1 Psychometric parameters

To measure the effect of stimulus and participant characteristics on the psychometric function, I modelled the disparity threshold and slope using mixed-effects linear regression (implemented via the `mixed` function of the R package `afex`; Singmann & Bolker, 2014). The models contained factors for occlusion configuration (occluding, conflict, beside) and disparity sign (crossed, uncrossed) of the stimuli, as well as diagnostic group (ASD, TD) and continuous predictors in the form of crossed and uncrossed stereoscopic ability (threshold obtained for the baseline occlusion configuration condition). All measures of threshold were log-transformed. The baseline threshold measures entered into the model as continuous predictors were also mean-centred to aid in interpretation of coefficient values. Sum contrast coding was used for categorical variables. Random intercepts and fully-crossed random slopes were included in the models, as recommended by Barr et al. (2013). I report omnibus Type-III tests[2], with denominator degrees of freedom, *F*-scaling factors, and *p* values obtained via Kenward-Roger approximation (Halekoh & Højsgaard, 2014) in Tables B.1 and B.3 in Appendix B.3.1. β-values for continuous variables can be seen in Tables B.2 and B.4, also in Appendix B.3.1. To counteract the increased likelihood of Type I error in the case of multiple statistical tests, all *p* values in the omnibus tests were Bonferroni-corrected (O. J. Dunn, 1959, 1961). In cases where a significant main effect or interaction was found, pairwise comparisons were made with *p* values adjusted using the Tukey method (Tukey, 1977), using the R package `lsmeans` (Lenth, 2014).

5.3.1.1 Threshold

Analysis revealed no main effects of or interaction including disparity sign (all $p < 0.05$; see Table B.1 in Appendix B.3), so all summary statistics for this measure are collapsed across disparity sign.

Occlusion configuration had a significant effect on threshold (F(2, 38.413) = 35.246, p = <0.001), as can be seen in the left panel of Figure 5.5. Multiple pairwise comparisons revealed that the thresholds obtained from all three occlusion conditions significantly differed from one another. When the occlusion cue was conflicting, thresholds were higher compared to when the occlusion cue did not conflict (t(39.789) = -6.786, p = <0.001), or when the figure was beside the target (t(39.823) = -8.523, p = <0.001). Thresholds were also significantly lower for the beside condition compared to the congruent occlusion condition (t(38.226) = -3.443, p = 0.004).

A significant, strong, main effect of uncrossed baseline stereoacuity (β = 0.74; F(1, 39.329) = 24.43, p = <0.001) showed that individuals with higher (i.e. worse) baseline uncrossed disparity thresholds were also likely to have increased thresholds for all other occlusion configurations.

There was no main effect of diagnostic group (p = 1.000), and there were no significant interactions.

[2] The reason for doing so is that the summary output of fitted models, while showing the parameter estimates, their standard errors, and corresponding t-statistics, differs substantially depending on the contrast coding (Cohen, Cohen, West, & Aiken, 2003, p. 374-375; J. Fox & Weisberg, 2011, p. 196). It is important to note that the types of hypotheses commonly postulated in the discipline of psychology are difficult or impossible to express in terms of a specific coding (e.g. there is no single contrast to test all pairwise comparisons among a set of means). Additionally, especially when the number of factor levels > 2, it can be difficult to correctly interpret the estimates provided by contrast variables (specifically for higher-order or interaction effects). Thus, using omnibus Type III tests in circumstances where there are factors with ≥ 3 levels is the best choice, as it allows for the testing of specific hypotheses.

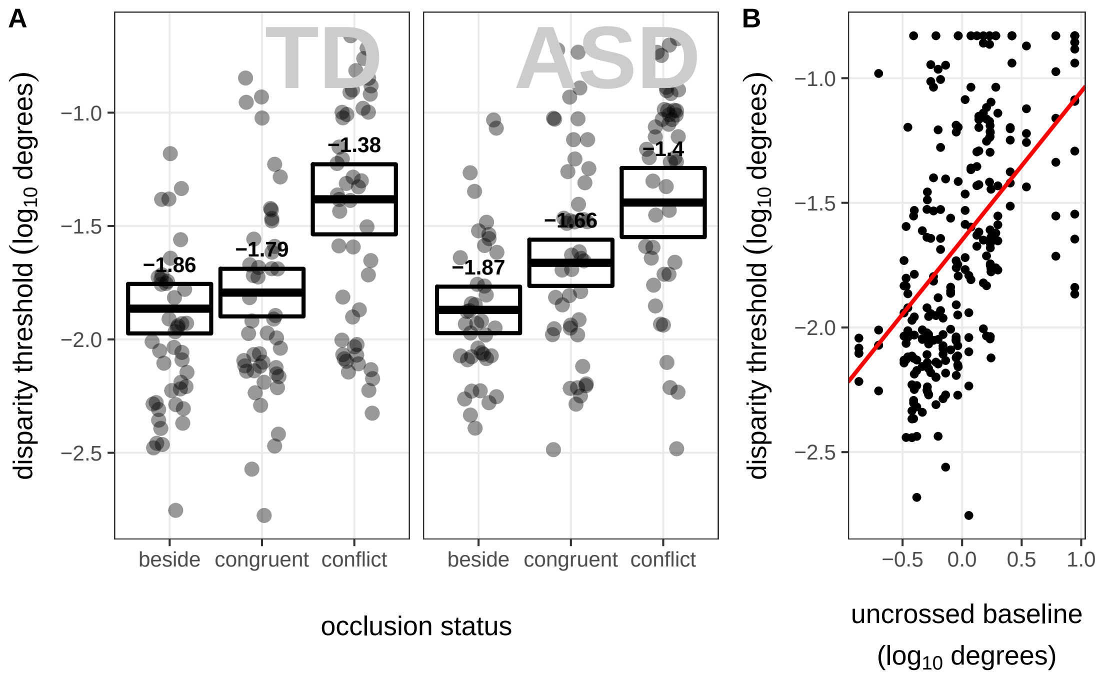


Figure 5.5: Main effect of occlusion configuration (left panel) and uncrossed baseline stereoacuity (right panel) upon relative disparity threshold. Left panel depicts least squares mean (± 95% confidence interval) disparity threshold for ASD and TD groups for the main effect of occlusion configuration. Right panel shows how disparity threshold changes as a function of uncrossed baseline stereoacuity; the points are the data of individual observers and the red line corresponds to the line-of-best-fit output by the linear mixed model.

5.3.1.2 Slope

Similar main effects of occlusion configuration (F(2, 37.869) = 67.37, p = <0.001) and uncrossed (F(1, 41.406) = 18.038, p = <0.001) baseline measures also applied to the slope of the psychometric function. As can be seen in Figure 5.6, the slope had a significantly shallower gradient in the case of conflicting occlusion (LSM = 4.267 [SE = 0.878]), compared to when the occlusion cue was congruent (LSM = 17.055 [SE = 1.299]; t(37.558) = 8.905, p = <0.001), or when the figure was beside the target (LSM = 20.261 [SE = 1.311]; t(38.193) = 10.783, p = <0.001). The slope was steeper for the beside condition than for the congruent occlusion condition (t(38.215) = 2.785, p = 0.022)). With regards to the baseline measures, there was an effect involving both crossed and uncrossed baseline stereoacuity, though the effect was stronger for uncrossed (β = -0.573) compared to crossed (β = -0.248).

However, for slope there was a significant interaction between disparity sign and occlusion configuration (F(2, 73.846) = 6.862, p = 0.007). The least-squared mean slopes presented in Figure 5.6 suggest that for both ASD and TD participants, there was a disparity sign-dependent difference in slope for the beside occlusion configuration only. Follow-up posthoc tests confirmed this, with the difference in slope between crossed

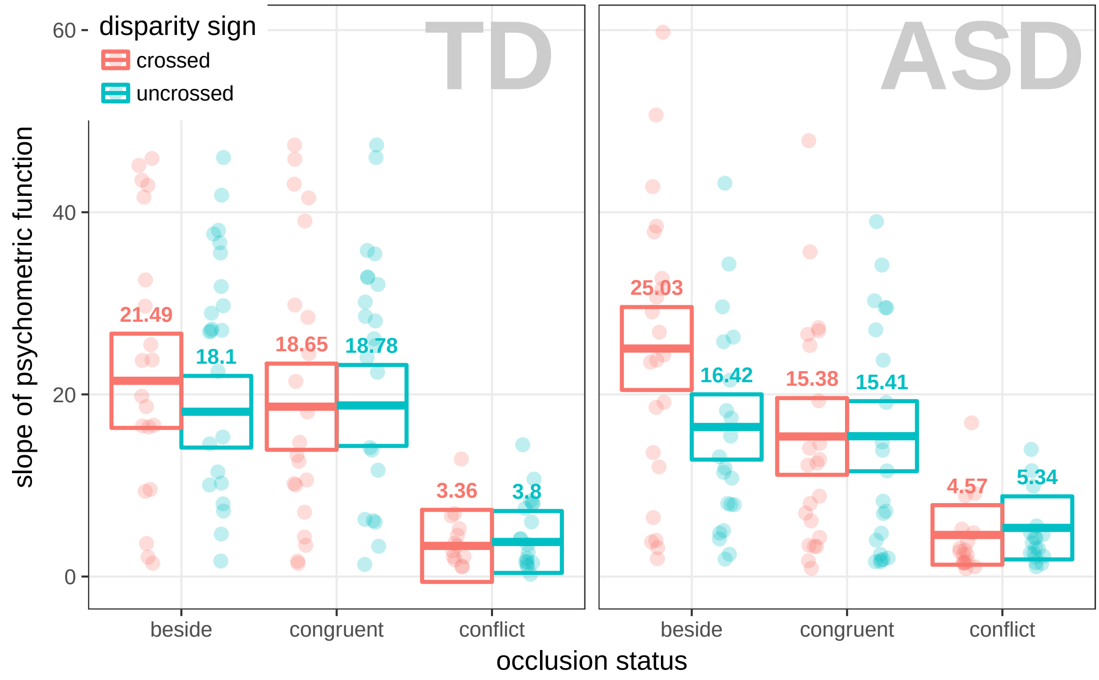


Figure 5.6: Mean (± 95% confidence interval) slope of psychometric function for ASD and TD groups for the two-way interaction between occlusion configuration and disparity sign.

and uncrossed disparities only being significant for the beside-type occlusion (t(93.584) = 3.782, p = <0.001), and not the congruent (p = 0.959) or conflicted types (p = 0.748).

5.3.2 Reaction time measures

To measure the effect of stimulus and participant characteristics on reaction time, I constructed two more linear mixed-effects models (using the `mixed` function of the R package `afex`), with outcome measures of median response speed and the standard deviation of response speed. Like before, these models contained factors for occlusion configuration and disparity sign of the stimuli, as well as diagnostic group and continuous predictors in the form of crossed and uncrossed stereoscopic ability. The baseline measures of threshold were log-transformed and mean-centred to aid in interpretation of coefficient values. Sum contrast coding was used for categorical variables. Random intercepts and fully-crossed random slopes were included. Again, I report Bonferroni-corrected omnibus type-III tests with denominator degrees of freedom, F-scaling factors, and p values obtained via Kenward-Roger approximation (Halekoh & Højsgaard, 2014). The results of these tests may be observed in Tables B.5 and B.7 in Appendix B.3.2. β-values for continuous variables can be seen in Tables B.6 and B.8, also in Appendix B.3.2.

5.3.2.1 Response speed

As observed for other measures, there was a main effect of occlusion configuration ($F(2, 38.467) = 5.24$, $p = 0.039$). Response speed significantly differed between the conflict (LSM = 1.209 [SE = 0.04]) and congruent (LSM = 1.291 [SE = 0.042]) conditions ($t(39.778) = 3.062$, $p = 0.011$), and conflict and beside (LSM = 1.29 [SE = 0.044]) conditions ($t(39.615) = 2.651$, $p = 0.03$), but not for the congruent and occlusion conditions ($p = 1$). There was also a main effect of uncrossed baseline ($F(1, 39.152) = 17.644$, $p = <0.001$), where individuals with a higher uncrossed baseline threshold tended to respond faster ($\beta = 0.973$).

Overall, participants with ASD exhibited slower response speeds (LSM = 1.147 [SE = 0.053]) than their TD counterparts (LSM = 1.379 [SE = 0.056]) ; $F(1, 39.049) = 9.003$, $p = 0.019$. Though there was no main effect of disparity sign, an interaction between diagnostic group and disparity sign ($F(1, 39.258) = 8.297$, $p = 0.026$; the descriptive statistics of which can be seen in Table 5.4) revealed that the ASD group had significantly slower response speeds to uncrossed disparities only ($t(39.173) = 3.936$, $p = <0.001$); response speeds for crossed disparities did not differ between the two diagnostic groups ($p = 0.112$).

Table 5.4: Mean (± SE) speed of response for the two-way interaction between group and disparity sign.

Disparity sign	Mean response speed ± SE		
	TD	ASD	overall
crossed	1.35 ± 0.06	1.21 ± 0.06	1.28 ± 0.04
uncrossed	1.41 ± 0.06	1.08 ± 0.06	1.24 ± 0.04
overall	1.38 ± 0.06	1.15 ± 0.05	1.24 ± <0.01

5.3.2.2 Response speed variability

Occlusion configuration also had an effect on response speed variability ($F(2, 38.367) = 13.932$, $p = <0.001$), with – as for median response speed – variability being significantly higher for the conflict condition (LSM = 0.415 [SE = 0.013]), compared to the congruent occlusion (LSM = 0.39 [SE = 0.011]; $t(39.702) = -5.283$, $p = <0.001$) or beside (LSM = 0.39 [SE = 0.011]; $t(39.875) = -3.491$, $p = 0.003$) conditions. Response speed variability did not significantly differ between the congruent occlusion and beside conditions ($p = 0.134$). However, an interaction between diagnostic group and occlusion configuration showed that this condition-dependent effect upon response speed variability was only present in the TD group; response speed variability did not significantly differ between occlusion conditions for the ASD group. Table 5.5 shows descriptives and pair-wise comparisons at all levels of diagnostic group and occlusion configuration.

Table 5.5: Pair-wise comparisons of least-squared means for two-way interaction between diagnostic group and occlusion configuration (the latter denoted by "condition" in the table), using Tukey's honest significant difference test with α = .05. *Note*. Rows containing the same letter are not significantly different to each other (Piepho, 2004). Acronyms: typically-developing (TD), autism spectrum disorder (ASD), least squares mean (LSM), standard error of the mean (SE), confidence limit (CL).

Group	Condition	LSM	SE	df	lower CL	upper CL	Posthoc
td	beside	0.397	0.016	39.125	0.365	0.429	a
	occlusion	0.372	0.014	38.852	0.343	0.402	a
	conflict	0.430	0.018	38.685	0.393	0.466	b
asd	beside	0.384	0.016	38.838	0.353	0.416	ab
	occlusion	0.386	0.014	38.997	0.357	0.415	ab
	conflict	0.401	0.018	40.120	0.365	0.438	ab

5.4 Discussion

This study examined the impact of occlusion cues upon perceived depth in adults with and without ASD, in order to determine whether true differences are present in cue integration in ASD or if poor stereopsis is the underlying cause. The results showed that, overall, when occlusion conflicted with the depth order specified by disparity, estimates of relative depth became less precise (i.e. threshold increased) and more varied, and time taken to make the judgement increased; this was the case in both the TD and ASD groups. An effect of diagnostic group was found in three instances. Those with ASD were less sensitive to uncrossed disparities, measured psychophysically when no occlusion or reference planes were present (the 'baseline' occlusion configuration). Time taken to judge uncrossed relative disparities were increased for this group across all occlusion configurations, even when accounting for uncrossed baseline disparity sensitivity. Additionally, variability of response speed did not depend on whether the occlusion cue was congruent for the ASD group, whereas response speed became more variable for the TD group when occlusion conflicted with disparity information. Finally, while an increase in relative disparity threshold for the baseline condition made it more likely that an individual would have similarly decreased performance across the occlusion and reference figure conditions, it also caused faster response speeds (across both the TD and ASD groups). First, I place these results in relation to previous research which has used TD populations, followed by discussion of what they indicate about cue integration in individuals with reduced stereopsis and those with ASD.

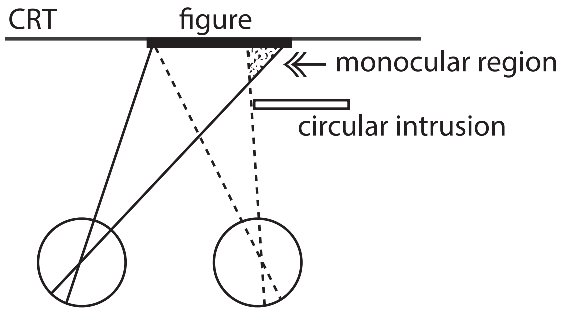


Figure 5.7: An example of a monocular region. Note how the monocular region caused by the intrusion (which would be the target or reference circle in this case) can be seen by the left eye only.

5.4.1 Combination of metric and ordinal depth cues

As has been observed in previous studies involving occlusion, all performance measures decreased when this cue conflicted with the information given by disparity (Schriever, 1924; Braunstein et al., 1986; Stevenson & Körding, 2009). Surprisingly, the presence of congruent occlusion did not increase performance – in fact, judgements were both more precise and less variable for the 'beside' occlusion configuration, where a non-occluded reference figure was present. This is inconsistent with previous evidence that occlusion can hasten the processing of disparity and improve the precision of depth judgements (Gillam & Borsting, 1988) This may be due to the presence of monocular regions, which are present when one object is occluded by another. They occur because one eye is able to see a portion of the background that is occluded in the other eye's view by the foreground object; see Figure 5.7 for a top-down view of a display in which a monocularly half-occluded region results from occlusion. Past research concerning depth perception regarded these monocular regions as 'noise' - a potential source of false matches and ambiguity which could impede the processing of overall depth by the visual system. Recently the potential importance of these 'monocularly half-occluded regions' in the formation of an overall percept of depth has been highlighted (Harris & Wilcox, 2009), especially in the identification of 'depth edges' manifested by disparity discontinuities which indicate object boundaries (Tsirlin et al., 2010). However, the depth of a monocular region cannot be precisely specified as, according to occlusion geometry, it may theoretically reside anywhere inside what Nakayama and Shimojo (1990) designated the 'depth constraint zone' (shown in Figure 5.7 as a pattered area). Thus, although occlusion may be in itself a highly reliable depth cue, the monocularly-occluded regions that result are arguably less discrete and may cause perceptual judgements to become more varied or even biased (Tsirlin, Wilcox, & Allison, 2011).

5.4.2 The impact of stereoacuity

In this study I obtained a psychophysical measure of sensitivity to both crossed and uncrossed binocular disparities (stereoacuity) for each participant, where no occlusion or reference planes were present (the 'baseline' occlusion configuration). It was found that worse stereoacuity (i.e. decreased sensitivity to disparity) made it more likely that these participants would also exhibit decreased precision and increased variability of relative disparity judgement for all experimental conditions including occlusion and reference figures. Contrary to my predictions, participants with worse stereoacuity did not have improved performance when occlusion was present and congruent with disparity information. As discussed above, this may be due to the fact that monocular regions do not have a defined depth and are therefore not a reliable source of depth information. Regrettably, although individuals with worse stereoacuity may have given an increased weighting to the occlusion cue, it is not possible to assess the weighting given to this ordinal cue as in typical depth cue integration paradigms. This is because whilst the statistical likelihood of a metric (disparity-defined) depth value may be enhanced, biased, or otherwise altered by the presence of an ordinal depth cue (occlusion), according to Bayesian models of cue integration the Gaussian likelihood of each individual cue must be characterised in addition to the resultant joint likelihood (Landy et al., 2011, p. 11, Figure 1.1). Only then can individual cue weightings be evaluated. This means that, in the case of ordinal cues, they can only provide boundaries of possible depths as opposed to precise depth estimates (Stevenson & Körding, 2009), precluding empirical measurement of relative cue weighting.

It is interesting that individuals with reduced stereopsis showed, on average, a faster median response speed but no difference in response speed variability (as measured by the standard deviation of response speed). To my knowledge, no studies have yet examined the relationship between stereoacuity and speed of response to computerised stimulus configurations involving disparity. Increased response speed may reflect attentional difficulties (Tamm et al., 2012). It can reasonably be assumed that those with poor stereopsis found the task more difficult. Heightened task difficulty has been shown to decrease neural activity associated with successful attentional orienting and subsequent task completion (Ress, Backus, & Heeger, 2000). Thus, the faster response speeds may reflect the increased difficulty experienced by these participants, as they may have not necessarily been able to make the required forced-choice decision to complete the task, instead choosing to make an essentially random response on each trial. However, if this were the case the psychometric functions obtained for these participants would be abnormal in the extreme; this was not so. Though the slopes were undoubtedly more shallow, indicating increased response variability, the characteristic psychometric function was still recognisable and `R`'s `glm` function was able to fit to the data without issue.

Instead, these stereoacuity-dependent differences in median response speed may be driven by the magnitude of the disparities being shown. In the first part of the study, rough estimates of threshold were calculated for each participant using an adaptive method, and the main experiment used this threshold for the generation of stimulus levels to be used as part of the method of constant stimuli. Those with worse stereoacuity required larger amounts of disparity to perceive depth, with some individuals displaying thresholds as large as 0.25 degrees. While disparity is continuous, the point of diplopia (the amount of disparity where binocular single vision ends and double vision begins) signals a partitioning between *fine* and *coarse* stereopsis mechanisms (Wilcox & Allison, 2009). For horizontal disparities in the fovea, diplopia threshold ranges from 0.03 – 0.3, with a large amount of individual variability (Duwaer & van den Brink, 1981). Though stereo-deficient people may be unable to process fine disparities, it has been shown that coarse stereopsis is generally spared in those with poor stereoacuity (Giaschi, Lo, Narasimhan, Lyons, & Wilcox, 2013). Since the thresholds of these individuals were largely within the 'coarse'-type range, it is likely that they experienced reduced sensory uncertainty compared to those with 'good' stereoacuity and were therefore able to make relative disparity judgements more quickly. I am unable to substantiate this claim, as the observers' diplopia thresholds were not obtained in the current study – it is, however, recommended that this measure be obtained in future research investigating relationships between stereoacuity and speed of response to disparity.

5.4.3 An absence of occlusion-oriented group differences

I was particularly interested in whether individuals with autism exhibited true differences in depth cue utilisation, or if these were instead due to reduced stereopsis. It should be noted that there was a group difference in baseline threshold, with the ASD group exhibiting increased *uncrossed* thresholds compared to the TD group. Though not inconsistent with previous evidence – reduced stereoacuity in ASD has been identified numerous times (Scharre & Creedon, 1992; Adams et al., 2010; Anketell et al., 2013; Coulter et al., 2013) – this is the first study to have tested for and observed a difference between crossed and uncrossed disparity threshold in ASD. An overall reduction in response speed (especially for uncrossed disparities) was also found. Slower reaction times are not characteristic of ASD (Ferraro, 2016), reflecting a specific difficulty in processing disparity information.

A deficit localised to uncrossed disparities was unexpected, as it *does not* correspond with increased prevalence of convergence insufficiency seen in autism (in which case it might be predicted that those with ASD are less sensitive to crossed disparities). The perception of uncrossed disparities requires divergence, an ability which remains intact in ASD (Milne et al., 2009). It should be noted, however, that those with autism exhibit a substantial increase in prevalence of strabismus compared to TD populations. Sensi-

Table 5.6: Incidence of difference types of strabismus in studies of visual function in ASD

Study	*N* strabismic (% of sample)	*N* esodeviation	*N* exodeviation
Kaplan et al. (1999)	17 (50%)	6	11
Ikeda et al. (2012)	32 (21%)	20	11
Black et al. (2013)	18 (41%)	1	1
Kabatas et al. (2015)	28 (8.6%)	13	14
Milne et al. (2009)	5 (10.6%)	3	2
Scharre and Creedon (1992)	7 (21%)	1	6
Denis et al. (1997)	6 (60%)	2	4
Total =	113 (18.4%)	46	49

tivity to uncrossed disparity is specifically reduced in the case of exo-phoria or -tropia, a type of strabismus where one or both of the eyes deviate outwards (Lam, Tse, Choy, & Chung, 2002). While those with autism are not significantly more likely to have exo- compared to eso-deviations (where one or both of the eyes deviate inwards; see Table 5.6), the increase in prevalence of strabismus compared to the general population could nonetheless account for this localised deficit.

Despite the group difference in baseline thresholds, there were no interactions involving diagnostic group for the psychometric parameters, suggesting that populations with ASD do not differ in the utilisation of occlusion. Individuals with autism showed an identical pattern to their TD peers regarding the effect of occlusion configuration upon disparity threshold; for both groups, threshold was lowest when a reference figure was present, introduction of a congruent occlusion cue increased thresholds by a small but significant amount, and conflicting occlusion caused disparity thresholds to increase by a factor of three compared to those obtained for the reference figure conditions. That there was a difference between the reference and congruent occlusion conditions indicates the group with ASD were not simply using the occluded figure as a reference plane, but were utilising the (indeterminate) constraints afforded by occlusion. The conflicting occlusion condition was the most informative – that those with ASD showed increased thresholds for conflicting compared to congruent occlusion indicates that the integration of metric and ordinal uni-modal cues is automatic in this population. This is inconsistent with the results of Bedford et al. (2016), who found that when two metric cues were incongruent, disparity sensitivity was no lower than for the single worst cue. While here I used a highly-reliable ordinal cue, Bedford et al. (2016) used texture. As seen in Chapter 3, reduced stereoacuity appears to bias cue-weighting towards metric monocular cues. While I was unable to measure the likelihood function of the occlusion cue, it seems that the texture cue was over-weighted in Bedford et al.'s ASD group (for evidence, see Figure 2 in Bedford et al., 2016, conditions D+ and T+). This use of qualitatively different cues may account for the discrepancy between my findings and those of Bedford et al. (2016).

There was one difference between the ASD and TD groups with respect to when the occlusion and disparity cues were conflicting – those with ASD did not show increased response speed variability for this condition, suggesting that although the introduction of conflicting cues caused a breakdown in performance, it did not increase judgement uncertainty in the ASD group. This is not consistent with the flattened perceptual prior suggested by Pellicano and Burr (2012); while a flattened occlusion prior could account for the fixed variability in response speed for those with ASD, it does not readily explain the deleterious effect of conflicting occlusion on disparity threshold. A more parsimonious consideration would be that while the occlusion prior is similar for ASD and TD populations, there may be group differences in the decision-making aspect of the 2AFC task used to assess the level of cue integration. In other words, though the performance of individuals with ASD may be reduced when cues are conflicting, their perceived difficulty of the task may remain the same causing within-subject response speed variability to be unchanged. Future work looking at within- or across-modality cue combination in ASD should use entirely monocular cues such as blur or cast shadows to prevent poor stereoacuity biasing the results.

5.4.4 Conclusions

The present study provided an examination of the impact of occlusion cues upon perceived depth-from-disparity. Cue integration did not depend upon level of stereoacuity or autism diagnosis. Unlike previous work, people with ASD were found to automatically integrate conflicting depth cues, lending support to the idea that the occlusion prior remains intact in ASD and that cue integration is automatic in this population. Future work should focus on use of cue combination paradigms which do not require the estimation of depth-from-disparity, as this has been shown to be disrupted in ASD.

CHAPTER 6

The functional significance of stereopsis does not follow a developmental trajectory

Accurate judgement of depth plays a fundamental role in a number of activities; for instance, advantages for binocular viewing and good stereoacuity have been demonstrated in hand-eye coordination tasks. However, it is not yet known whether the functional significance of stereopsis follows a developmental trajectory. Additionally, it has not been explored whether the relative size of the binocular advantage, or the effect of acute sensitivity to disparity, depends on motor skill sub-domain. Here, I sought to determine how motor performance is impacted by (a) monocular vs. binocular viewing, (b) stereoacuity and (c) age. Seventy-two children, aged 4 - 11 years, performed three different motor tasks (ball-catching, bead-threading and balancing on a beam) both binocularly and monocularly. Crossed and uncrossed stereoacuity thresholds were measured using the TNO stereotest. The scores for each activity (balls caught, beads threaded and foot touchdowns) were standardised and analysed using a series of linear mixed models. As expected, motor proficiency improved with age, but there was no age-dependent effect of binocular vs. monocular viewing or stereoacuity, indicating that the functional significance of stereopsis is not moderated by age. The relative utility of binocular viewing was most important for catching compared to the other motor tasks. However, stereoacuity affected performance in the same way across all motor tasks, with those who were less sensitive to stereopsis performing worse overall. Since the influence of stereopsis deficit does not seem limited to hand-eye coordination tasks, this means that we may need to re-think the relative importance of deficits in stereopsis.

6.1 Introduction

PREVIOUS chapters explored the development of depth perception and depth cue combination in both normal and atypical populations. From these findings, a consistent theme emerged; those with poor stereopsis tend to perform differently from those who are more sensitive to disparity information. While stereopsis is just one of the many cues that can be used to infer 3-dimensionality (see Chapter 1), it has been shown to produce a particularly strong sensation of depth in individuals with normal binocular vision even when highly reliable monocular cues are present (Hillis et al., 2004; Johnston et al., 1993; Knill & Saunders, 2003; Lovell et al., 2012; Vuong et al., 2006). For naive observers, binocular depth thresholds are improved by an order of magnitude compared to monocular thresholds (McKee & Taylor, 2010), and when stereopsis is recovered in individuals who were previously unable to perceive disparity, the quale of depth undergoes a striking change (Barry, 2009).

In the field of vision science, perception is generally regarded as encompassing the processing of sensory data, and this is reflected in the popularity of binocular vision as a field of study. However, in reality processing of sensory input is only a single component of the perception-action cycle (Sperry, 1952), where it is used to inform behaviour and modulate interactions with the surrounding environment. This is especially true for the domain of depth perception, where accurate judgement of location in depth could conceivably play a major role in a number of activities such as navigation/object avoidance, reaching and grasping. In spite of this, the potential advantages of stereopsis for performing such everyday visually guided tasks has received comparatively little attention; the evidence is particularly sparse regarding the functional consequence of stereoscopic deficits.

It is important to understand the role of binocular vision and stereoacuity in motor skill development, as both stereoacuity and motor skills continue to improve well into the second decade of life (Giaschi, Narasimhan, Solski, Harrison, & Wilcox, 2013; Branta, Haubenstricker, & Seefeldt, 1984; Davies & Rose, 2009). If one impacts upon the other, this has obvious consequences for rehabilitation. Disturbance of binocular vision is one of the most common childhood vision disorders (with amblyopia[1] and strabismus accounting for 5 - 7% of all vision disorders and ocular pathology in this group; Scheiman et al., 1996; C. Williams et al., 2008), but a variety of other causes have been known to result in poor stereopsis (such as convergence insufficiency, early unilateral cataract and retinal damage; it may also be disturbed by disruption of the particular neural machinery that underlies stereopsis, resulting in reduced stereoacuity with no specific underlying disorder). Children with developmental disorders such as cerebral palsy, Downs and Williams syndromes, and autism also have greater prevalence of binocular vision problems and subsequently reduced stereoacuity compared to their typically-developing peers (Ghasia et al., 2008; Tsiaras et al., 1999; Atkinson et al., 2001; Simmons et al., 2009). Around 60% of the general population have acute disparity sensitivity ($\leq$ 20 arc seconds), but of the remaining 40% as many as are quarter are reported as being stereo-blind (Zaroff et al., 2003; Bohr & Read, 2013; Bosten et al., 2015). With a significant proportion of the population (and a number of developmental disorders) exhibiting sub-standard stereoacuity, it seems prudent to re-visit the question of the functional significance of stereopsis, with particular attention paid towards whether it follows a

[1]A disorder of sight which results in decreased vision in an eye that otherwise appears normal, or out of proportion to associated structural problems of the eye. Amblyopia has three main causes: strabismus, anisometropia, and deprivation by vision-obstructing disorders such as congenital cataract.

developmental trajectory.

6.1.1 Normal binocular vision

The vast majority of the research that has assessed the utility of binocular vision has focused on fine motor control in the form of hand movements using either reach-to-point or reach-to-grasp paradigms. Stereoscopic information affords significant advantages during the planning and execution of these goal-directed movements. Appreciation of depth from disparity occurs by approximately 4 months of age (Fawcett, Wang, & Birch, 2005) and the benefits of stereopsis are seen within weeks of this development (Patterson, Gwiazda, & Held, 1982). They are better able to judge whether objects are within their range of reach and execute movement towards them when using two eyes, compared to when one eye is covered (von Hofsten, 1977; von Hofsten & Fazel-Zandy, 1984; Granrud, Yonas, & Pettersen, 1984; van Hof, van der Kamp, & Savelsbergh, 2006). For adults with normal binocular vision, visually-guided hand movements are slower and less accurate when viewing monocularly (Fielder & Moseley, 1996; Melmoth, Finlay, Morgan, & Grant, 2009; O'Connor et al., 2010; Servos, Goodale, & Jakobson, 1992). When viewing is restricted to a single eye, observers also tend to make more corrective movements (Melmoth & Grant, 2006), indicating that the planning of hand movements in 3D space is more uncertain when stereoscopic information is removed.

On-line visual feedback from the the hand and arm are critical to motor control; in a series of studies, Saunders and Knill (2004, 2005) demonstrated that when the perceived speed or trajectory of a reaching fingertip was perturbed, participants unconsciously compensated for both types of visual shift. While it is clear that having reliable visual feedback about hand position is important for movement execution, a study by B. Hu and Knill (2011) confirmed that stereoscopic information plays a particularly important role. In this study, on-line corrections to hand movements were significantly impaired under monocular viewing even when cues about hand position and movement were available. Taken together, these findings indicate that the removal of stereoscopic information causes deficits in both the planning and on-line control of fine motor movements.

The few studies which have assessed the significance of intact binocular vision in children have found that, though binocular advantage increases with age, the function of binocular vision differs depending upon the stage of development (Grant, Suttle, Melmoth, Conway, & Sloper, 2014; Suttle et al., 2011; Watt, Bradshaw, Clarke, & Elliot, 2003). Younger children (i.e. < 8 years of age) tend to rely on binocular vision when planning movements, whereas older children (like normal adults) use it during the latter stages of movement execution. Aside from reach-to-grasp movements, little is known about the functional significance of binocular vision during motor actions in visually-normal children.

Although the majority of the research on the functional significance of stereopsis has focused on fine motor control, gross motor performance has also been shown to be affected by monocular viewing. For instance, walking is slowed and more caution is taken when stepping over obstacles (i.e. the foot is lifted higher; Hayhoe, Gillam, Chajka, & Vecellio, 2009). Participants also become worse at catching when viewing monocularly, with earlier grasping (indicating an underestimation of time-to-contact; van der Kamp, Savelsbergh, & Smeets, 1997) and larger grip aperture (demonstrating higher levels of perceptual uncertainty; Watt & Bradshaw, 2000) towards the thrown object, as well as actual interception occurring closer to the body (Mazyn, Lenoir, Montagne, & Savelsbergh, 2004).

6.1.2 Abnormal binocular vision

The evidence relating stereoscopic information and binocular advantage to certain aspects of visuo-motor performance (i.e. hand-eye coordination) in those with normal binocular vision is strong. However, the picture is less clear for those who have impaired stereoacuity. Much of the research on the relationship between impaired stereopsis and motor proficiency has used amblyopic child and adult patients. Amblyopia, defined as a "decrease of visual acuity in one eye caused by abnormal binocular interaction. . . or vision deprivation. . . for which no cause can be detected by the physical examination of the eye(s)" (von Noorden & Campos, 2002, p.246), affects between 1 - 4% of the general population (Webber & Wood, 2005). Many persons with amblyopia, especially those with strabismus, suffer from a large or complete loss of stereoscopic vision alongside the requisite reduction in visual acuity (see Levi, Knill, & Bavelier, 2015 for a detailed review of stereopsis in amblyopia).

Deficits in visually-guided hand movements observed in adult amblyopes are thought to be due to impaired stereopsis, as opposed to reduced visual acuity (Grant et al., 2007; Melmoth et al., 2009; Niechwiej-Szwedo, Goltz, Chandrakumar, & Wong, 2012; Suttle et al., 2011), fixation instability (Subramanian, Jost, & Birch, 2013), or impaired vergence control (Melmoth et al., 2007). Due to the co-occurrence of strabismus, amblyopia, and reduced stereopsis, it is not possible to conclusively state direct causation between reduced stereopsis and motor proficiency. Nevertheless, Melmoth et al. (2009) showed that reduced motor proficiency remained in amblyopic patients whose visual acuity had been successfully corrected, but stereoacuity was still impaired. The fine motor deficits seen in amblyopes are similar to when one eye is occluded for subjects with normal binocular vision; hand movements are significantly longer and less accurate, suggesting that on-line visual feedback is particularly impaired (Grant et al., 2007). The impact of reduced stereopsis of amblyopic origin also affect gross motor skills, causing reduced ability to adapt to changes in terrain (Buckley et al., 2010), possibly due to an impaired perception of space (Ooi & He, 2015).

In contrast to adults, for children with amblyopia the relative significance of reduced stereopsis is not so clear. Using a reach-to-grasp paradigm, Suttle et al. (2011) reported that children with amblyopia exhibited worse performance under *all* viewing conditions (even when viewing monocularly with the dominant eye), though – like adult amblyopes – binocular advantage for the clinical group was significantly less than for participants with normal binocular vision. Similarly, Grant et al. (2014) found that amblyopia severity was the main contributor to reduced motor proficiency, with stereo-vision being a secondary factor (though the latter was the unique determinant of reaching and grasping errors). In real-world visuo-motor integration tasks, reduced stereopsis has been shown to predict deficits, whereas severity of amblyopia has not (Hrisos et al., 2006). However, when the etiology of amblyopia (particularly that of strabismus) is taken into account, level of stereopsis ceases to be a significant factor (Webber et al., 2008).

Collectively, these studies indicate that while having poor stereoacuity may cause problems in a variety of motor tasks, the use of amblyopic subjects as a 'stereo-impaired' group is not practical, due to the numerous additional features of this disorder which can also affect motor proficiency, particularly in child populations. However, non-amblopic stereopsis impairment has recieved scant attention in the research literature, and the results thus far are in disagreement. Read, Begum, McDonald, and Trowbridge (2013) report that while participants performed faster and more accurately on a manual dexterity task when viewing binocularly, the level of binocular advantage did not correlate with their level of stereoacuity. In a similar vein, Murdoch et al. (1991) found that while those with poor or absent stereopsis performed poorly on a task which included binocular 3D cues, some individuals had better dexterity than would be anticipated by their stereoacuity levels. On the other hand, O'Connor et al. (2010) showed that performance on natural prehension movements such as bead-threading was related to stereoacuity, with those with normal stereoacuity performing best. It is clear that much uncertainty still exists regarding the functional significance of stereoacuity.

6.1.3 Motivation for the current study

Previous research has two major limitations, which will be laid out here for the reader. Firstly, earlier work has tended to focus on adult populations, with studies on children either being restricted to a very narrow age band or transforming the continuous variable of age into a discrete di- or tri-chotomous variable (i.e. young vs. old). This precludes the investigation of whether a true developmental trajectory might exist between stereoacuity and motor proficiency; the transformation of age into a discrete variable is particularly problematic, as this characterises individuals on either side of the arbitrary cut-off points as being very different, rather than very similar. Similarly, few studies make full use of stereoacuity data, instead using arbitrary cut-offs to create discrete groups with 'normal', 'poor', and 'nil' stereopsis. This is partially due to the widespread use of amblyopic patients as a general 'stereo-deficient' group and creates problems similar to those detailed for the transformation of age.

Splitting the data in this way results in the loss of information regarding individual differences, a reduction of effect size and statistical power, the occurrence of spurious significant main effects and interactions, and problems in comparing and aggregating findings across studies. Indeed, MacCallum, Zhang, Preacher, and Rucker (2002, p. 29) go as far to say that "there have been no findings of positive consequences of dichotomsation of data". In order to truly determine if sensitivity to stereopsis moderates motor proficiency, and if this relationship follows a developmental trajectory (i.e. if poor stereopsis exerts less of an impact on younger children compared to their older peers), it is recommended that both age and stereoacuity measurements are not transformed into categorical variables and instead are entered into analysis as continuous variables (MacCallum et al., 2002).

Second, fine motor movements are disproportionately represented in past work, especially so within the context of reach-to-grasp or reach-to-point paradigms. While the motor-control literature tends to differentiate between 'gross' and 'fine' motor control, movement assessment tools such as the Movement Assessment Battery for Children (Henderson, Sugden, & Barnett, 2007) and the Bruininks-Oseretsky Test of Motor Proficiency (Bruininks, 2005) aim to test three different subcomponents (also known as 'taxons', established through use of factor analysis; Schulz, Henderson, Sugden, & Barnett, 2011) of motor control: 'manual dexterity', 'aiming and catching', and 'balance'. Though real-world tasks have been used when assessing the link between motor proficiency and stereopsis, again, the majority focus on fine-motor/manual dexterity type skills (Read et al., 2013; Schiller, Kendall, Kwak, & Slocum, 2012; Murdoch et al., 1991; Webber et al., 2008; O'Connor et al., 2010). Very few have used motor tasks which assess both fine and gross motor coordination across all three domains (Hrisos et al., 2006). While it would appear that binocular advantage is present across a range of tasks involving manual dexterity (see above), presence of and sensitivity to stereopsis may contribute more to certain subcomponents of motor control compared to others (Grant et al., 2014). For this reason, it is important to assess motor skill proficiency across a variety of domains in the same cohort.

In the present study, I specifically wish to examine whether the functional significance of stereopsis (i.e. the utility of stereopsis when performing motor tasks) follows a developmental trajectory. Unlike previous studies, the current research will measure motor proficiency across three motor domains in the same cohort – manual dexterity will be assessed using bead-threading; aiming and catching will evaluated through two-handed ball catching; and balance will be appraised by having the child balance on one leg for an extended amount of time. It is predicted that children with poor stereoacuity will perform significantly worse across all motor tasks than those who are acutely sensitive to stereopsis. However, the former group should exhibit a reduced binocular advantage compared to the latter. The extent of the binocular advantage should increase with age (as has been observed in other studies; Watt et al., 2003; Suttle et al., 2011; Grant et al., 2014). Accordingly, it is predicted that there will also be an age-dependent effect of stereoscopic sensitivity, where older children with poor stereo are more adversely affected than their younger peers.

6.2 Methods

6.2.1 Participants

Seventy-two children aged 4 to 11 years took part in this study. See Table 6.1 for descriptives regarding the age of child participants. Children were recruited through the 'Summer Scientist Week 2014' public engagement event at the University of Nottingham. The study was approved by the University of Nottingham School of Psychology Ethics Committee. All parents/guardians gave written, informed consent for their child to take part in the study. Children gave verbal consent to participate in line with the University of Nottingham's Ethics Committee Guidelines. All participants had normal or corrected-to-normal visual acuity, but presence of stereopsis was not required.

Table 6.1: Child participant age breakdown

age	$\bar{x}$ (years)	σ	n (female)
4	4.688	0.213	4 (2)
5	5.623	0.276	6 (3)
6	6.546	0.317	10 (6)
7	7.498	0.221	11 (2)
8	8.495	0.314	16 (9)
9	9.566	0.368	11 (3)
10	10.507	0.300	9 (6)
11	11.496	0.344	5 (3)

6.2.2 Design

A repeated measures design was used, including within-subject factors of viewing condition and motor activity. Presence of binocular disparity ('viewing condition') was manipulated within participants by means of an eye patch occluding their non-dominant eye; viewing could therefore be either monocular or binocular. All children undertook three motor activities – balancing on a beam, catching a ball, and threading beads onto a string. The full details of these activities can be found below. Each activity was repeated three times under both binocular and monocular viewing, giving a total of 18 experimental blocks. Viewing condition was counterbalanced within each activity and order of activity was counterbalanced across participants, both using a balanced Latin square.

6.2.3 Procedure

The testing location was a large, quiet room, with participants tested one at a time. Parents were present if the child preferred it, and sat behind the child so they were not distracting. A video camera recorded the child's actions to allow independent scoring on each of the motor activities. Each child completed the following tasks in a fixed order, with exception of the motor activities which were administered according to counterbalancing.

6.2.3.1 Ophthalmic measures

Crossed and uncrossed stereoacuity was measured using the TNO stereotest (TNO, 1972); see Chapter 3, subsection 3.2.1.2 for detailed information about this clinical test. When shown in the intended orientation, the TNO test measures crossed disparity threshold. Uncrossed disparity threshold can also be measured by inverting the testing booklet.

6.2.3.2 Assessing laterality

Prior to the experimental task, the child's dominant eye, hand, and foot were recorded. Ocular dominance was evaluated using the distance-hole-in-the-card test (also known as the Dolman method; Durand & Gould, 1910), where the child was given a piece of card with a 3cm diameter circular hole in the center. They were instructed to hold the card with both hands straight ahead at arm's length while viewing a cartoon character at ~ 1.5 metres with both eyes. The child was then asked to slowly draw the card slowly back toward their head while maintaining fixation on the cartoon character. The eye that was underneath the hole in the card was considered to be the dominant eye. Preferred hand was measured using the Edinburgh Handedness Inventory – Short Form (Veale, 2013), which uses four tasks to determine hand dominance: writing (my participants to draw a circle), throwing (in my instance, a small beanbag was thrown to the experimenter), make-believe teeth-brushing (with the child either miming holding the handle of a toothbrush or through symbolic use of the index finger), and use of a spoon (I asked the children to mime eating soup or cereal). Since foot dominance is recommended to be assessed in context of the functional characteristics of footedness inherent to the experimental task (Gabbard & Hart, 1996), I asked the participants to execute three tasks which required stabilising support: miming kicking a ball (foot used to kick recorded as dominant), balancing on one foot (ditto for foot balanced upon), and stepping onto a block (ditto for foot initially used to step).

6.2.3.3 Motor activities

A standardised methodology (Bruininks, 2005) was used for all three motor activities, all of which are items taken from the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition (BOT-2). All activities were first demonstrated by the experimenter, and the child was allowed two practice trials for each task to ensure they had understood the instructions. Scores for each task were aggregated over all trial blocks for each viewing condition.

Beam-balancing ('balancing') task. The balancing task required the participant to balance on a wooden beam on their dominant foot, with arms outstretched and non-dominant foot raised, for 10 seconds. If the child became unsteady and had to ground themselves by means of their non-dominant leg, they were instructed to resume the balance position as quickly as possible. The number of non-dominant foot-on-floor touchdowns were recorded and used as an indicator of instability; since the score measured a deficit, it was given a negative sign (i.e. if a child touched their foot on the floor twice, they were given a score of -2).

Ball-catching ('catching') task. This task involved two-handed catching of a ball thrown underhand by the experimenter (a trained pitcher) from a distance of 1 metre. The participant was required to keep both feet within a small 'bounding box' marked out with masking tape on the floor throughout this activity, preventing them lunging forward in order to catch the ball. The child was also instructed to begin the trial with their hands by their sides; if any child began a trial with hands in the catching position, or made anticipatory movements before the experimenter threw the ball, the trial was discarded and repeated. The number of successful catches were recorded – any trials where the ball was trapped against the body by the arms or wrists were discarded and repeated. In each experimental block, the ball was thrown twice, giving a maximum possible score of six for each viewing condition.

Bead-threading ('threading') task: For the threading task, participants were asked to thread beads onto a string as quickly as possible for 15 seconds. A neutral starting position was assumed before the initiation of a trial, with the index fingers of each hand touching a sandpaper target on the edge of a table. The cube-shaped beads were above and directly within reach of the participant's dominant hand, whereas the string was placed above the non-dominant hand. The number of beads threaded in the allotted

Table 6.2: Pearson correlation coefficients for between-participant characteristics. Significant relationships are indicated by asterisks.

	age	BPVS	SAS	SES	$TNO_{crossed}$
age	–				
BPVS	−0.13	–			
SAS	0.01	0.15	–		
SES	0.22	−0.24	0.06	–	
$TNO_{crossed}$	−0.32	0.05	−0.17	−0.14	–
$TNO_{uncrossed}$	−0.44 **	0.14	−0.04	−0.20	0.81***

Note: $*p < 0.05$, $**p < 0.01$, $***p < .001$. Significance values Bonferroni-corrected in order to adjust for multiple comparisons.

time was recorded.

6.2.3.4 Standardised measures

In addition to the tasks described here, each child completed the BPVS-2, a standard measure of verbal abilities (L. M. Dunn & Dunn, 2009) with a separate researcher, and parents completed the Social Aptitudes Scale (SAS; Liddle et al., 2008), a general measure of social ability. These measures were completed to check if they correlated with TNO score.

6.3 Results

Stereoacuity (as measured by the TNO test) of the sample as a whole ranged between 0.004 – 0.556 degrees for both crossed and uncrossed disparities (median = 0.017). No children were stereoblind – all possessed, at minimum, coarse stereopsis. Thresholds for crossed and uncrossed disparities were highly correlated, as can be seen in Figure 6.1 . Uncrossed stereoacuity was also found to correlate with age (see correlation matrix in Table 6.2).

Motor proficiency (i.e. aggregate 'score' attained for each task) was entered as the dependent variable in a series of linear mixed-effects models (implemented via the `mixed` function of the R package `afex`; Singmann & Bolker, 2014). All models contained factors for viewing condition (monocular, binocular) and activity (balancing, catching, threading), and a continuous mean-centred predictor in the form of age. Select models had additional predictors in the form of crossed and uncrossed stereoscopic acuity (as measured by the TNO) – these measures were log-transformed and mean-centred.

The measure of motor proficiency was standardised through transformation to z-scores activity-wise, so that performance might be fairly compared across different motor tasks

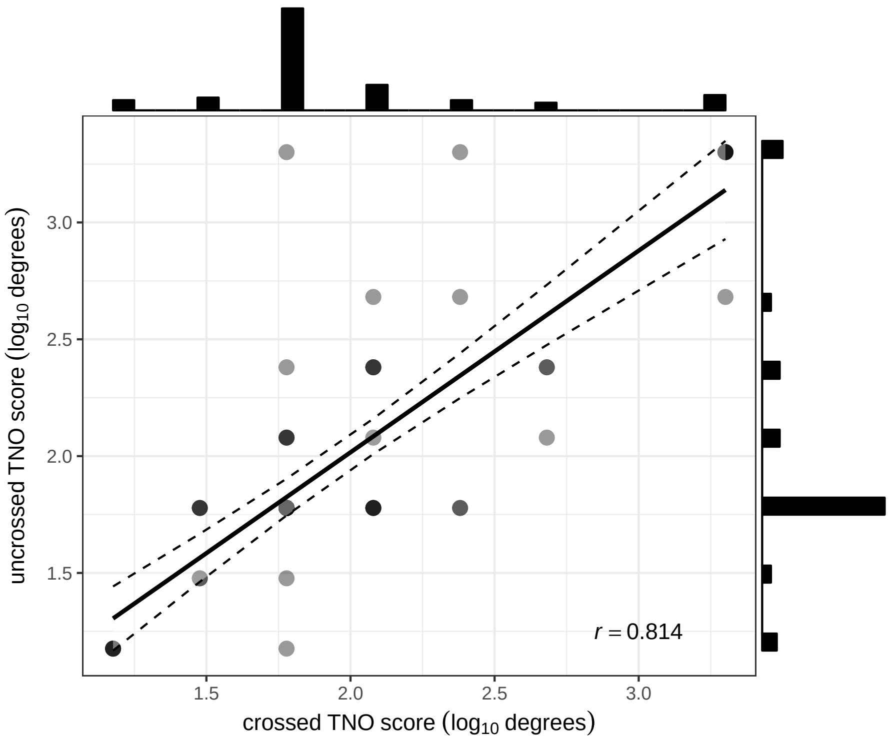


Figure 6.1: Correlation between crossed and uncrossed log-transformed TNO scores. Opacity of points relates to the number of individuals with those scores, where darker indicates a higher proportion. This incidence data is also reflected in the histograms at the top (for crossed stereoacuity) and right (for uncrossed stereoacuity) of the graph. Dotted curves around line of best fit indicate ± 95% confidence interval.

and to prevent a nuisance main effect. Sum contrast coding was used for categorical variables.

Initially, an attempt was made to fit a fully-specified model with random intercepts and fully crossed slopes including all factors and continuous predictors specified above. However, severe collinearity between the TNO score predictors (indicated by Variance Inflation Factor (VIF) = 6.288 and kappa = 9.949, where VIF ≥ 3 and kappa ≥ 6 indicate collinearity; Baayen, 2008; Zuur, Ieno, & Elphick, 2010) made estimating effects using restricted maximum likelihood impossible as the model failed to converge, even when using a different optimiser (Bates, Mächler, Bolker, & Walker, 2014).

To ameliorate the issue of collinearity, three separate models were specified.The first model (the 'truncated' model) did not contain stereoscopic acuity as a predictor, whereas the second and third models included crossed and uncrossed stereoscopic acuity respectively (the 'crossed' and 'uncrossed' models). For all three models, random intercepts and fully-crossed slopes were included as recommended by Barr (2013).

I report omnibus Type-III tests, with denominator degrees of freedom, F-scaling factors and p values obtained via Kenward-Roger approximation (Halekoh & Højsgaard, 2014) in Appendix C.1 Tables C.1, C.3, and C.5. β-values for continuous variables can be seen

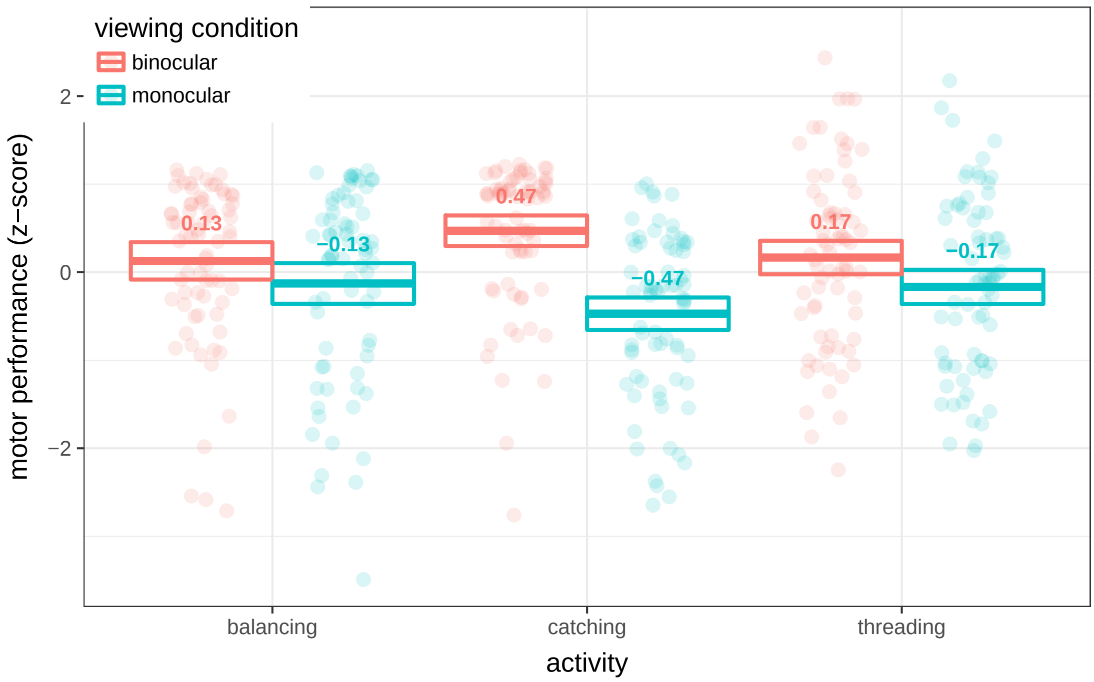


Figure 6.2: Mean ± 95% confidence interval of motor performance (z-score) for the two-way interaction between viewing condition and motor activity. Thick bars and number annotations are least-squared means, bounding box is 95% confidence interval, and points are the scores of individual children.

in Appendix C.1 Tables C.2, C.4, and C.6. To counteract the increased likelihood of Type I error in the case of multiple statistical tests, all p values in the omnibus tests were Bonferroni-corrected (O. J. Dunn, 1959, 1961). In cases where a significant main effect or interaction was found, pairwise comparisons were made with p values adjusted using the Tukey method (Tukey, 1977), using the R package `lsmeans` (Lenth, 2014).

All three models revealed consistent main effects of viewing condition and age, as well as an interaction between viewing condition and activity. For these predictors, I report statistics from the first model only; statistics for the other models are extremely similar and can be seen in Appendix C.1. A significant main effect of viewing condition (F(1, 70) = 88.642, p = <0.001) revealed that children exhibited a moderate increase in performance when viewing binocularly, compared to monocularly (z-score difference = 0.51 [SE = 0.054]). Figure 6.2 suggests an interaction between viewing condition and motor activity, which was confirmed by the omnibus test (F(2, 140) = 17.927, p = <0.001).

Post-hoc tests showed that while performance was increased for binocular compared to monocular viewing for all three tasks (balancing – t(209.385) = 2.834, p = 0.005; catching – t(209.385) = 10.41, p = <0.001; threading – t(209.385) = 3.677, p = <0.001), there was an increased binocular advantage for catching compared to balancing (t(112.812) = -2.615, p = 0.027) or threading (t(139.96) = 2.802, p = 0.016).

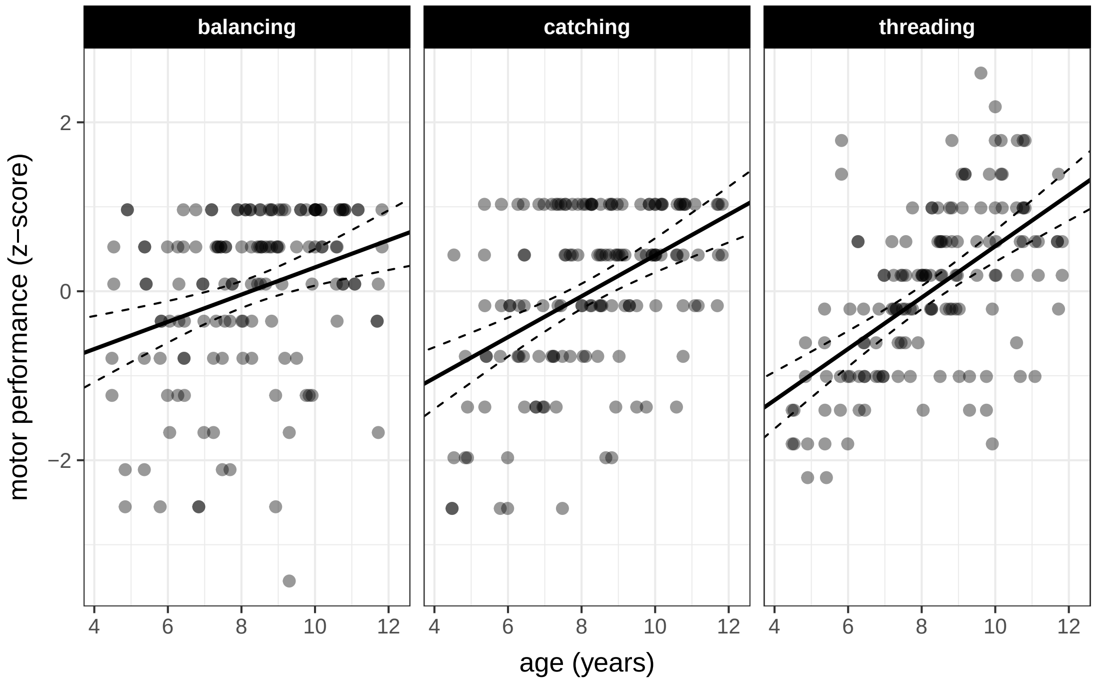


Figure 6.3: Linear developmental trajectory (± 95% confidence interval) of motor performance (z-score) for the main effect of age is similar regardless of motor activity.

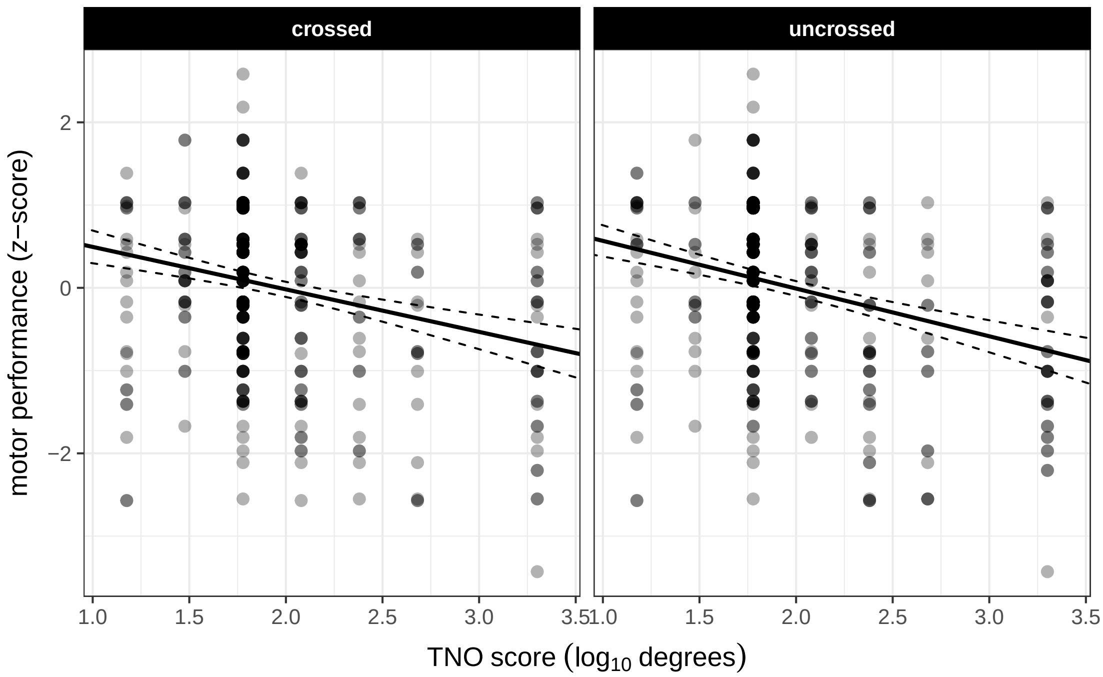


Figure 6.4: Motor performance (z-score; all scores from all activities across all participants) as a function of stereoacuity (as measured by TNO score). Left facet shows crossed TNO score, right facet shows uncrossed TNO score. Dotted curves around lines of best fit indicate ± 95% confidence interval.

Scores did not significantly differ under binocular viewing between the balancing and threading tasks (p = 0.958).

A significant main effect of age ($F(1, 70) = 49.255$, $p = <0.001$) indicated that as children matured, motor proficiency increased across all tasks ($\beta = 0.318$; see Figure 6.3 for developmental trajectories for each task). There were no interactions involving age in the truncated model.

The stereoacuity models showed main effects of both crossed ($F(1, 68) = 8.785$, $p = 0.013$) and uncrossed ($F(1, 68) = 9.497$, $p = 0.009$) stereoscopic acuity, where individuals with higher (i.e. worse) stereoacuity tended to perform worse across all motor tasks (see Figure 6.4; $\beta_{crossed} = -0.424$, $\beta_{uncrossed} = -0.479$).

However, there were no second order interactions between stereoscopic acuity and viewing condition ($p_{crossed} = 1.000$, $p_{uncrossed} = 0.225$), activity ($p_{crossed} = 1.000$, $p_{uncrossed} = 1.000$), or age ($p_{crossed} = 0.569$, $p_{uncrossed} = 0.267$), nor any higher order interactions (see Tables C.3 and C.5), for either of the stereoacuity models.

6.4 Discussion

This study aimed to identify whether the functional significance of stereopsis (expressed either through binocular advantage [intra-individual] or stereoacuity [inter-individual]) followed a developmental trajectory. I found that while there was an overall binocular advantage (i.e. performance was increased when viewing binocularly as opposed to monocularly), binocular viewing afforded larger gains within the context of certain motor domains (catching) compared to others (balancing, manual dexterity). Children with poor stereoacuity performed significantly worse across all tasks, but level of stereoacuity did not affect the extent of binocular advantage, nor was it moderated by age.

Other research has previously reported the existence of a binocular advantage for a variety of motor activities (see Sections 6.1.1 and 6.1.2), and has also noted that as task difficulty increases, the utility of binocular viewing becomes greater. However, few have reported the extent of binocular advantage across *different motor tasks*. Read et al. (2013) found that binocular vision was least useful when a task allowed for proprioceptive feedback (i.e. directly gripping manipulanda) and became progressively more useful as this kinaesthetic cue was reduced/removed (i.e. gripping manipulanda with forceps, buzz-wire task where success was indicated by lack of feedback). Across the three motor tasks used in the current study, catching displayed the largest binocular advantage – but a note of caution is due here.

A limitation of the current study is that the monocular condition was created by covering one eye, which results in more than simply a loss of disparity; additional binocular and monocular information such as vergence, tau (the rate of retinal expansion of an object), and interocular motion parallax are also removed (Collewijn & Erkelens, 1990). Previously in paradigms involving catching, it has been shown that when temporal constraints are imposed by increased ball speed, participants become less able to use monocular cues as these require longer processing times relative to stereopsis (Mazyn et al., 2004). Due to the slow pitching speed required when working with children (in the current study, the ball was in flight for ~ 1 second), it is possible that when viewing binocularly, participants were able to make use of more cues (both binocular and monocular, compared to those available when viewing monocularly) to consequentially make the good estimate of time-to-contact required for a successful catch. In other words, it may be the case that cues other that binocular disparity are responsible for the relative increase in binocular advantage for catching observed here.

Based on previous studies (Przekoracka-Krawczyk, Nawrot, Czaińska, & Michalak, 2014; Niechwiej-Szwedo et al., 2012; Grant et al., 2007; Webber et al., 2008; Hrisos et al., 2006; Grant et al., 2014; Murdoch et al., 1991; O'Connor et al., 2010; Suttle et al., 2011), I predicted that motor performance would increase as stereoacuity decreased (i.e. those with more acute stereoscopic acuity would have increased motor proficiency). This prediction was confirmed, as a main effect of stereoacuity was found across all motor tasks. However, unlike O'Connor et al. (2010) and Hrisos et al. (2006), I did not find that reduced stereoacuity affected only a certain subset of tasks. This may be due to differences in participant characteristics; O'Connor et al. and Hrisos et al. used patient (including those with severe refractive error, amblyopia, and strabismus) and control groups which were composed of limited age ranges (10+ and 5 - 6 years old respectively). As stated previously, stereoacuity and motor skills follow protracted developmental trajectories, continuing to improve even as the child reaches adolescence (Giaschi, Narasimhan, et al., 2013; Branta et al., 1984; Davies & Rose, 2009). Since the sub-domains of motor skill follow different developmental trajectories (Darrah, Senthilselvan, & Magill-Evans, 2009), it may be that the interaction of stereoacuity and motor task observed in these previous studies actually reflects the developmental level of the children involved rather than a deficit in stereopsis.

Another possible explanation for the lack of task-specific contribution of stereoscopic acuity is my use of mixed-effects models. 'Standard' statistical 'fixed-effects only' models, such as analysis of variance, may fail to account for individual differences in the effects of experimental manipulations (Kliegl et al., 2010). This can lead to spurious main effects and/or interactions, where only a small subset of individuals are responsible for such outcomes. It has already been seen that some individuals are comparatively less hindered by their stereopsis deficit , possibly due to task-specific training (Murdoch et al., 1991); a mixed-effects model is able to model *random* as well as *fixed effects*, ameliorating the impact of such individual differences (in this case, going some way toward accounting for the fact that some children will show particular proficiency at some motor tasks and not others).

This finding regarding the universal impact of reduced stereoacuity, while preliminary, suggests that we may need to re-think the relative importance of deficits in stereopsis. Until now, the majority of the literature has focused on manual dexterity. That reduced stereoacuity appears to also be of consequence in the other motor domains of aiming/catching and balance means that its influence is not only limited to daily skills such as writing or using cutlery, but also other activities such as playing games with other children involving physical activity, sports, and navigation. Furthermore, these broader motor competencies exhibit a strong link with social and emotional development (Cummins, Piek, & Dyck, 2005; Rigoli, Piek, & Kane, 2012; Skinner & Piek, 2001; Cairney, Rigoli, & Piek, 2013), indicating that reduced stereopsis may have deeper repercussions than simply affecting motor ability.

Various earlier work established that the degree of binocular advantage differed according to stereoacuity, with those who exhibited weak stereopsis (Mazyn et al., 2004; Grant et al., 2007) or were stereo-blind (Melmoth et al., 2009; Grant et al., 2014; Schiller et al., 2012) exhibiting equivalent performance under both monocular and binocular conditions, in contrast to their peers with normal stereopsis. The pattern of results observed in the current study do not reflect these previous findings. However, past studies which have assessed gross as opposed to fine motor ability (i.e. walking; Buckley et al., 2010) have also been unable to replicate this link between stereoacuity and the extent of binocular advantage. This has also been the case when stereoacuity is used as a continuous rather than categorical variable (Read et al., 2013).

Additionally, the measures of success used in the current study (number of balls caught, beads threaded, and foot touchdowns) are gross unrefined measures of motor proficiency. Almost without exception, research which found that those with reduced stereopsis also showed a lessened binocular advantage used landmarks extracted from kinematic analysis[2] as their dependent variables. It is possible (and, indeed, the studies mentioned above seem to corroborate this hypothesis) that stereoacuity only moderates binocular advantage in the case of select aspects of movement kinematics, rather than overall performance. While those with poor stereoacuity appear to have a degraded visual signal that effectively translates into a motor plan characterised by reduced precision, those individuals may to be able to compensate for this increase in uncertainty. Specifically, they may reduce motor output (a reduction in speed would allow for increased on-line adjustments to allow the integration of proprioceptive signals; Melmoth et al., 2009) or re-weight visual and proprioceptive cues (Niechwiej-Szwedo et al., 2012; Legrand et al., 2011). Being able to counteract in this way allows these individuals to effectively utilise binocular vision, despite their reduced ability to do so in the first in-

[2]While these vary depending on the study, common landmarks in reach-to-grasp research include reach errors, grip adjustment, total movement time, deceleration time, peak velocity, and number of velocity corrections (Bennett & Castiello, 1994).

stance or under time constraint. Further studies which utilise kinematic analysis across the entire range of motor sub-domains will be needed to understand the form which these compensations may take and their exact role in motor proficiency.

Here, I explored the contribution of binocular vision and stereopsis over the 4 – 11 year old age range. Unsurprisingly, I found that motor proficiency increases with age – this was expected, as motor skills tend to improve as a child gets older and results in the child being able to perform increasingly complex movements (Branta et al., 1984). In contrast to earlier findings, however, age did not interact with the extent of binocular advantage or stereoacuity.

Previously it has been been observed that the importance of binocular information for efficient [reach-to-grasp] performance increases (though to varying degrees) during development of children with normal binocular vision (Watt et al., 2003; Suttle et al., 2011; Grant et al., 2014). It has also been reported that sensitivity to stereopsis is moderated by age. For instance, Grant et al. (2014) showed that younger patient groups were more affected by their poor stereoacuity, compared to older patient groups who are able to compensate for these deficits (see the previous paragraph).

However, these apparent effects of age could be driven by the transformation of a continuous variable into a categorical one. All of the studies mentioned in the above paragraph converted their age variable into discrete groups consisting of younger and older children. Although such dichotomisation tends to lead to a reduction in power and subsequent increase in Type I error (Altman & Royston, 2006), when multiple predictors are involved it has been noted that spurious interactions involving the aforementioned transformed variable can occur (Maxwell & Delaney, 1993; MacCallum et al., 2002). Given that the age-related improvements in performance associated with the binocular advantage in these studies were relatively small (though significant), caution must be taken when interpreting these kinds of interaction. The statistical analyses of the current study – where all continuous variables were entered as such into the analysis – adds to the existing literature, as it allows for a more nuanced understanding on whether the importance of acute stereopsis and/or the extent of binocular advantage truly changes with age. The apparent absence of an interaction between age and either stereoacuity or viewing condition should be investigated more thoroughly in larger cohort of children.

6.4.1 Conclusions

The present study demonstrates that while there is an overall binocular advantage when performing a variety of motor tasks, and sensitivity to stereopsis affects overall motor proficiency, neither of these effects are moderated by age. This argues against a developmental trajectory for the functional significance of stereopsis, and demonstrates that stereoacuity plays an important role in motor proficiency from early childhood. Additionally, while certain motor domains appear to show an increased binocular advantage, the impact of reduced stereoacuity was universal across all tasks. Therefore, the repercussions of poor stereopsis may reach further than first thought, including possibly acting as a partial explanation for the relationship between motor proficiency and socio-emotional development. This conjecture is the topic of study in the next chapter.

CHAPTER 7

Does stereopsis account for the link between motor and social skills?

Experimental and longitudinal evidence suggests that motor proficiency plays a non-trivial role in the development of social skills. In support of this link, individuals with a developmental disorder such as autism spectrum disorder or developmental coordination disorder often present with both motor abnormalities and difficulties with social skills, as well as reduced depth perception. Stereopsis, or depth perception, may play a fundamental role in motor activities necessary for the initiation and maintenance of social interaction. To date, no systematic study has investigated the relationship between social skills and motor ability in the general adult population, and whether poor stereopsis may contribute to this association.

In order to test this hypothesis, 650 participants completed three validated questionnaires, the Stereopsis Screening Inventory (Coren & Hakstian, 1996), the Adult Developmental Coordination Disorder Checklist (Kirby, Edwards, Sugden, & Rosenblum, 2010), and the Autism Spectrum Quotient (Baron-Cohen et al., 2001). Exploratory and confirmatory factor analysis, and subsequent mediation analyses, were used to identify how social skill, motor ability, and stereopsis may relate to one another. An exploratory factor analysis on pooled items across all measures revealed ten factors that were largely composed of items from a single scale, indicating that any co-occurrence of poor stereopsis, reduced motor proficiency, and difficulties with social interaction cannot be attributed to a single underlying mechanism.

Correlations between extracted factor scores found associations between motor skill and social skill in a participant sample composed entirely of adults; this complements previous research conducted with children. Mediation analyses suggested that while fine motor skill and coordination explained the relationship between stereopsis and social skill to some extent, stereopsis nonetheless exerted a substantial direct effect upon social skill. This suggests that the functional significance of stereopsis is not limited to motor ability.

7.1 Introduction

THROUGHOUT this thesis it has been established that individuals with poor stereopsis perform differently on both perceptual and motor tasks. In the previous chapter, it was observed that stereopsis impairment affected performance across a wide range of tasks requiring both gross and fine motor proficiency. Since the influence of stereopsis does not appear limited to any single motor domain, this suggests that the relative importance of stereopsis deficits may be greater than first thought. The goal of this final chapter is to explore the wider implications of the reduction in motor proficiency that occurs alongside stereopsis impairment. In establishing the rationale for the current experiment, the relationship between motor and social cognitive abilities in typical development will first be considered. Focus will then be brought upon two neurodevelopmental disorders which exhibit co-occurring impairments in stereopsis, motor, and social skills, namely ASD and developmental coordination disorder (DCD).

7.1.1 The relationship between motor and social skills in typical development

Motor development cannot be considered an independent process, as it exhibits rich and complex relationships with regards to the development of other cognitive domains (Leonard & Hill, 2014). This so-called ‘dynamic systems’ approach (Thelen & Smith, 1994; K. L. Marsh, Richardson, & Schmidt, 2009) emphasises the multi-factor cyclic nature of the development of perception, action, and cognition. When reflecting upon development within the context of this framework, it is possible to see how a relatively small disruption in one of the interacting systems could be thus compounded and have escalating effects on other systems. It can also explain how seemingly independent skills such as stereoscopic acuity, motor control, and social interaction can be linked through similar underlying processes in the same system (see Iverson (2010) for a specific example involving the relationship between motor and language development). A basic movement repertoire of functional actions (involving both fine and gross motor domains) aids in the initiation and sustainment of successful social interactions; if these actions cannot be performed proficiently, this can have an impact on that individual’s social ability[1]. Motor control also plays an important role in joint attention (through actions such as head-turning, reaching, pointing, giving, and showing) and imitation, both crucial components of social relations (Bhat, Landa, & Galloway, 2011).

By far the greatest proportion of the research assessing the link between social and motor skills in typical development has focused on infants and young children (Leonard & Hill, 2014). A relationship between social and motor ability has been identified in children as young as 8 months (Lamb, Garn, & Keating, 1982), with development from crawling to walking encouraging the use of more advanced social interaction behaviours, including initiation of bids for joint attention and directed gestures (Clearfield, Osborne, & Mullen, 2008; Karasik, Tamis-LeMonda, & Adolph, 2011). A questionnaire-based study by Wang, Lekhal, Aarø, and Schjølberg (2012) collected data from parent reports

[1]However, it should be noted that while individuals with certain physical disabilities (who are unable to perform a number of these functional actions) can have difficulty tackling certain social situations (A. P. Thomas, Bax, & Smyth, 1988; Hebl & Kleck, 2000), appropriate supports can enable them to have typical social relations (Lippold & Burns, 2009).

at 18 months and 3 years for 62944 children. These data suggested that early motor skill (measured at 18 months) is a better predictor of communication ability measured at 3 years of age, than early communicative ability is at forecasting later motor proficiency.

Other research which used longitudinal designs reported relationships between motor function at 5–6 years and a range of social behaviours at 6–7 years (Bart, Hajami, & Bar Haim, 2007), and between motor abilities at 6–7 years and social status with peers at 9–10 years (Ommundsen, Gundersen, & Mjaavatn, 2010). Additionally, a reduction in social play and increased social reticence has been noted in children with poor motor skills (Bar Haim & Bart, 2006). Such co-occurrences are to be expected – if a child has poor coordination and slowed movement, it can be reasoned that they are less likely to interact socially in a play setting, reducing the opportunity to form friendships and social connections and thus leading to introverted behaviour.

As well as evidence of direct links between motor and social skills, motor competency has been associated with other cognitive domains that play an essential role in social relationships, such as language development (Cheng, Chen, Tsai, Chen, & Cherng, 2009) and emotion comprehension (Piek, Bradbury, Elsley, & Tate, 2008). Mental illness is also more common in those with poor motor control (Moruzzi et al., 2010; Hill et al., 2016); Wilson, Piek, and Kane (2013) have suggested that this may be due to social skills playing a mediatory role in the development of young children's motor skills and internalising behaviours (such as anxiety, depression, and worry).

7.1.2 Links between motor and psycho-social development in clinical populations

Poor motor and social skills often exist alongside one another in a number of developmental disabilities, including ASD and DCD (Diamond, 2000; Hartman, Houwen, Scherder, & Visscher, 2010; H. Kim, Carlson, Curby, & Winsler, 2016). While poor social skills are part of the diagnostic criteria of ASD (American Psychiatric Association, 2013), gross and fine motor impairment as well as difficulties in motor planning have been reported in up to 90% of those wth ASD (Gillberg, 1989; Klin, Volkmar, Sparrow, Cicchetti, & Rourke, 1995; Manjiviona & Prior, 1995; Ming, Brimacombe, & Wagner, 2007; D. Green et al., 2009; Lingam, Hunt, Golding, Jongmans, & Emond, 2009). Furthermore, there are well-established links between motor and social deficits in ASD, with significant correlations between motor skills and socialisation (Sipes, Matson, & Horovitz, 2011) and degree of social impairment (Dyck, Piek, Hay, & Hallmayer, 2007; Hilton et al., 2007; Perry, Flanagan, Dunn Geier, & Freeman, 2009; Hilton, Zhang, White, Klohr, & Constantino, 2011) in this clinical group. Conversely, though motor dysfunction is central to the diagnosis of DCD (which is also referred to as 'dyspraxia' and affects around 5% of the population; Lingam et al., 2009), there has been an increasing interest in the social functioning of individuals with DCD in recent years. Both clinical and screening studies have reported significant relationships between motor abilities and parent-reported peer or social problems (Cummins et al., 2005; D. Green, Baird, & Sugden, 2006; Wagner, Bös, Jascenoka, Jekauc, & Petermann, 2012; Jarus, Lourie-Gelberg, Engel-Yeger, & Bart, 2011), with those with impaired motor skills conducting more social activities alone and generally being more isolated from their peers.

From the few studies that have made a direct comparison between ASD and DCD it would appear that both disorders exhibit a similar range of social and motor issues (Dewey, Cantell, & Crawford, 2007; D. Green et al., 2002) [2] and it may be that the co-occurrence of these patterns of impairment is attributable to another underlying or 'latent' factor. Both those with ASD and DCD have a higher incidence of poor stereopsis – the binocular vision and stereoacuity issues seen in those with ASD have been discussed in previous chapter, but those with DCD are also more likely to have problems with binocular vision. Markedly, a study by Creavin, Lingam, Northstone, and Williams (2014) reported that those with DCD were on average 8 percentage points more likely to have impaired stereopsis (i.e. stereoacuity of > 60 arc seconds) than their TD peers (though those with severe DCD were more likely to show evidence of poor depth perception than those with moderate DCD).

7.1.3 The current study

As noted in the last chapter, reduced depth perception is associated with reduced motor proficiency across both fine and gross motor domains. The previous research surveyed here suggests that effect of diminished motor skills can be seen in childhood, influencing one's ability to play and interact with others in a socially acceptable way. Reduction in motor ability may prevent gaining an understanding of the general skills necessary to initiate and sustain social interactions, and could therefore influence later social standing with peers. Given the relationship between earlier peer acceptance or friendships and later academic achievement (Wentzel & Caldwell, 1997) and adult adjustment (Bagwell, Newcomb, & Bukowski, 1998), understanding the possible risks (i.e. impaired stereopsis) associated with poor motor skills on the development of appropriate social behaviour and friendships could have far-reaching consequences.

It is clear that many aspects of development work in parallel, with progress in one domain being held back if there are significant impairments in others. However, causal relationships between these domains are not explicit and the key directions of causation

[2] It should be noted, however, that the DSM-IV (American Psychiatric Association, 2000) precluded those with ASD from also obtaining a DCD diagnosis. In the past, it has been difficult to know if social difficulties are brought about by reduced peer contact due to the emphasis on physical play in the playground, or whether social difficulties were pre-existing and are independent of motor difficulties. This is no longer the case in the DSM-5, though no studies have yet addressed the co-morbidity rate of ASD and DCD.

are as yet unknown. Furthermore, much of the previous work that has investigated the relationship between motor and social skills has focused exclusively on children, with a remarkable paucity of research involving adults. This study has two primary aims. The first is to extend the previous research linking motor and social skill impairment in children to an adult sample, identifying the possible later consequences of early deficit in these domains. Secondly, I wished to examine which particular aspects of motor and social skill impairment were contributed to by reduced stereopsis; it is not evident if the effects of poor stereoacuity are strong enough to be able to affect social skill through mediation by motor ability. To further assess the presence of possible links between stereopsis, motor proficiency, and social skill, I administered the Adult Developmental Coordination Disorder Checklist (ADC), Autism Spectrum Quotient (AQ), Stereopsis Screening Inventory (SSI), three validated questionnaires used in clinical settings, as well as a self-assessment of autostereogram skill, to a large group of adults.

7.2 Method

7.2.1 Participants and recruitment

A total of 650 participants completed a series of questionnaires (see subsection 7.2.2), although not all participants completed all measures. Demographic data were optional; of the participants who completed these items 369 were female, 227 were male, and 6 identified as 'other'. Ages of participants who chose to divulge this information ranged from 16 - 70 years old, with a median age of 23.

Ethical permission from the University of Nottingham's School of Psychology Ethics Committee was granted prior to recruitment. Participants were sampled opportunistically from Reddit (`www.reddit.com`; n = 311, 47.8%), social media and email (n = 193, 29.7%), and an internal recruitment system for undergraduate students at the University of Nottingham for partial completion of course credit (n = 146, 22.5%). The survey was advertised on Reddit in areas relating to research in general (`www.reddit.com/r/samplesize`), Asperger's Syndrome (`www.reddit.com/r/aspergers`), and autism (`www.reddit.com/r/autism`). Specific details of the number of respondents from each of the sub-forums were not taken. Both of the ASD-related forums are aimed towards people with autism/related conditions and their families and friends, and include discussion of autism-related research.

Potential participants were provided with a paragraph explaining the study and a hyperlink taking them to the survey website; the experiment was carried out entirely on-line with no face-to-face contact. Although all materials used were originally developed as 'pen-and-paper' questionnaires, it appears there is little variation in responses when 'pen and paper' questionnaires are presented on-line (Van De Looij-Jansen & De Wilde, 2008; Wu et al., 2009). Individuals were advised the completion of the study would take approximately 20 minutes. All participants were offered the chance to enter into a prize draw for one of two £15 vouchers.

Although some participants disclosed that they had a diagnosis of ASD (n = 3), data from all participants was included, as recent evidence suggests that autistic traits lie on a continuum in the general population (Constantino et al., 2003).

7.2.2 Materials

ADC: the ADC (Kirby et al., 2010) is a validated screening tool for identifying the difficulties experienced by adults with DCD. The ADC consists of three sub-scales; the first relates to difficulties that the individual experienced as a child (10 items). This enables a history of childhood difficulties which can then be distinguished from acquired problems in adulthood. The second (10 items) and third sub-scales (20 items), relate to current difficulties that the individual considers are affecting their performance. The second sub-scale focuses on the individual's perception of their performance, whereas the third sub-scale relates to current feelings about their performance as reflected upon by others. All items are rated on a four-point scale (never, sometimes, frequently or always). Participants receive a score of 0 - 3 for each question, resulting in possible scores ranging from 0 to 120. Recommended cut off scores include ≥ 56 for "at risk of DCD" and ≥ 65 for "probable DCD" (Kirby et al., 2010).

AQ: the AQ (Baron-Cohen et al., 2001) is a self-report questionnaire comprising of 50 statements with four-point response options (strongly agree, slightly agree, slightly disagree or strongly disagree). It was initially designed as a measure of autistic characteristics in the general population. Although a 4-point response format is used, it is typically scored in a binary manner, where a response is scored as a one if it indicates an autistic trait and zero if this is not the case; this yields a score that can range from 0 to 50. Higher scores indicate more symptoms of ASD; using this scoring approach, Baron-Cohen et al. (2001) determined the optimal cut-off for identifying people with clinically significant levels of autistic traits to be 32 or above. The AQ can also be scored according to the four-point response option (E. J. Austin, 2005; Hoekstra et al., 2011), which potentially yields a more sensitive index of ASD severity. In the current study, binary scoring was used to determine the proportion of participants that scored above the 32-point threshold mentioned previously. For all other analyses, including the exploratory factor analysis, the four-point response option format was used.

Autostereogram Self-Assessment (ASA): the ASA is a short four-item survey created by the author of the current study where the participant self-assessed their autostereogram skill. Based upon short reports by Wilmer and Backus (2008) and Cisarik, Davis, Kindy, and Butterfield (2012), the questions asked the subject to identify two autostereograms (which can be seen in Figure 7.1; the respondent was offered four possible choice plus an 'I don't know' option. Correct answers were designated a score of 1, all other answers were given a 0), how difficult they found viewing the autostereograms (on a scale from 1 to 5, where 1 was extremely difficult and 5 very easy), and whether they had successfully perceived stereopsis in an autostereogram previously ('yes' answers were given a score of 1, all others a 0). Self-reported skill to perceive depth in autostereograms has been found to be predictive of stereoacuity, as measured by the TNO test (r = .45; Wilmer & Backus, 2008; Cisarik et al., 2012).

SSI: the SSI is a self-report screening inventory for stereopsis (Coren & Hakstian, 1996). It is composed of 10 statements with five response options (never, seldom, occasionally, frequently, always). Responses are summed to obtain a scale total. It has an acceptable internal consistency (.88) and test-retest reliability (.88). Additionally, Coren and Hakstian (1996) demonstrated that the scores obtained using the SSI correlate highly (r = .8) with laboratory measures of stereopsis such as the TNO test, with others demonstrating a moderate relationship between these measures (r = .34; Wilmer & Backus, 2008). Recommended cut-offs are ≥ 17 for moderate stereopsis deficit and ≥ 30 for major stereopsis deficit.

7.2.3 Missing data

If a participant left more than 10% of responses across all items blank, the data were excluded from the analysis (n = 0; highest proportion of missing data for a single participant was 8.308%). The proportion of missing data for any individual questionnaire item ranged from 0 - 30%. Closer inspection of the pattern of missingness revealed that two items relating to driving ability in the Adult Developmental Coordination Disorder Checklist ("Did it take you longer than others to learn to drive?" and "If you are a driver, do you have difficulty parking a car?") accounted for the highest amount of missing data (28.154% and 30% respectively). When the data from these questions were removed from the analysis, the highest proportion of missing data for a single item was reduced to 10.154%.

Although the number of subjects in the study was 650, 290 cases were missing a response for at least one item. Thus, utilising a listwise method of data analysis (also known as 'complete-cases analysis') would have resulted in a 44.615% reduction in sample size. Additionally, if data are not missing in a completely random pattern ('Missing Completely at Random (MCAR)'), use of complete-case analysis can lead to biased results (Little & Rubin, 2002). Homoscedasiticy of the data was tested using the `TestMCARNormality` function (see Jamshidian & Jalal, 2010), which is part of the `MissMech` package in R. The test of homoscedasiticy was rejected, indicating that the data violated the MCAR assumption.

When data are not MCAR, it is recommended that the missing values are imputed to avoid the issues stated above (J. W. Graham, 2009). I used the R package `missForest` (Stekhoven & Buhlmann, 2011) to impute the missing data. Although multiple methods have been developed in order to deal with missing data - including single/multiple imputation, multivariate imputation by chained equations and nearest neighbour estimation - `missForest` has been demonstrated to introduce the least imputation error and has the smallest prediction difference from actual non-imputed values (Waljee et al., 2013).

7.2.4 Data analysis

Statistical analyses were performed using R 3.0.1. The relationship between scores on the ADC, AQ, ASA and SSI were first examined using Pearson correlation analysis. The data were then randomly split into two equally-sized groups, where n = 325, to act as training and test data in a cross validation procedure. All items from all measures (minus the two ADC items mentioned above) within the training data set were subjected to exploratory factor analysis (EFA). Oblique rotation was specified for the EFA, given that the factors were expected to correlate with one another based on theoretical and empirical grounds (Fabrigar, Wegener, MacCallum, & Strahan, 1999). Parallel analysis and Velicier's Minimum Average Partial Test (available as part of the `psych` package) were used to determine the number of factors to retain. Factors were further interpreted if the grouping of the loading variables made conceptual sense. Given the fairly large sample size, items were considered to load onto a factor if their loading was ≥ .32 (Tabachnick & Fidell, 2012).

Cross-validation was then performed using the test data set, with the factors extracted using EFA being used to specify the factor structure for confirmatory factor analysis (CFA). In CFA there is no single definitive indicator of model fit. The overall model fit was therefore assessed in terms of five measures from two perspectives: absolute fit and comparative fit to a base model, with index cut-offs (seen in brackets) informed by recommendations in the literature (L.-t. Hu & Bentler, 1999; Schermelleh-Engel & Moosbrugger, 2003; H. W. Marsh, Hau, & Wen, 2004; Hooper, Coughlan, & Mullen, 2008). Absolute fit measures included the model chi square/degrees of freedom (χ^2/df < 3.0)[3], standardized root mean square residual (SRMR; < .08), and root mean square error of approximation (RMSEA; < .06). The comparative measures were comparative fit index (CFI; ≥ .9) and Tucker-Lewis index (TLI; ≥ .9). Post hoc modification indices were applied to improve model fit. These indices were only used when modifications could be supported with theory as suggested by the literature; here, modifications con-

[3]The chi square (χ^2) statistic was not used to assess model fit due to its sensitivity to sample sizes where $n > 200$ and diminished validity when distributional assumptions are violated (Jöreskog, 1969; Bentler & Bonett, 1980; Kenny, 2015); it *was* used for comparing modified and unmodified models via chi-square difference testing.

sisted of allowing correlated residuals between items which loaded on to the same factor (Jackson, Gillaspy, & Purc-Stephenson, 2009).

In the case where CFA fit indices indicated an adequate fit to the test data, bivariate correlations and subsequent moderation and mediation analyses in the form of structural equation modelling were conducted upon the extracted factor scores from the CFA to determine how they related to one another.

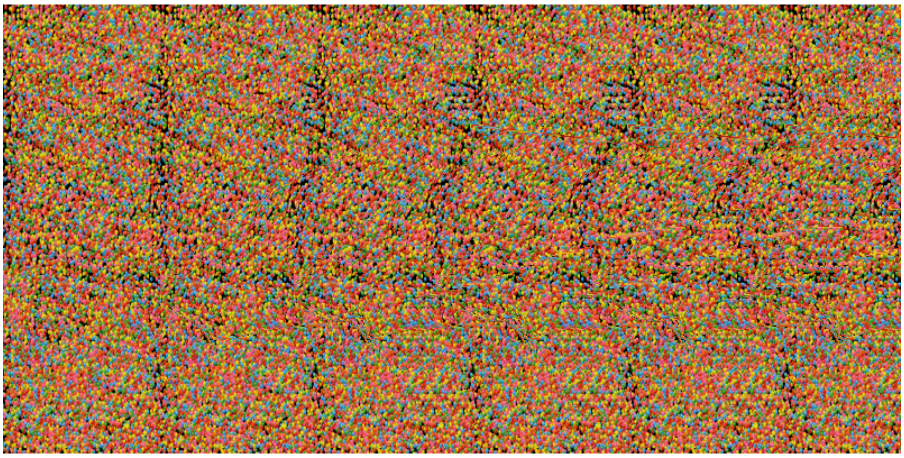
7.3 Results

7.3.1 Descriptive statistics

Tests of multi- and uni-variate normality indicated that the scores across all items did not meet the assumption of normality (Royston's H test (Royston, 1983), an extension of the Shapiro-Wilk test, was used to assess multivariate normality; $H = 11580.473$, $p = <0.001$). For large sample sizes, significant results can be derived even in the case of a small deviation from normality (Öztuna, Elhan, & Tüccar, 2006). In this case, however, the variables were clearly not normally distributed, see Figure D.1 in Appendix D.1.

All scales demonstrated acceptable internal consistency – see Table 7.1 for these and other descriptive data. Fifteen participants (2.308% of the sample) met 'DCD at risk' criteria [≥ 55], whereas 85 (13.077%) were at or above the threshold for 'probable DCD' [≥ 65]. One hundred and sixty-two participants (24.923% of the sample) obtained total (binary-scored) AQ scores of 32 or greater, indicating clinically significant levels of autistic traits and need for further diagnostic evaluation (Baron-Cohen et al., 2001). Two hundred and twenty-five participants (34.615% of the sample) had a moderate stereopsis deficit [> 17 but < 30, denoted by Coren and Hakstian (1996) to equal stereoacuity of more then 60 but less than 280 arc seconds] whereas a further 228 (35.077% of the sample) had a major stereopsis deficit [≥ 30, correlating to a stereoacuity of 280 arc seconds or greater (Coren & Hakstian, 1996)]. These are higher incidences than would be expected from participants drawn from the general population (where DCD has a prevalence of approimately 5% (Lingam et al., 2009), ASD 1.1-2.4% (Brugha, Cooper, McManus, Purdon, & Smith, 2012; Zablotsky, Black, Maenner, Schieve, & Blumberg, 2015), and stereopsis deficit 40% (Bosten et al., 2015)), but are ultimately unsurprising given that a significant proportion of the sample were recruited via a forum for those with autism or Aspergers syndrome.

It was not uncommon for participants who had a score above threshold for one measure to also score above threshold for at least one of the other measures. The most substantial *amount* of overlap between measures was for the AQ and the SSI, with 10.615 % of



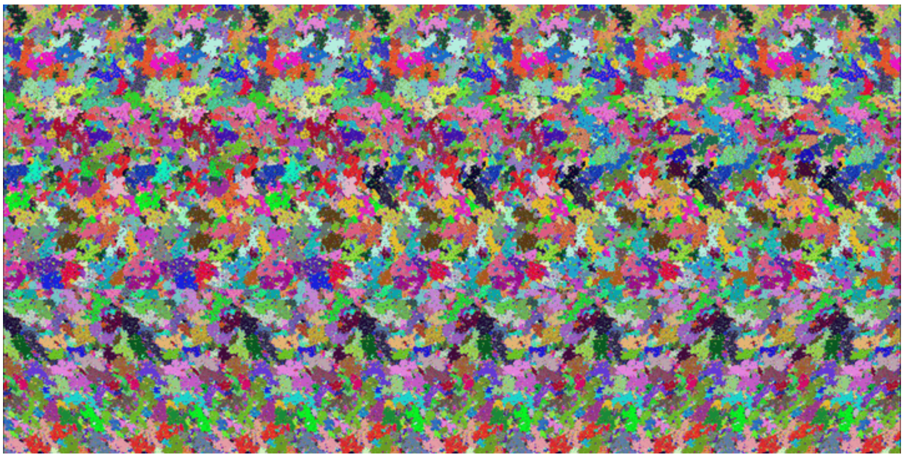


Figure 7.1: The two autostereograms used in the current study. The top autostereogram contains a shark, and the bottom a teapot. The instructions for viewing are as follows:

Above is an autostereogram or Magic Eye© picture - to reveal the hidden 3D illusion, you must diverge your eyes (i.e. focus beyond the image). First, bring your face close to the page (so that you are almost touching it with your nose). The image should appear blurry. Focus as though you are looking through the image into the distance. Very slowly move away from the page until you begin to perceive depth in the image. At this point, hold very still and the hidden image will slowly appear.

Table 7.1: Descriptive statistics for the Adult Developmental Coordination Disorder Checklist (ADC), Autism Spectrum Quotient (AQ), Autostereogram Self-Assessment (ASA), and Stereopsis Screening Inventory (SSI) (n = 650)

	M (SD)	range	skewness	kurtosis	Cronbach's α
ADC	41.7 (21.97)	0 – 116	0.75	3.09	0.94
AQ	121.52 (22.5)	78 – 179	0.29	2.16	0.91
ASA	3.6 (2.53)	1 – 8	0.61	1.82	0.72
SSI	24.14 (9.28)	9 – 45	-0.07	1.78	0.87

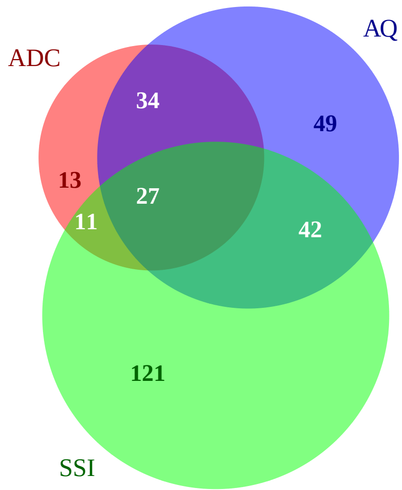


Figure 7.2: Depicted is a 3-set venn diagram where the size of the ovals indicates relative magnitude and the numbers within portray the number of participants who scored above threshold on th(at|ose) measure(s). Note that for the SSI, the higher threshold boundary indicating major stereopsis deficit was used.

the total participant sample scoring above threshold on both of these measures (note that the higher SSI threshold indicating major stereopsis deficit was used in this case). However, the largest *degree* of overlap was between the ADC and AQ, with 71.765% of participants who met the threshold for 'probable developmental coordination disorder' also scoring above threshold on the AQ. Figure 7.2 shows a venn diagram illustrating the extent of the overlap between the ADC, AQ, and SSI.

7.3.2 Correlation of measure totals

Bivariate correlations of measure scores revealed a number of significant associations. A strong positive relationship was observed between AQ and ADC total scores ($r(648) = 0.628$, $p = <0.001$), meaning that those with higher levels of autistic traits were also likely to exhibit higher levels of dyspraxic traits. Small-to-moderate positive correlations were observed between SSI and both AQ ($r(648) = 0.277$, $p = <0.001$) and ADC ($r(648) = 0.268$, $p = <0.001$) scores, indicating that higher levels of autistic and dyspraxic traits were associated with an increased degree of stereoscopic deficit. A small negative relationship was also observed between ASA and ADC scores ($r(648) = -0.106$, $p = 0.007$), denoting that those with increased dyspraxic traits tended to be worse at perceiving autostereograms. No significant relationship was found between between ASA and either AQ (p = 0.056) or (surprisingly) SSI scores (p = 0.502).

7.3.3 Exploratory factor analysis

Two of the measures used in the current study are conceptualised as being composed of pre-determined sub-scales. The AQ covers five purported domains associated with the autism spectrum: social skills; communication skills; imagination; attention to detail; and attention switching/intolerance of change (Baron-Cohen et al., 2001). Past factor analyses of AQ items have been inconsistent, with studies finding two, three, or four factors rather than five (Hoekstra, Bartels, Cath, & Boomsma, 2008). The ADC was designed around three sub-scales: the first relating to difficulties the individual being assessed experienced as a child; the second relating to the influence of dyspraxic symptomatology on the individual's perception of their own performance as an adult; and the third relating to the individual's current feeling about their performance as reflected upon by others (Kirby et al., 2010). However, the latent structure of the ADC has not yet been confirmed using factor analysis. Since the aim of this study is to assess the existence of latent variables that link autistic and dyspraxic symptomatology to reduced stereopsis, I used EFA to determine the dimensional structure of pooled items across the four measures previously described.

To ensure I met the assumptions of EFA, I first checked the factorability of the 'training' dataset (n = 325). The Kaiser-Meyer-Olkin coefficient of sampling adequacy was good (0.857; > .6 recommended by Cerny & Kaiser, 1977) and Bartlett's test of sphericity was signficant (χ^2 (5151) = 17439.845, p = <0.001; Bartlett, 1950), indicating that the data were suitable for factor analysis. Parallel analysis (Horn, 1965) and Velicer's Minimum Average Partial Test (Velicer, 1976), widely regarded as the most accurate methods for determining factor extraction and thus highly recommended as the principal methods for determining factor retention (Costello & Osborne, 2005; Ledesma & Valero-Mora, 2007), were used to determine the optimal number of factors. Both methods recommended that ten factors be extracted from the data. Factor loadings were calculated using principal axis factoring with oblmin (oblique) rotation on 102 of 104 Likert scale questions across all four measures (omitting the two items of the ADC which had a high proportion of missing data), and are shown in Table 7.2.

Labels have been provided for the 10 extracted factors, based on an interpretation of the items that constitute them. There was a small amount of cross-loading between factors, but this was not so substantial as to cause concern. The first factor was titled 'social skill', as it represents awareness of how easy/enjoyable the individual finds social interactions. Factor 2 has been termed 'stereopsis', as it seems to represent aspects of vision required for stereopsis. The third factor has been given the title 'attention to detail', as all items under this factor involved the processing and/or planning of small details. Factor 4 was called 'fine motor skill', as it comprises mostly of items related to writing ability which requires a relatively high level of fine motor proficiency. Factor 5 was titled 'organisation' as it represents issues with general organisation and forward planning. The sixth factor

Table 7.2: Factor loadings of an ten-factor EFA solution for items pooled across all measures. Principal axis factoring, oblmin rotation. Loadings below .32 (which explain less than 10% of the variance in that item) are not highlighted and are considered to be negligible loadings for the purposes of analysis.

Measure	Item	Social	Stereo	Detail	Fine motor	Org	Magic Eye	Isolation	Coord	Imagine	Multi
AQ	Enjoy social chitchat	0.70	0.01	−0.06	−0.09	−0.06	−0.03	−0.04	0.07	0.01	0.08
AQ	Good at social chitchat	0.70	0.04	0.02	−0.05	0.03	0.12	0.03	0.01	−0.05	−0.03
AQ	Find social situations easy	0.67	−0.05	0.07	−0.01	0.01	0.03	0.01	0.00	0.02	−0.08
AQ	Prefer people over things	0.59	−0.01	−0.12	−0.04	0.02	0.04	−0.01	−0.04	0.04	0.09
AQ	Enjoy social occasions	0.56	−0.07	−0.10	−0.14	0.02	−0.02	−0.10	−0.09	0.08	0.01
AQ	Enjoy meeting new people	0.53	−0.07	−0.12	0.02	0.00	0.02	−0.04	−0.20	0.05	0.04
ADC	Choose to spend leisure time on own	−0.48	0.05	0.09	0.20	−0.02	0.02	0.25	−0.01	0.01	0.06
AQ	Easily keep track of several conversations	0.44	−0.03	0.15	0.00	−0.08	−0.01	0.01	0.07	0.19	−0.19
AQ	Can work out what someone is feeling from their face	0.43	−0.02	0.00	−0.06	−0.08	−0.01	−0.02	0.06	0.34	−0.10
AQ	Prefer to do things with others	0.43	0.05	0.02	0.13	−0.11	−0.02	−0.11	0.02	−0.22	−0.05
AQ	Find it hard to make new friends	−0.41	−0.06	0.30	−0.05	−0.04	−0.06	0.20	0.15	−0.16	−0.06
AQ	New situations bring on anxiety	−0.35	0.08	0.11	−0.11	0.01	0.06	0.17	0.09	−0.08	0.24
AQ	Don't know how to keep conversation going	−0.33	−0.04	0.22	0.04	0.02	−0.09	0.11	−0.00	−0.25	0.11
AQ	Can easily to 'read between the lines'	0.32	−0.03	0.02	−0.10	−0.03	0.10	0.06	0.03	0.31	−0.14
SSI	Do you think you need glasses	0.03	0.94	0.02	0.05	0.01	−0.01	−0.03	−0.03	0.03	0.01
SSI	Glasses/contact lens wearer	−0.05	0.90	−0.00	−0.00	0.01	0.02	−0.02	−0.02	0.02	−0.00
SSI	W/out correction, clearness of vision in LEFT eye	0.08	0.89	0.02	0.03	−0.04	−0.01	0.07	−0.05	−0.04	0.05
SSI	W/out correction, clearness of vision in RIGHT eye	−0.08	0.88	−0.06	−0.03	0.00	0.02	−0.02	0.03	0.06	−0.03
SSI	Vision as good as other people's	0.06	0.87	0.02	−0.03	0.03	−0.04	−0.00	−0.00	−0.06	−0.01
SSI	Correction needed for reading	−0.02	0.53	0.01	−0.04	−0.02	0.05	−0.09	0.21	−0.05	−0.08
AQ	Notice patterns in things all the time	−0.13	0.05	0.67	−0.08	0.10	0.02	−0.03	−0.08	0.05	−0.05
AQ	Notice car number plates or similar	−0.01	0.02	0.56	−0.03	0.04	0.06	0.03	−0.01	−0.02	−0.07
AQ	Tend to notice details that others do not	−0.14	−0.02	0.55	0.12	0.06	−0.00	−0.10	0.01	0.30	−0.09
AQ	Strong interests, get upset if can't pursue	0.01	0.04	0.55	0.14	−0.02	−0.04	0.05	−0.03	0.03	0.16
AQ	Notice small sounds	−0.13	0.07	0.47	0.07	0.07	0.06	0.01	0.05	0.18	0.07
AQ	Get strongly absorbed in one thing	−0.24	0.12	0.46	−0.06	0.18	−0.02	−0.02	−0.01	−0.03	−0.02

Measure	Item	Social	Stereo	Detail	Fine motor	Org	Magic Eye	Isolation	Coord	Imagine	Multi
AQ	Enjoy collecting information about categories	−0.01	−0.07	0.45	0.13	−0.08	0.02	0.04	0.09	−0.07	0.05
AQ	Repetitive topic of conversation	0.06	0.03	0.45	0.11	0.03	−0.01	0.13	−0.01	−0.18	0.01
AQ	Tend to dominate conversation	0.18	0.03	0.43	0.05	−0.06	0.06	0.09	−0.02	−0.04	0.12
AQ	Fascinated by numbers	−0.07	−0.05	0.41	0.07	0.03	0.03	−0.07	0.04	−0.08	−0.06
AQ	Difficult to work out people's intentions	−0.06	0.06	0.39	−0.00	0.04	−0.03	0.06	−0.00	−0.29	0.16
AQ	Difficulty imagining being someone else	0.08	−0.09	0.37	0.14	−0.01	−0.12	0.09	−0.06	−0.16	0.19
AQ	Say impolite things without realising	0.09	−0.02	0.36	0.14	−0.12	−0.03	0.12	0.02	−0.04	0.25
AQ	Difficulty speaking in turns on phone	−0.01	0.03	0.35	0.13	0.07	−0.05	0.10	0.09	−0.05	0.10
AQ	Difficultly working out characters' intentions in story	0.12	0.01	0.34	0.06	−0.04	0.14	0.13	0.13	−0.24	0.02
ADC	Others find it difficult to read your writing	0.01	0.04	0.00	0.79	−0.07	0.01	0.05	−0.07	0.01	−0.06
ADC	Difficulty with writing neatly AND quickly	−0.06	0.02	−0.03	0.73	0.03	−0.04	0.02	−0.02	0.03	0.09
ADC	Difficulty with neat writing when child	−0.07	−0.01	0.07	0.70	0.13	−0.04	0.07	−0.11	0.00	0.00
ADC	Difficulties reading own writing	−0.04	0.07	−0.05	0.66	−0.04	0.03	−0.08	0.18	−0.01	−0.15
ADC	Difficulties with writing as fast as peers	0.00	−0.04	0.07	0.65	0.06	0.03	−0.04	0.09	−0.12	0.05
ADC	Difficulty with fast writing as child	0.04	−0.06	0.06	0.62	0.15	0.03	0.01	0.06	−0.07	0.06
ADC	Difficulty copying without mistakes	−0.09	−0.06	−0.09	0.43	0.10	−0.02	−0.15	0.27	0.04	0.08
ADC	Difficulty with organisation	−0.04	0.07	−0.06	0.14	0.71	0.07	−0.09	0.02	−0.00	−0.03
ADC	Difficulties with organisation as child	−0.01	0.09	−0.05	0.06	0.68	−0.02	0.10	−0.06	−0.01	−0.09
ADC	Others call you disorganised	0.06	0.00	0.11	0.08	0.66	0.09	0.01	0.02	−0.04	0.00
ADC	Tend to lose possessions	0.01	−0.09	−0.03	0.04	0.58	−0.04	0.15	0.03	0.05	0.03
ADC	Difficulty sitting still	−0.08	−0.07	0.23	0.05	0.52	−0.04	−0.02	−0.05	0.07	0.18
ADC	Difficulty planning ahead	−0.08	0.03	0.09	−0.02	0.48	0.04	−0.14	0.02	−0.18	0.29
ADC	Bump into, spill, or break things	−0.00	−0.07	−0.02	−0.04	0.43	−0.10	0.41	0.19	0.04	0.02
ADC	Difficulty managing money	−0.02	−0.04	0.05	0.01	0.43	0.04	−0.17	0.23	−0.03	0.15
ADC	Can lose attention in certain situations	−0.02	0.05	0.12	0.02	0.42	−0.02	−0.05	0.04	−0.07	0.31
ADC	Bumped into objects more than other children	0.03	−0.07	0.09	0.05	0.38	−0.13	0.36	0.20	−0.02	−0.03
MEA	Identify shape in autostereogram [shark]	−0.05	0.00	−0.03	0.01	−0.00	0.91	0.04	0.01	0.01	0.02
MEA	Identify shape in autostereogram [teapot]	0.05	−0.00	0.01	−0.03	0.04	0.91	0.00	0.06	−0.06	−0.03

Measure	Item	Social	Stereo	Detail	Fine motor	Org	Magic Eye	Isolation	Coord	Imagine	Multi
MEA	Ease of percieving shapes in autostereograms above	0.03	–0.02	0.03	0.04	0.01	0.85	0.01	–0.03	0.06	0.04
MEA	Previous successful completion of autostereogram	–0.09	0.10	0.09	–0.01	–0.01	0.35	0.22	–0.15	0.04	–0.04
ADC	If do sport, likely to be on your own	–0.16	–0.01	0.04	0.05	–0.04	0.06	0.63	–0.08	–0.04	–0.03
ADC	Avoid team games/sports	–0.18	0.11	0.05	0.02	0.00	0.09	0.60	0.03	0.02	0.08
ADC	Difficulties playing team games as child	–0.04	0.13	–0.01	0.14	0.02	0.01	0.47	0.17	–0.05	0.12
ADC	Others commented on clumsiness as child	0.13	0.02	0.06	0.01	0.35	–0.16	0.44	0.23	–0.04	–0.06
ADC	Difficulties with hobbies requiring good coordination	–0.03	0.10	–0.10	0.02	0.09	–0.03	0.25	0.57	0.03	0.05
ADC	Difficulties eating with utensils	–0.03	–0.08	0.06	0.08	0.01	0.05	–0.09	0.57	–0.09	0.06
ADC	Self-care difficulties	–0.08	0.02	0.05	0.19	0.07	–0.08	–0.01	0.48	–0.08	0.08
ADC	Avoid hobbies that require good coordination	–0.02	0.13	–0.08	0.02	–0.02	–0.02	0.36	0.45	–0.03	0.15
AQ	Can easily imagine what characters in story look like	0.00	–0.01	0.08	–0.16	–0.08	0.08	–0.00	0.05	0.52	–0.00
AQ	Easily play games with children involving pretending	0.28	–0.07	–0.05	–0.10	0.05	0.05	0.08	–0.15	0.43	0.14
AQ	Easy to create a picture using imagination	0.01	–0.01	0.25	–0.03	–0.08	0.08	–0.09	–0.01	0.42	0.02
AQ	Is a good diplomat	0.28	0.02	–0.00	0.05	–0.08	–0.00	–0.11	–0.01	0.37	–0.05
AQ	Making up stories is easy	0.06	0.00	0.23	–0.08	0.08	0.05	0.12	–0.08	0.37	–0.02
ADC	Difficulty performing concurrent tasks	–0.11	0.04	0.02	0.20	0.10	–0.02	–0.05	0.24	0.08	0.41
ADC	Difficulty with distance estimation	0.06	0.12	0.02	–0.06	0.14	–0.07	0.23	0.13	–0.04	0.39
AQ	Easy to do more than one thing at once	0.28	0.04	0.04	–0.05	–0.02	0.02	0.03	–0.09	0.13	–0.34
ADC	Difficulty with navigation	0.00	0.09	–0.09	0.09	0.03	–0.07	0.18	0.16	–0.06	0.32
ADC	Difficulty packing suitcase to go away	0.03	–0.05	0.13	0.09	0.21	0.00	–0.05	0.26	–0.02	0.29
ADC	Difficulty learning to ride bike as child	0.06	0.05	0.04	0.12	0.04	–0.03	0.25	0.13	0.02	0.28
ADC	Difficulty preparing meal from scratch	–0.03	–0.02	0.14	–0.01	0.04	–0.05	–0.09	0.27	–0.16	0.25
AQ	Prefer to do things the same way over and over	–0.05	0.00	0.30	0.16	–0.10	–0.06	0.11	0.02	0.04	0.25
AQ	Know if someone listening to me is getting bored	0.27	–0.05	–0.10	0.03	–0.05	–0.04	–0.07	–0.07	0.29	–0.23
ADC	Difficulties with self-care when child	0.10	–0.03	0.01	0.18	0.15	–0.12	0.18	0.26	0.07	0.22

Measure	Item	Social	Stereo	Detail	Fine motor	Org	Magic Eye	Isolation	Coord	Imagine	Multi
ADC	Difficulty folding and putting away clothes	0.11	0.07	0.13	0.28	0.24	0.00	−0.01	0.20	−0.03	0.22
AQ	Not upset if daily routine is disturbed	0.27	−0.12	−0.06	0.05	0.06	0.04	−0.05	−0.04	0.04	−0.21
AQ	Enjoy doing things spontaneously	0.29	−0.16	−0.09	0.08	0.15	0.10	−0.13	−0.18	0.06	−0.21
AQ	Quickly go back to previous activity after interruption	0.19	−0.04	−0.01	0.04	−0.10	0.09	0.08	−0.01	0.23	−0.21
ADC	Slower at getting ready	−0.00	0.07	0.08	0.17	0.28	0.07	−0.03	0.12	−0.13	0.20
AQ	When younger, enjoyed pretend games with others	0.10	0.04	−0.25	−0.08	0.08	0.10	0.03	−0.20	0.29	0.19
AQ	Carefully plan any activities participated in	−0.13	0.06	0.31	0.07	−0.27	−0.07	0.09	0.14	0.16	0.19
SSI	Book too close to eyes when reading	−0.09	0.29	0.03	−0.09	0.09	−0.05	0.18	0.09	−0.09	−0.18
AQ	Not very good at remembering phone numbers	−0.01	0.04	−0.24	0.19	−0.08	−0.03	0.14	0.01	0.11	0.18
SSI	Experience temporary loss of vision	−0.05	0.16	0.03	0.04	0.13	−0.15	0.00	0.30	0.10	−0.17
AQ	Not good at remembering people's date of birth	−0.09	−0.02	−0.15	0.20	0.11	0.04	0.12	−0.17	0.09	0.17
AQ	Don't enjoy reading fiction	0.10	−0.02	0.07	0.03	0.02	0.04	0.06	−0.01	−0.06	0.15
AQ	Rather go to library than a party	−0.24	0.12	0.22	0.08	−0.05	0.04	0.25	0.09	0.08	−0.13
AQ	Concentrate on whole rather than parts	0.13	−0.04	−0.23	−0.05	0.09	0.02	0.00	0.07	0.11	−0.11
ADC	Do you avoid going to clubs/dancing	−0.30	0.09	0.15	0.08	0.06	0.01	0.25	−0.06	−0.04	−0.06
AQ	Last to understand the point of a joke	0.14	0.00	0.32	0.01	0.05	−0.14	0.09	0.16	−0.12	0.05
AQ	Fascinated by dates	0.07	0.03	0.26	−0.02	−0.06	0.10	−0.03	0.14	−0.03	−0.05
AQ	Don't notice small changes	0.01	0.12	0.02	0.20	−0.02	−0.00	0.11	−0.13	−0.20	0.03
AQ	Rather go to the theater than to a museum	0.29	0.01	−0.09	−0.10	−0.05	−0.05	−0.18	0.18	0.04	0.03
ADC	Difficulties playing music instrument when child	0.04	−0.03	−0.03	0.21	0.18	−0.17	0.18	0.15	−0.01	0.01
SSI	Difference between items 8 and 9	0.01	0.05	0.08	−0.01	−0.04	−0.10	0.04	0.03	0.02	−0.01
SSI	Eyes feel 'tired'	0.09	0.30	−0.02	0.10	0.06	−0.07	−0.03	0.25	0.04	−0.00

was termed 'Magic Eye proficiency', as all items from the ASA measure fell under this category. The seventh factor was given the title 'isolation due to motor proficiency', and it appears to have two facets (both of which were present across child- and adulthood: difficulties with and aversions to engaging in sporting activity with others; and other people commenting on the individual's level of clumsiness. Factor 8 was called 'coordination', as it seems to represent general clumsiness and lack of awareness of one's surroundings, though it also had a number of items related to activities of daily living. The ninth factor was titled 'imagination', as it seems to represent the ability to utilise imagination across a number of different contexts, including for oneself and when interacting with others. The final factor was termed 'multitasking' and encompassed difficulties in the planning and execution of a number of concurrent tasks.

7.3.4 Confirmatory factor analysis

Next, the factor structure suggested by EFA was cross-validated by means of CFA, using the R software package `lavaan`. The 'test' data (n = 325) were analysed using the MLR estimator, which is robust to the obvious non-normality of the observed variables (Li, 2015). In the first model, items (indicators in CFA terminology) which had a sufficiently high factor loading in the initial EFA ($\geq$ .32) were estimated as free parameters; all other items were fixed to zero. The factors (or latent variables in CFA terminology) were allowed to covary freely. Though the initial model showed a reasonable fit on some of the indicators, it did not meet criteria for acceptable fit for the comparative fit indices (χ^2/df = 2.013, CFI = 0.782, TLI = 0.771, SRMR = 0.08, RMSEA = 0.056). This is to be expected, as the initial model to be tested through CFA had more stringent restrictions than the factor model obtained through EFA, where no factor loadings were fixed to zero. In studies using cross-validation procedures such as those performed here, it is recommended that a less constrained model is tested where some parameters are freed (van Prooijen & van der Kloot, 2001). It is for this reason I allowed modification indices to be used in the creation of an adjusted model, though with restrictions upon which changes could be reasonably made to the initial model (see subsection 7.2.4).

After modification indices were applied (where the residuals between indicators loading on to the same latent variable were allowed to correlate with one another if this significantly improved the fit of the model) all indices indicated an acceptable fit (χ^2/df = 1.485, CFI = 0.899, TLI = 0.89, SRMR = 0.069, RMSEA = 0.039). A scaled chi-square difference test (Satorra & Bentler, 2001) showed that this modification-index-adjusted model exhibited a significantly better fit compared to the initial model ($\Delta\chi^2(88)$ = 1261.05, p = <0.001). Factor scores were calculated from the adjusted CFA model using simple regression (Thurstone, 1935, p. 226-231) for each participant; this refined method is thought to maximise validity compared to other (non-)refined methods (see DiStefano, Zhu, & Mindrila, 2009 and Estabrook & Neale, 2013 for an overview of the

Table 7.3: Spearman correlation coefficients for factor scores extracted using confirmatory factor analysis (CFA). Significant relationships are indicated by asterisks.

	Stereo	Magic Eye	Social	Isolation	Coord
Stereo	–				
Magic Eye	0.14*	–			
Social	−0.34***	0.05	–		
Isolation	0.21**	−0.12	−0.53***	–	
Coord	0.20**	−0.18**	−0.55***	0.86***	–
Fine motor	0.19**	−0.08	−0.54***	0.64***	0.67***

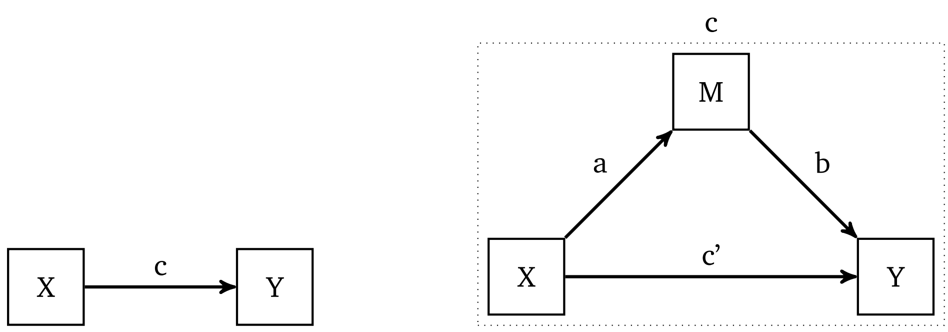
Note: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < .001$. Significance values Bonferroni-corrected in order to adjust for multiple comparisons.

different methods of constructing factor scores). These scores were then used to perform mediation analyses in order to better understand the relationships between the factors or latent variables.

7.3.5 Mediation

Factors were only included in this aspect of the analysis where strong a-priori hypotheses could be made (see Section 7.1). Therefore, the stereopsis, Magic Eye proficiency, fine motor skill, coordination, isolation due to motor proficiency, and social skill factor scores were retained. As can be seen in Table 7.3, the majority of these factors showed medium-to-large correlations with one another, with the exception of Magic Eye proficiency.

Mediation analysis was used to assess how these factors related to one another. Such models seek to identify and explicate the underlying mechanism or process that underlies an observed relationship between an antecedent variable (X) and an outcome variable (Y) through inclusion of a third variable (M), known as a mediating variable.



(a) (b)

Figure 7.3: Models showing the effect of X on Y [(a)], and the effect of X on Y taking into account mediation via M [(b)].

In contrast to a direct causal relationship between the antecedent and outcome variables, mediation proposes that the antecedent variable influences the mediator variable, which in turn influences the outcome variable.

In an un-mediated model, the effect of X on Y is called the total effect, represented by c; see Figure 7.3(a). In mediation analysis, depicted in Figure 7.3(b), the effect of X on M is referred to as a, the effect of M on Y is b, the total effect of X on Y is c, and the direct effect of X on Y is c'. The latter path is the residual effect of X on Y after M has been partialed out of Y. The indirect effect ab is the product of a and b, and is equivalent to the difference between the total and direct effect c - c' (Hayes, 2009). If this indirect effect is substantially different from zero (i.e. the 95% confidence interval of the unstandardised estimate does not include zero), then M can be said to explain the effect X→Y in as far as it "...transmits the effect of an antecedent variable on to an outcome variable, thereby providing more detailed understanding of relations among variables." (MacKinnon & Fairchild, 2009, p. 16). A mediator variable can either account for all (full mediation; *ab* is significant, *c'* is no longer significant) or some (partial mediation; both *ab* and *c'* are significant) of the observed relationship between two variables. All mediation analyses reported here were performed using `lavaan`'s structural equation modelling (SEM) framework.

7.3.5.1 Mediators of the link between stereopsis and social skills

Fine motor skill, coordination, and isolation due to motor proficiency were entered into a multiple mediation analysis to investigate the relationship between stereopsis impairment and reduced social ability. A significant total effect of stereopsis on social skills emerged, β = -0.312, z = -6.143, p = <0.001. When dividing this total effect into the direct effect of stereopsis, and the total indirect effects of all three mediators, the direct effect of stereopsis remained significant after adjusting for all three mediators, β = -0.216, z = -4.615, p = <0.001. The total indirect effect was also significant, β = -0.096, z = -3.441, p = <0.001. Of the three mediator variables, only fine motor skill contributed significantly to the indirect effect of stereopsis upon social skills (12.436% of the total effect; β = -0.039, z = -2.276, p = 0.02). Neither coordination nor isolation exhibited a significant amount of mediation (p = 0.061 and 0.178, respectively).

7.3.5.2 Mediators of the link between stereopsis and isolation

To investigate why individuals with worse stereopsis reported increased isolation due to motor proficiency, a multiple mediation analysis was performed with the mediator variables being fine motor skill and coordination. A significant total effect of stereopsis on isolation emerged, β = 0.179, z = 3.47, p = <0.001. When dividing this total effect into the direct effect of stereopsis, and the total indirect effects of both mediators, the direct

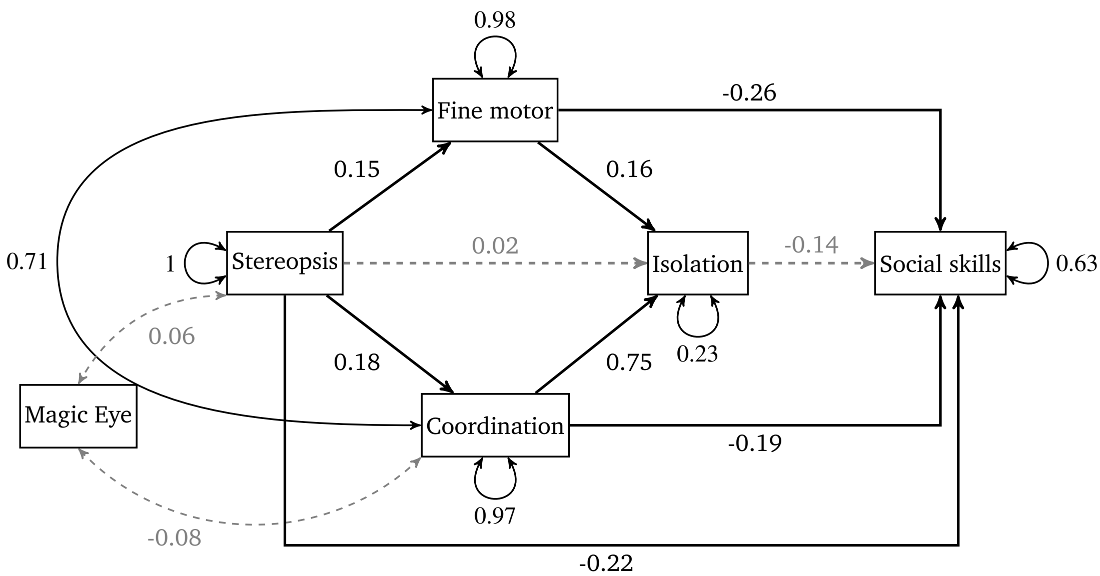


Figure 7.4: Path model with standardised estimates, created as an amalgamation of the mediation analyses reported in Section 7.3.5. Paths with solid arrows (→) signify a significant predictive relationship, whereas dashed arrows (⇢) indicate a non-significant relationship.

effect of stereopsis was no longer significant, β = 0.02, z = 0.772, p = 0.44, but the total indirect effect was significant, β = 0.158, z = 3.545, p = <0.001. Both mediator variables contributed significantly to the indirect effect of stereopsis upon isolation due to motor proficiency, though coordination exhibited a greater proportion of mediation (75.3% of the total effect; β = 0.134, z = 3.471, p = <0.001) than fine motor skills (13.273% of the total effect; β = 0.024, z = 2.294, p = 0.02).

7.3.5.3 Isolation as a mediator between coordination/fine motor skills and social skills

Two final mediation models indicated that isolation due to motor proficiency was a significant mediator both in the relationship between coordination and social skills (39.772% of the total effect; β = -0.211, z = -2.533, p = 0.01) and fine motor skill and social skills (40.941% of the total effect; β = -0.214, z = -4.477, p = <0.001). Partial mediation occurred in both cases, as coordination and fine motor skill were still significant predictors of social skills after adjusting for the indirect effect of isolation (coordination: β = -0.32, z = -3.647, p = <0.001, fine motor skills: β = -0.309, z = -4.605, p = <0.001).

7.4 Path analysis

Finally, the above mediation models were aggregated into a larger path model specified using `lavaan`. This final model included relationships with Magic Eye proficiency as detailed in Table 7.3. The results of the path analysis with standardised regression coefficients are presented in Figure 7.4. This model had a good fit, with χ^2/df = 0.418, CFI = 1, TLI = 1.011, SRMR = 0.017, and RMSEA = <0.001. All of the direct and indirect effects reported in Section 7.3.5 held in this larger model, with the exception of isolation due to motor proficiency acting as a mediator between fine motor skill/coordination and social skills. While fine motor skill and coordination were responsible for full mediation of the relationship between stereopsis and isolation due to motor proficiency, there was no serial mediation from the fine motor/coordination variables to social skills via the isolation variable.

7.5 Discussion

The aim of the present study was to explore the relationship between stereopsis, motor ability, and social skills in a sample of adults. This question was driven primarily by the work detailed in the previous chapters, in which impaired stereopsis was found to impact both on perceptual and motor functioning. The current research builds upon prior work by investigating whether the impact of motor impairment upon social functioning persists in adulthood, as well as incorporating a variable, stereopsis, which may underlie deficits in motor ability and thus have an impact upon social skill. I hoped to expand the understanding of these variables and their associations, as intervention in childhood (in the form of vision or physical therapy) may be critical in preventing the deterioration of motor and social functioning seen in developmental disorders such as ASD and DCD. The results indicated that impaired stereopsis both directly and indirectly affected social skills, in the latter case through mediation by coordination and fine motor skill. Additionally, both fine motor skill and coordination fully mediated the relationship between stereopsis and isolation due to motor proficiency, with coordination explaining much larger proportion of variance. However, in the full model, isolation due to motor proficiency did not have a significant relationship with social skills.

Overall, the results of this study support the hypothesis that stereopsis impairment can affect both motor skill proficiency and social skills. Additionally, as the final aggregate path model was good fit for the data, preliminary support is provided for the validity of the causal pathways in the model. It is important to note that the results do not imply causal relationships, as the data were correlational and were collected at a single time point. Thus, further longitudinal and experimental research is recommended to clarify the causal mechanisms involved in the associations between stereopsis, motor ability, and social skills/social isolation.

7.5.1 Associations between stereopsis, motor skills, and isolation

Findings here support the results obtained in the previous chapter, with clear links between impaired stereopsis and both fine and gross motor skills. In the current study, there was also a relationship between stereopsis impairment and coordination/daily living skills. Little previous research has looked at this more functional consequence of impaired stereopsis; while it has been observed that the sensation of depth afforded by binocular viewing is important for certain gross motor skills, such as obstacle avoidance while walking (Buckley et al., 2010) and intercepting thrown objects (Mazyn et al., 2004), only two studies have specifically looked at the contribution of reduced stereopsis to daily living skills.

In a group of older individuals (aged $\geq$ 65 years), Kuang, Hsu, Chou, Tsai, and Chou (2005) found no effect of stereopsis on daily living tasks such as cooking and writing, but they did observe that those with poor stereopsis exhibited a reduction in energy/vitality as measured by the Short Form (36) Health Survey, indicating that more effort may be required to accomplish daily living tasks. Conversely, Cao and Markowitz (2014) noted that in a group of older subjects (aged > 50 years) with age-related macular degeneration, those with reduced stereopsis experienced difficulty with visual motor skills required for daily living. As an individual ages, stereoacuity tends to worsen, necessitating larger amounts of disparity for a sensation of depth to be elicited – this deterioration is more marked after the age of 60 (Zaroff et al., 2003). Therefore, an over-representation of individuals with poor stereoacuity may account for these past findings. The observers in the current study tended to be much younger than the groups surveyed by Kuang et al. (2005) and Cao and Markowitz (2014), with 92.615% of the participants who disclosed their age being < 60 years old, and so my findings extend this earlier work to young- and middle-aged adult populations with stereopsis impairment.

While there was a relationship between stereopsis and both types of motor proficiency, the size of this effect was small within the context of the path model. A much stronger association was present between fine motor skill/coordination and isolation. Of these two facets of motor skill that showed links with isolation, it was coordination/daily living skills (which require gross motor ability) that exhibited the largest amount of mediation between stereopsis and isolation. While there is already evidence that motor ability correlates with feelings of isolation and social standing with peers (Bar Haim & Bart, 2006; Bart et al., 2007; Ommundsen et al., 2010; Smyth & Anderson, 2000; Jarus et al., 2011), these studies do not tend to differentiate between fine and gross motor skill. Future work might look at whether social isolation is due to simple impairment in gross motor skills, or if it might be more specifically attributed to a reduction in daily living skills; such knowledge would allow more targeted treatment (such as physical therapy for gross motor skills versus occupational therapy for daily living skills).

7.5.2 The impact of impaired stereopsis on social skills

Earlier, I hypothesised that impaired stereopsis may affect social skill by causing a reduction in general motor ability. The current results are consistent with those who have previously found an association between motor proficiency and social competence (Wang et al., 2012; Bart et al., 2007; Sipes et al., 2011; Dyck et al., 2007; Hilton et al., 2007; Perry et al., 2009; Hilton et al., 2011). Interestingly, while I found that fine motor skill and coordination did mediate the relationship between stereopsis and social skill, this effect was only partial (the mediation model accounted for around a third of the variance in the relationship between stereopsis and social skill) – all three of these predictor variables (fine motor skill, coordination, and stereopsis) exhibited a similar strength of effect in their relationship with social skill. That the mediators between stereopsis and social skill accounted for only a small amount of variance suggests that there are other unmeasured factors that play a part the relationship between impaired stereopsis and reduced social skill. Currently, the functional significance of stereopsis is generally framed in terms of interacting with the world around us, including estimating distance and shape, as well as moving around our environment and manipulating objects within it (Fielder & Moseley, 1996; Wilmer, 2006; Levi et al., 2015; Read, 2015). The findings here suggest that stereopsis may prove useful in other, as yet unexplored domains related to social interaction – for instance, the estimation of interpersonal distance.

7.5.3 Isolation due to motor proficiency does not predict general social ability

In contrast to previous research which has established that perceived and/or actual social isolation causes individuals to change their behaviour and have lower-quality social interactions by altering the nature and likelihood of engagement (with social situations appearing more threatening and difficult for these individuals; Cacioppo & Hawkley, 2005, 2009; Hawkley et al., 2008), I did not find that isolation due to motor proficiency significantly predicted social skill in the full path model. It is likely that motor ability (represented by the fine motor skill and coordination variables) is responsible for this relationship, especially considering the items that constitute the isolation factor all relate to motor proficiency, specifically in the context of sport and team games. When isolation is characterised more fully, including indicators such as social network size, participation in a range of social activities (not just those that require motor proficiency), and perceived lack of social support, the relationship between isolation and social ability is likely to hold true.

7.5.4 Limitations

It is assumed that the greater correlations between the AQ and ADC scores compared to the SSI score, and the motor (fine motor and coordination) and social skills factor scores compared to the stereopsis factor score reflects a greater interdependence of social and motor skills in development. However, it is possible that the stronger correlation may be an artefact of the questionnaires used, with the two questionnaires with the largest number of questions and covering a range of domains (the AQ and ADC) correlating most strongly. Coren and Hakstian (1996) have established that while the SSI has a relatively high specificity, the sensitivity is relatively poor (59.7%). A lab- or clinic-derived measure of stereoacuity, as have been discussed throughout this thesis, might highlight relatively larger (or smaller, dependent on whether the stereopsis factor extracted in the current study actually measures this function) correlations with social and motor skills. However, it would be difficult to recruit this many participants to participate in a lab-based study.

A main limitation of this study is the generalisability of the results. Extensive recruitment efforts meant that data was collected both from the general population and a subset therein who were likely to have a diagnosis of or a personal interest in autism; this meant that a larger proportion than would be expected of my 'general population' sample scored over the threshold for the AQ measure (24.923% of the current sample vs 2% in the seminal Baron-Cohen et al., 2001 paper), despite the fact that only 3 individuals disclosed a diagnosis of ASD. It would have been preferable to recruit separate TD, ASD, and DCD samples in order to fully explore the relationship between stereopsis, motor skills, and social ability in typical and atypical development.

While the sample used in this study may be a potential drawback, the use of questionnaires widely used in ASD and DCD diagnosis is considered a clear strength. These questionnaires are well suited to investigate a range of social and motor behaviours, are well standardised and have demonstrable construct validity. Additionally, the ADC has been found to correlate moderately with performance-based measures used in DCD diagnosis (Wilmut, Byrne, & Barnett, 2013; Hyde et al., 2014) and the AQ has been found to adequately address a number of subtle atypical social behaviours associated with ASD (Hoekstra et al., 2008). Other studies tend to use brief questionnaires, subscales of questionnaires, or subcomponents of observational tools (such as the Autism Diagnostic Observation Schedule, Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, or Movement Assessment Battery for Children, Second Edition) to assess these constructs and this reduces the scope of these studies to the single aspect of social or motor development being assessed.

7.5.5 Conclusions

This study has demonstrated the presence of a relationship between stereopsis, motor ability, and social skill. Using a large group of adults, this work complements a large body of research previously conducted with children, in addition to providing evidence for an underlying contributor to impairment in both motor and social skill. Preliminary support for causal pathways between stereopsis, motor ability, and social skill has been provided, but further evidence is needed to clarify the mechanisms responsible, especially in clinical populations. The repercussions of poor stereopsis have been demonstrated to be far-reaching, limiting not only motor skill, but also social competence.

CHAPTER 8

General Discussion

8.1 Introduction

In this thesis, I aimed to characterise better the impact of reduced stereopsis, both on perception and regarding the wider functional significance of such a deficit. I also wanted to examine whether perceptual differences in autism stemmed from the disorder or from an underlying deficit in stereopsis. The experiments within this thesis drew on a range of methods; first, I used a mixture of real-world and virtual psychophysical paradigms in order to measure how individual differences in stereopsis affected the utilisation of other depth cues and the overall percept of depth (Chapters 3,4, and 5). I then assessed the relative utility of binocular vision and stereopsis in the performance of a range of tasks that required the involvement of gross and/or fine motor skills (Chapter 6). Finally, to understand the wider implications of deficits in stereopsis, an exploratory study was conducted into the connections between stereopsis, clumsiness, and social skill, as assessed by established and validated questionnaires (Chapter 7). First I summarise the main findings from this thesis regarding the effect of abnormal stereopsis and atypical development on perception, as well as the wider functional significance of stereopsis (Section 8.2). I will then explain how the findings from this thesis have furthered the field of depth perception (Section 8.3). Next, I will consider the main implications of this thesis (Section 8.4) before reflecting on the limitations of the research (Section 8.5). Finally, I will suggest some future directions that will help further elucidate the nature of stereopsis impairment, and bridge the gap between impairment in stereopsis and everyday functioning (Section 8.6).

8.2 Summary of main findings

8.2.1 The effect of stereopsis impairment and atypical development on depth perception

Chapter 3 investigated how individual cues to depth are utilised and combined in typical development and adulthood using a shape constancy paradigm. While I found children were more sensitive to monocular cues (as has been previously established by Nardini et al. (2010)), it appeared that this sensitivity depended on stereoscopic ability – the children with worse stereopsis tended to place a greater weight on the texture cue as they grew older, whereas this did not happen with the children with normal stereopsis. This stereoacuity-dependent sensitivity to the texture cue was present across both the adult and child groups, and supports other research which has highlighted the impact of individual differences on cue weighting (Zalevski et al., 2007; Nefs et al., 2010). Unexpectedly, I did not find an age-dependent effect of contextual information; instead, the interaction between the low-level disparity cues and the high-level context cue ('feedback') remained constant throughout childhood and persisted into adulthood. As this is one of the only studies which has investigated feedback without using a task intended specifically stimulate attentional mechanisms, our understanding of how the effect of feedback changes with development (especially in the visual part of the brain) is still in its infancy, with task demands, stimulus features, and participant characteristics all likely to contribute to overall perception (Smith et al., 2015).

Chapter 4 used the same paradigm to investigate the nature of altered perception in ASD. I was particularly interested in establishing whether these differences (if present), were attributable to ASD or simply caused by deficits in stereopsis. Unlike in the previous chapter, here no evidence was found that stereopsis impairment altered relative cue sensitivity. Instead, participants with ASD showed similar effects to their TD peers of both the texture cue (including increased shape constancy when it was present alongside disparity, indicating intact cue integration) and the prior knowledge cue (which interacted with the presence of disparity to either suppress or increase shape constancy, indicating intact feedback mechanisms), though the overall amount of shape constancy elicited in those with ASD was reduced. Stereoscopic ability of the ASD group was worse than that of the TD group, but this did not account for the reduced shape constancy in those with ASD, lending support to theories of autism that have proposed underlying neurological differences specific to the disorder (Pellicano & Burr, 2012).

It remains a challenge to explain the lack of an effect of stereoacuity in Chapter 4. Chapter 3 found that age interacted with stereoacuity when predicting sensitivity to texture cues and there was also an interaction between stereoacuity and sensitivity to texture overall (when the data from TD adults and children were combined). However, children were over-represented in the sample, with a ratio of 2.8 children to every 1 adult. This could have driven the interaction in the larger model and might also explain the absence of an effect of stereoacuity in Chapter 4, as the the TD and ASD groups were significantly older than the child participants recruited in Chapter 3. An interesting avenue for future research may determine the relative importance of stereoacuity to the weighting of cues over the course of development (from ages 5 to 18). It is possible that by adulthood the importance of stereoacuity is somewhat less as the relative weightings of cues become more settled (which is thought to occur around 12 years of age; Nardini et al., 2010).

In Chapter 5, I looked at how a reliable ordinal cue (occlusion) altered perception of depth from disparity in TD and ASD individuals who presented with a range of stereoscopic ability. While individuals with autism exhibited worse uncrossed stereoacuity thresholds, neither stereoacuity nor autism diagnosis affected how the disparity and occlusion cues were integrated. Individuals with poor stereoacuity did not assign a higher weighting to the occlusion cue, extending a similar finding regarding a metric depth cue in Chapter 4 to a highly reliable ordinal cue.

Unlike previous work which suggests that individuals with autism are able to access depth percepts from individual cues in the case of cue conflict (Happé & Frith, 2006; Mottron et al., 2006; Bedford et al., 2016), I found that both TD and ASD individuals automatically integrated conflicting occlusion information into the overall depth percept, causing a reduction in performance – however, the ASD group did not appear to experience an increase in judgement uncertainty when conflicting cues were present. This tells us that while cue combination may not cause differences in overall perception in those with ASD, the decision-making process and therefore underlying cue combination mechanism may be subtly different.

8.2.2 The wider functional significance of stereopsis

Chapter 6 looked at which motor domains were most affected by a reduction in stereopsis – until now, research has focused almost exclusively on hand-eye coordination. I assessed gross and fine motor function across the three main subcomponents of motor control: manual dexterity, aiming and catching, and balance. I also wanted to see whether the impact of stereopsis on motor skill ability followed a developmental trajectory. I found that while binocular viewing was more important for some tasks than others, those with worse stereoacuity demonstrated a universal deficit in motor skill across all domains. Moreover, the relative contribution of stereoacuity did not change with age, causing me to speculate that the motor deficits associated with worse stereopsis persist from an early age.

The final chapter (Chapter 7) scrutinized whether the influence of stereoacuity was limited to motor skills or if it affected other aspects of development using a series of questionnaires. Those with impairments in stereopsis reported increased clumsiness and exhibition of autistic traits. Factor analysis and subsequent path analysis suggested that while stereopsis affected both fine and gross motor skill, which in turn affected social skills, stereopsis also directly affected social skill. It is in no way proposed that there is a simple one-to-one mapping between behaviour and perception, but it gives the impression that stereopsis impairment has wider implications than just motor ability – future work should assess other factors which contribute to the relationship between stereopsis and social skill. Before this takes place, however, the factor structure and the relationships between the factors requires validation in a larger sample composed of three sub-groups: those with ASD, those with developmental coordination disorder (a developmental disorder that affects motor ability), and a group of typically-developed individuals.

8.3 Contributions to the field

As reviewed in Chapter 1, while depth perception has been fairly extensively investigated, little is known about the effect of individual differences. Paradigms involving estimation of depth are also a little-used means to study the development of vision, both in typical development and in the case of developmental disorders. The experiments reported in this thesis demonstrate that individual differences in stereopsis do not consistently modulate sensitivity to other depth cues (Chapters 3, 4, and 5), though there is some evidence for this occurring in childhood (Chapter 3). However, it has been observed throughout this thesis that the overall perception of depth appears reduced in those with reduced stereoacuity. Future work should focus on identifications of the mechanisms responsible for this difference. Moreover, studies of depth perception should aim to include the data of individuals with impaired stereopsis, as testing of a broader sample may give greater confidence that the result truly generalises beyond the canonical ‘expert psychophysical observer’ (McKee & Taylor, 2010).

In the studies involving participants with ASD, I did not find evidence of differences in cue utilisation and integration in this group. It is therefore not clear how to interpret studies that report differences in cue utilisation and integration between ASD and TD groups (such as Bedford et al. (2016) and Ropar and Mitchell (2002)), though discrepancies may be due to differences inherent in the stimulus and task used. Divergence from the typical depth cue integration paradigm involving multiple metric cues has led to new insights into cue integration in autism (namely, that neural mechanisms governing feedback appear relatively intact in ASD), which will serve to progress the field beyond the ubiquitous weak central coherence versus enhanced perceptual functioning argument seen in much of the research regarding visual perception in ASD.

Previously, in the dissection of the larger issue of the functional significance of stereopsis into specific problems of manageable scope, research has tended to focus exclusively on hand-eye coordination based on the recommendations of a single individual or group (Fielder & Moseley, 1996). By considering a wider range of possible implications, here the utility of stereopsis was shown to extend beyond hand-eye coordination into both fine and gross motor domains as well as contributing to the development of social skills. Hopefully this will lead to a broader investigation into the significance of stereopsis, which – at the present moment – remains mostly unexplored (Levi et al., 2015).

8.4 Implications of research

8.4.1 Do individual differences affect individual cue utilisation or overall depth perception?

In individuals with normal vision, the contribution of stereopsis to the overall percept of depth is notable, with some researchers denoting that "stereopsis sits at the top of the food chain of vision" (Saladin, 1998, p. 899). While this may not necessarily always be the case (as the reliability of disparity decreases when viewing objects which are further away; Cutting & Vishton, 1995), stereopsis nonetheless grants a sensation of depth above and beyond that provided by a variety of rich monocular cues (Lim Lee & Saunders, 2011) and is therefore given substantial weight when combining different cues to form the overall depth percept (Hillis et al., 2004).

In Chapter 1, I suggested that since the disparity cue is arguably not as reliable for individuals who are stereodeficient, this may cause re-weighting of other cues to depth, causing them to have an increased impact on the overall depth percept. Though individuals with impaired or absent stereopsis have previously been shown to demonstrate greater dependence on certain monocular cues such as linear perspective (Harwerth, Moeller, & Wensveen, 1998) and motion parallax (van Ee, 2003), I found only limited evidence for this pattern of perception. While sensitivity to texture was modulated by stereoacuity in Chapter 3, this effect was not replicated in Chapter 4. Furthermore, ability to utilise stereopsis was not shown to affect integration of occlusion into the overall depth percept (Chapter 5). Together, these results intimate that a reduced ability to utilise stereopsis does not necessarily result in altered sensitivity to monocular depth cues. However, it remains to be seen whether the cue-specific likelihood distributions elicited by depth from disparity and other, monocular, cues during integration differs as a function of stereoacuity (see Section 8.5).

Throughout this thesis, participants with ASD were recruited as a comparison group ostensibly characterised by an increased likelihood of stereopsis deficit. Though I confirmed that those with ASD exhibited increased stereoacuity thresholds (Chapters 4 and

5), this group also showed differences in perception that could not be attributed to a reduction in stereopsis. By accounting for general deficits in visual functioning, the resulting double dissociations provide support for the idea that pattern of perceptual differences found in ASD is due to underlying neurological differences inherent to the disorder, as opposed to a secondary cause.

8.4.2 Stereopsis is just one aspect of depth perception

Reading about the advent of three-dimensional film, or even by skimming this thesis, one might think the term ‘stereopsis’ to be synonymous with ‘depth perception’. However, the current work highlights that stereopsis is only but one aspect of depth perception, as increased thresholds in a task involving binocular disparity do not imply a drastic reduction in overall depth percept. This distinction is demonstrated in Chapters 3 and 4, whereby those with worse stereopsis experienced amounts of overall shape constancy comparable to others who had ‘normal’ levels of stereopsis. Depth perception involves the integration of a large number of different depth cues, all of which contribute their own information about depth, into a singular percept. While deficits in stereopsis may cause the world around us to lack certain qualities (Barry, 2009), those individuals who have reduced or absent stereopsis still undoubtedly experience a very real (and useful) sensation of depth.

8.4.3 The effect of impaired stereopsis on everyday life

Though stereopsis is not the ‘be all and end all’ of depth perception, impairment in this domain has tangible consequences. Aside from the obvious case of experiencing difficulty in the accurate judgement of distance, reduced stereopsis has been previously associated with a variety of difficulties with hand-eye coordination (see Chapter 6). In this thesis, I found that the consequences of poor stereoacuity extended beyond this to involve a reduction in ability across a range of gross and fine motor skills, as well as correlating with self-evaluated social skill. The next logical step is to consider how these and other related deficits may affect quality of life.

While general motor ability has been linked with feelings of isolation, social standing with peers, and social competence (Bar Haim & Bart, 2006; Bart et al., 2007; Ommundsen et al., 2010; Smyth & Anderson, 2000; Jarus et al., 2011; Wang et al., 2012), other [in]direct mechanisms explicating influence of stereoscopic ability on social skill are less immediately clear. It is possible that the reduced motor ability associated with stereopsis impairment is indicative of a wider range difficulties required for carrying out activities for daily living such as general organisation, forward planning, and multitasking, all of which play a part in social interaction. Future research will be needed to clarify the extent to which deficits in stereopsis impact upon activities of daily living.

8.5 Limitations of research

In the first part of this thesis, sensitivity to different cues to depth was measured in two ways: the method of adjustment within a shape constancy paradigm; and disparity threshold measured using adaptive psychophysical methods alongside the method of constant stimuli. Conducting these types of psychophysical studies with children and individuals with ASD requires sacrifice of the methodological rigour that is possible in studies conducted on TD adults. For example, in Chapters 3 and 4, children and teenagers were seen in a range of different settings (at school, during public engagement events, or at the School of Psychology) and light and noise levels in testing locations could not be tightly controlled. However, while different settings and light levels may potentially contribute to between-participants variability, these factors are likely to be negligible when comparing performance at the group level and when investigating within-participants effects.

In Chapter 5, participants were brought into the lab to allow more careful and accurate measurement of disparity threshold. After rapidly estimating threshold using a staircase procedure, five disparity levels were generated as a multiple of the threshold value, with a view to efficiently estimate both threshold and the slope of the psychometric function. However, due to time constraints, as well as attentional and motivational capabilities of the participants, only 190 trials were presented for each condition (and only 150 of those trials were used in the estimation of the final psychometric function). When using the method of constant stimuli, a minimum of 400 trials is recommended to adequately estimate slope and threshold (Kingdom & Prins, 2010, p. 62). Even when using adaptive psychophysical methods to sample optimal points of the psychometric function, such as the Ψ algorithm (Kontsevich & Tyler, 1999), a good estimate of the psychometric function takes around 300 trials.

Furthermore, high lapse rates (i.e. the rate of false negative responding, which are increased in ASD; Koldewyn et al., 2010) have been shown to be detrimental to the efficiency of adaptive procedures. These cause a small but significant amount of bias for $N \leq 200$, requiring a further increase in the number of trials presented to the participant to ensure sufficient accuracy of the obtained psychometric parameters (Shen, 2013). Thus, the absolute values of the thresholds obtained through relatively small number of trials used in Chapter 5 should be interpreted with caution. However, the data validation procedures followed, as well as the use of baseline measurements as a covariate and that findings broadly agreed across measurement domains (i.e. threshold and reaction speed), means that the overall results are still of value and impart considerable new knowledge.

None of the chapters which measured sensitivity to different cues to depth (Chapters 3-5) was able to follow the procedure typically used in studies of cue combination. In order to model the combination of two cues, the reliability of each cue when presented in isolation must first be estimated through generation of a psychometric function. Following this, similar functions are then created for when both cues are presented together, specifying congruent or incongruent depths. In the shape constancy paradigm used in Chapters 3 and 4, time constraints meant that there was no time to test a cue-conflict condition. Additionally, only three trials were presented for each condition preventing an accurate measurement of variance from being obtained which is essential for the calculation of cue reliability. In the disparity judgement paradigm used in Chapter 5, the ordinal nature of the occlusion cue made it impossible to generate the psychometric function used in linear cue combination models. While the evidence to suggest that individuals with reduced stereopsis and/or ASD re-weight certain cues to depth is sparse to non-existent within the context of this thesis, my inability to measure the individual cue reliabilities meant that this question could not be fully answered. It may be that the individual depth cue reliabilities are very different in these groups compared to the general population, but the integrated estimate remains unchanged.

Stereo tests are intended to provide a quick and effective measure of stereoacuity; throughout this thesis, the TNO test has been used for this purpose. Contour-based stereotests such as the Titmus or Randot-Circles/Randot-Animals tests typically contain monocular depth cues (Francis & Leske, 1999), which can allow even those with severe binocular deficits to identify the correct answer, causing them (erroneously) to appear to have little-to-no impairment in stereopsis (Fawcett, 2005). Being random-dot based, the TNO is more likely to obtain a measure of 'true' stereopsis through minimisation of monocular cues. However, the TNO exhibits comparatively poor sensitivity (46-80%; Ohlsson, Villarreal, & Abrahamsson, 2001; Farvardin & Afarid, 2007; Ancona et al., 2014) and specificity (87%; Ancona et al., 2014), and the test-retest reliability of the TNO is somewhat lower than for other 'gold-standard' tests such as the Frisby and Randot-Forms (thought to be due the step sizes used in the TNO; Antona, Barrio, Sanchez, Gonzalez, & Gonzalez, 2015). Furthermore, later versions of the TNO have been shown to have a manufacturing defect which causes an apparent 'ceiling effect' – van Doorn, Evans, Edgar, and Fortuin (2014) observed that the median stereoacuity for the 13th edition of the TNO was 30 arc seconds, compared to the 15th edition's 60 arc seconds, a statistically significant difference. While the same edition of the TNO (18th) was used throughout this thesis (meaning that comparisons between and within different participant groups remain valid), the ceiling effect is evident across all samples, with a large proportion of participants having a stereoacuity of 60 arc seconds as measured by the TNO.

It would have been preferable to obtain stereoacuity threshold for all participants psychophysically, as this would have allowed a more detailed comparison of adult vs. child and ASD vs. TD thresholds. Collecting this data would also have been beneficial for the statistical analyses which included stereoacuity as a covariate (Chapters 3, 4, and 6), as the TNO provides censored stereoacuity estimates which reduce predictive power – for instance, an individual who obtains a score of 120 arc seconds on the TNO may have a true stereoacuity threshold anywhere between 61 - 120 arc seconds[1]. While ideally all participants would visit the lab for extended testing sessions to allow for an accurate measure of stereoacuity, the age or developmental level of some groups precluded this option entirely. Besides, although the TNO may provide a biased measure of stereoacuity, Figure 5.4 shows a similar pattern of differences between the TD and ASD groups across all three measures. New technologies are emerging that allow for relatively fast and portable fine-grained psychophysics-based stereoacuity measurement (such as the ASTEROID project; ASTEROID Project, 2015); future research should take advantage of these opportunities.

Finally, in Chapters 3 and 6, age-related changes in depth cue utilisation and motor ability were measured using a cross-sectional design. However, there was a large amount of between-participant variability – while I tried to reduce the influence of such effects by using linear mixed modelling, the substantial amount of dispersion present in the data may have obscured the full extent of age-related changes. Longitudinal designs, which follow the same children at different time points, are much better suited to investigate developmental changes; however, use of such a design is both resource- and time-intensive and was therefore not possible within the context of this thesis.

8.6 Future directions

I now suggest two avenues for future research that serve to improve our understanding of the mechanisms responsible for impaired stereopsis and bridge the gap between reduced stereopsis and everyday functioning.

8.6.1 Understanding the mechanisms behind stereopsis impairment

As previously highlighted throughout this thesis, there exist large inter-individual differences in stereoscopic ability, with around 40% of the general population exhibiting at least moderate stereopsis impairment (Zaroff et al., 2003; Bohr & Read, 2013; Bosten et al., 2015). Elevated stereoacuity thresholds also occur in a range of developmental, neurological, and mental disorders (Ghasia et al., 2008; Tsiaras et al., 1999; Atkinson et al., 2001; Anketell et al., 2013; Coulter, 2009; Creavin et al., 2014).

[1]The poor level of agreement between different methods of measurement is illustrated by the Bland-Altman difference plot presented in Appendix B.2, Figure B.2, where the mean differences of bias between the TNO and lab-derived measures of stereoacuity approached the 0.30 log-arcsecond difference between any two grades of stereoacuity on the TNO test ($\text{mean}_{\text{crossed}}$ = 0.345, $\text{mean}_{\text{uncrossed}}$ = 0.272). Additionally, the 95% limits of the differences were as large as almost 5 steps on the TNO log-arcsecond scale. Together, these findings support the view that a clinically significant differences exists between the results obtained via the TNO and lab-based tests.

Poor stereopsis has a variety of known medical causes, including strabismus/anisometropia[2] and resultant amblyopia, convergence insufficiency, and unilateral cataract or retinal damage. Given their prevalence, however, these cannot completely account for the large proportion of the general population who have stereopsis impairment. Additionally, it has been established that individual differences in the amount of depth perceived are not explained by variability in physical attributes such as inter-ocular distance (Bosten et al., 2015). Another possible source of poor stereopsis is direct disruption of the neural machinery responsible for processing disparity information (Reynaud, Gao, & Hess, 2015); this would most likely manifest in extra-striate areas which contain disparity-selective neurons, particularly in the dorsal pathway in areas V3A, MT, and V7 (see Joly and Frankó (2014) for a review of neuroimaging of binocular vision).

This hypothesis corroborates with the 'dorsal stream vulnerability' theory posited by Braddick, Atkinson, and Wattam-Bell (2003), which suggests that the dorsal visual stream is particularly vulnerable during development and therefore is more likely to be disrupted in the case of neuro-developmental disorders. However, a recent review by Grinter, Maybery, and Badcock (2010) proposes that, unlike Braddick et al. (2003) who focused on early-level deficits, problems tend to occur further along in the dorsal stream in such disorders thus supporting a neurological cause for the increased incidence of stereopsis impairment in this group of individuals. Such disruption may also explain the increased incidence of strabismus in developmental disorders; while many perceive strabismus as resulting from abnormalities at the level of the oculomotor muscles or their innervation, it has been increasingly recognised in recent years that strabismus can also originate at the cortical level (Bui Quoc & Milleret, 2014).

It would be useful to investigate whether individuals with reduced stereoacuity show differences in cortical anatomy and neural connections (both more generally and focused within the dorsal stream) through use of neuroimaging techniques. This may allow for explanation of the relatively large amount of individuals with abnormal stereopsis in the general population, as well as the identification of a shared root cause for the increase in stereopsis impairment exhibited by those with neuro-developmental disorders.

8.6.2 Bridging the gap between reduced stereopsis, impairment in motor skill, and everyday functioning

Another challenge for future research is to more fully investigate how stereopsis impairment relates to everyday functioning. Proficiency across a variety of motor domains correlates with stereoacuity in typically-developing children (Chapter 6), and individuals with self-reported poor stereopsis are more likely to exhibit motor and social skill deficit (Chapter 7). However, these studies used either a truncated behavioural assess-

[2] A condition in which the two eyes have unequal refractive power (usually a difference ≥ 1 diopter).

ment, or general clinical questionnaires, to quantify motor and social skill proficiency. As a result, the full spectrum of motor and social deficits were not characterised – this lack of comprehensive evaluation was probably responsible for the smaller-than-expected amount of mediation attributable to motor skill in the relationship between stereopsis and social skill. Future studies should take the opportunity to measure stereoacuity, motor proficiency, and social skill meticulously, using a mixture of psychophysical methods (for a measure of visual functioning including stereopsis), standardised assessment batteries (such as the Movement Assessment Battery for Children, Second Edition and Bruininks-Oseretsky Test of Motor Proficiency, Second Edition for characterisation of motor proficiency), and behavioural observation/rating scales (such as the Autism Diagnostic Observation Schedule and the Social Responsiveness Scale for quantification of joint attention and social interaction).

Creation of more complex models of the relationship between stereopsis and social ability may also be necessary, as it is possible that other unmeasured factors besides frank motor proficiency play a role. For instance, the inability to master daily living skills of an appropriate developmental level (and the resulting lack of independence) attributable – in part – to poor stereopsis (Cao & Markowitz, 2014) may cause an individual to become self-concious, which in turn affects their ability to take part in social interaction (Reis, Sheldon, Gable, Roscoe, & Ryan, 2000). Another example regards an individual's ability to effectively perceive the distance between themselves and others, a key component of social interaction (E. T. Hall, 1966). Both underestimation of distance, causing an individual to stand too close and intrude into another's 'personal space' (Hayduk, 1978), and overestimation of distance, meaning the individual is too far away (Sundstrom & Altman, 1976), can have deleterious effects upon social interaction. Binocular disparity is one of the strongest cues to depth at close distances (see Figure 1.3 in Chapter 1), so it logically follows that individuals with poor stereopsis are more likely to mis-estimate personal distance and thus experience consequent negative impact.

While these are just two possibilities, consideration of the wider implications of abnormal stereopsis – by moving from the prescribed hand-eye coordination tasks that currently make up the majority of the literature to real-world tasks with increased ecological validity – could lead to a more informative understanding of how such deficits might affect everyday functioning and how to best treat these problems (for instance, by including occupational therapy alongside vision therapy in the program of treatment for stereopsis impairment).

8.7 Conclusion

This thesis aimed to characterise the consequences of reduced stereopsis on perception and the wider functional implications of such a deficit. I also wanted to address whether perceptual differences in autism were specific to the disorder or if they were attributable to an increased prevalence of poor stereoacuity within this population. The studies contained within this thesis show that though individual differences in stereoacuity may affect the quality of depth experienced, they do not affect the ability to combine different cues to depth. Furthermore, differences in perception experienced by individuals with an ASD seem to stem from the disorder and not the increased prevalence of impairment in stereopsis. It does, however, seem that individual differences in stereoacuity impact upon the development of motor proficiency and social skill, which – it should be noted – are typically compromised in those with ASD. Further research is required to form more nuanced accounts of how stereopsis impairment relates to everyday life.

APPENDIX A

Chapter 3

A.1 Tables for supplemental linear mixed model output

A.1.1 Experiment 2: children

Table A.1: Linear mixed-model analysis of child participant characteristics and low- and high-level predictors that contribute to the perceived circularity of the viewed shape *with the data from the two eldest children removed.*.

	β	B	B Std. Error	t value	p
Intercept		5.462	0.148	36.961	NA
Disparity	0.725	0.419	0.081	5.197	**<0.001**
Texture	−0.709	−0.410	0.071	−5.762	**<0.001**
c.Age	−0.028	−0.016	0.186	−0.088	0.930
sq.Age	−0.080	−0.046	0.080	−0.575	0.568
Stereo	−0.511	−0.295	0.461	−0.640	0.525
Prior	−0.218	−0.126	0.071	−1.766	0.079
Disparity:Texture	0.305	0.176	0.071	2.476	**0.014**
Disparity:c.Age	−0.080	−0.046	0.103	−0.449	0.655
Texture:c.Age	0.228	0.132	0.091	1.445	0.151
Disparity:sq.Age	−0.125	−0.072	0.044	−1.646	0.103
Texture:sq.Age	0.121	0.070	0.039	1.783	0.076
Disparity:Stereo	0.298	0.172	0.251	0.684	0.496
Texture:Stereo	0.715	0.413	0.221	1.866	0.064
c.Age:Stereo	1.375	0.795	0.692	1.147	0.256
sq.Age:Stereo	0.686	0.396	0.343	1.155	0.253
Disparity:Prior	0.183	0.106	0.071	1.481	0.140
c.Age:Prior	0.156	0.090	0.093	0.968	0.335
sq.Age:Prior	0.130	0.075	0.039	1.901	0.059
Stereo:Prior	0.272	0.157	0.222	0.708	0.480
Disparity:Texture:c.Age	−0.008	−0.005	0.091	−0.050	0.961
Disparity:Texture:sq.Age	0.046	0.026	0.039	0.678	0.499
Disparity:Texture:Stereo	−0.207	−0.119	0.221	−0.540	0.590

	β	B	B Std. Error	t value	p
Disparity:c.Age:Stereo	−1.149	−0.664	0.384	−1.729	0.087
Texture:c.Age:Stereo	−1.486	−0.859	0.338	−2.538	**0.012**
Disparity:sq.Age:Stereo	−0.458	−0.264	0.190	−1.395	0.167
Texture:sq.Age:Stereo	−0.868	−0.502	0.167	−2.997	**0.003**
Disparity:c.Age:Prior	−0.075	−0.043	0.093	−0.466	0.642
Disparity:sq.Age:Prior	0.040	0.023	0.039	0.583	0.561
Disparity:Stereo:Prior	0.111	0.064	0.222	0.290	0.772
c.Age:Stereo:Prior	−1.064	−0.615	0.348	−1.767	0.079
sq.Age:Stereo:Prior	−0.339	−0.196	0.171	−1.143	0.255
Disparity:Texture:c.Age:Stereo	0.823	0.476	0.338	1.406	0.162
Disparity:Texture:sq.Age:Stereo	0.315	0.182	0.167	1.088	0.279
Disparity:c.Age:Stereo:Prior	0.473	0.273	0.348	0.786	0.433
Disparity:sq.Age:Stereo:Prior	0.085	0.049	0.171	0.286	0.775

APPENDIX B

Chapter 5

B.1 Q-Q plots for thresholds

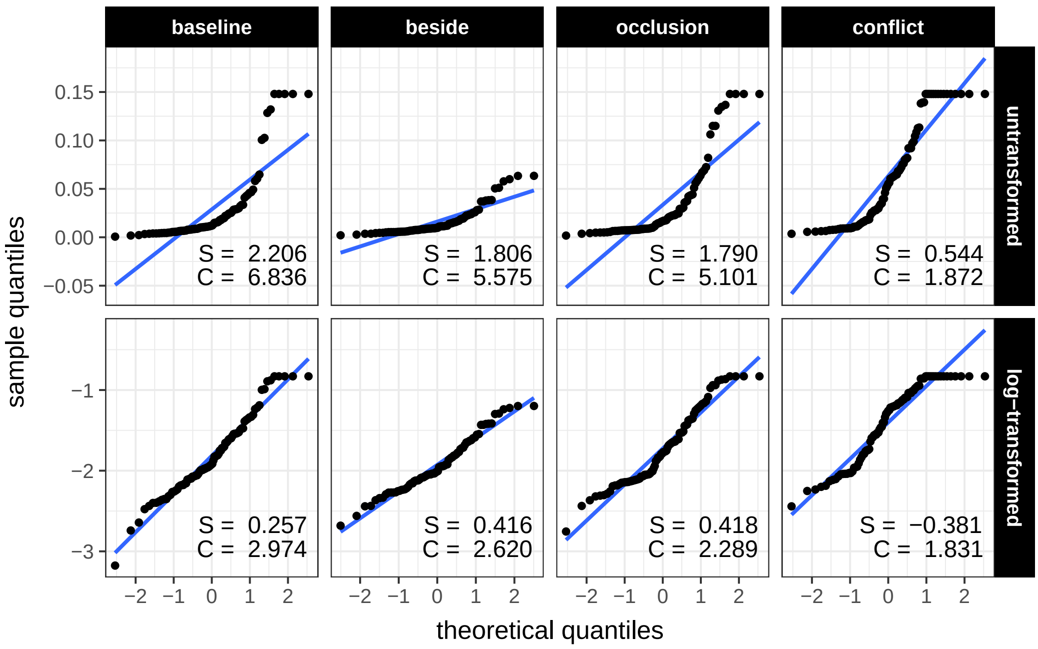


Figure B.1: Empirical-QQ plot of thresholds for the different occlusion configurations (collapsed across disparity sign) before and after log-transformation. Skewness (S) and kurtosis (C) can be seen for each distribution; note that both are significantly reduced after transformation (and are well under the recommended thresholds of skewness< 2 and kurtosis< 4; H.-Y. Kim, 2013).

B.2 Level of agreement between different measures of stereothreshold

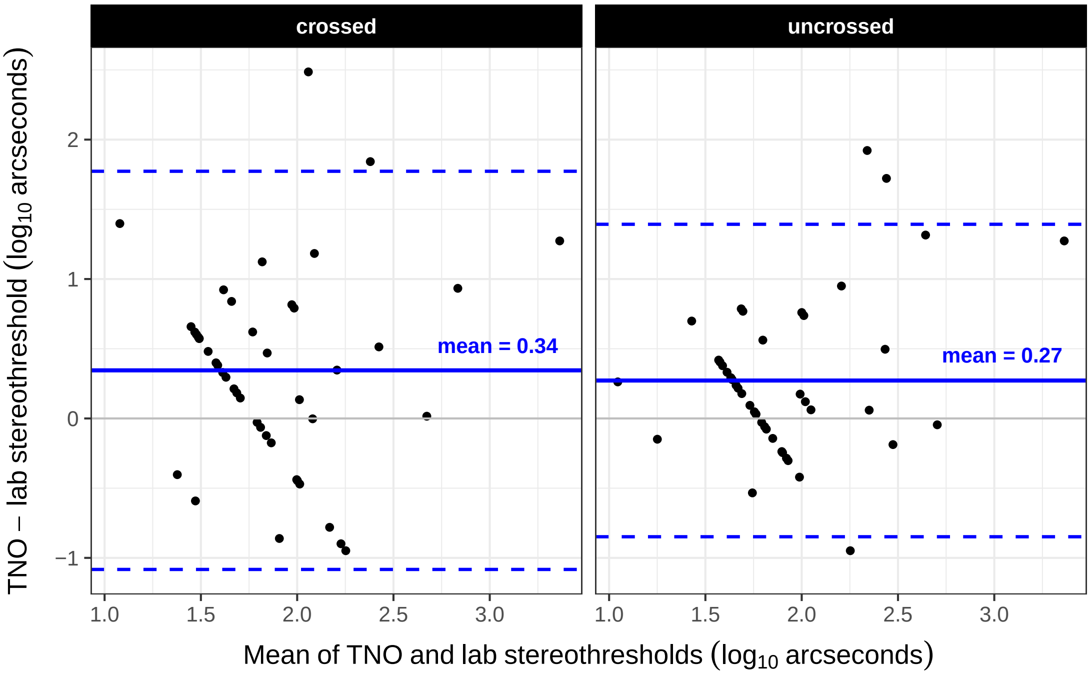


Figure B.2: Bland-Altman difference plot for thresholds derived by the TNO stereotest and the crossed and uncrossed experimental baseline conditions, with results recorded in log-arcseconds. Solid blue line is mean difference between the measures, and the dotted blue lines are the 95% confidence intervals.

B.3 Tables for omnibus type-III tests and linear mixed model output

B.3.1 Psychometric parameters

Table B.1: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including baseline stereoacuity and presence of ASD diagnosis), occlusion cues, and sign of disparity, and the effect of these predictors upon relative disparity threshold.

	F	df	F scaling	p
group	0.226	1, 39.56	1.000	1.000
condition	35.246	2, 38.413	0.975	**<0.001**
disparitySign	3.829	1, 40.315	1.000	0.229
crossedBaseline	6.530	1, 40.004	1.000	0.058
uncrossedBaseline	24.430	1, 39.329	1.000	**<0.001**
group:condition	2.002	2, 38.413	0.975	0.596

	F	df	F scaling	p
group:disparitySign	0.010	1, 40.315	1.000	1.000
condition:disparitySign	2.185	2, 78.133	1.000	0.477
group:crossedBaseline	0.021	1, 40.004	1.000	1.000
condition:crossedBaseline	2.459	2, 39.883	0.976	0.394
disparitySign:crossedBaseline	0.282	1, 42.684	1.000	1.000
group:uncrossedBaseline	2.622	1, 39.329	1.000	0.453
condition:uncrossedBaseline	0.500	2, 37.751	0.974	1.000
disparitySign:uncrossedBaseline	0.025	1, 39.671	1.000	1.000
group:condition:disparitySign	2.340	2, 78.133	1.000	0.412
group:condition:crossedBaseline	1.024	2, 39.883	0.976	1.000
group:disparitySign:crossedBaseline	0.066	1, 42.684	1.000	1.000
condition:disparitySign:crossedBaseline	0.089	2, 82.02	1.000	1.000
group:condition:uncrossedBaseline	1.743	2, 37.751	0.974	0.755
group:disparitySign:uncrossedBaseline	0.412	1, 39.671	1.000	1.000
condition:disparitySign:uncrossedBaseline	0.416	2, 77.221	1.000	1.000
group:condition:disparitySign:crossedBaseline	0.768	2, 82.02	1.000	1.000
group:condition:disparitySign:uncrossedBaseline	0.216	2, 77.221	1.000	1.000

Table B.2: Raw output from linear mixed-model analysis of participant characteristics (including crossed and uncrossed baseline stereoacuity and presence of ASD), disparity sign, and occlusion configuration, and the effect of these predictors upon relative disparity threshold.

	β	B	B Std. Error	t value
(Intercept)		−1.649	0.033	−50.332
group1	−0.019	−0.016	0.033	−0.476
condition1	−0.257	−0.206	0.028	−7.331
condition2	−0.081	−0.065	0.024	−2.721
disparitySign1	−0.040	−0.032	0.016	−1.965
crossedBaseline	0.247	0.199	0.078	2.560
uncrossedBaseline	0.740	0.595	0.120	4.949
group1:condition1	0.027	0.022	0.028	0.773
group1:condition2	−0.060	−0.048	0.024	−2.003
group1:disparitySign1	0.002	0.002	0.016	0.098
condition1:disparitySign1	−0.039	−0.031	0.023	−1.342
condition2:disparitySign1	0.058	0.046	0.022	2.068
group1:crossedBaseline	0.014	0.011	0.078	0.144
condition1:crossedBaseline	0.003	0.002	0.067	0.034
condition2:crossedBaseline	0.155	0.125	0.057	2.195
disparitySign1:crossedBaseline	0.026	0.021	0.039	0.535
group1:uncrossedBaseline	0.242	0.195	0.120	1.621
condition1:uncrossedBaseline	−0.062	−0.050	0.102	−0.489
condition2:uncrossedBaseline	−0.085	−0.069	0.088	−0.781
disparitySign1:uncrossedBaseline	−0.012	−0.009	0.059	−0.158

	β	B	B Std. Error	t value
group1:condition1:disparitySign1	0.011	0.009	0.023	0.382
group1:condition2:disparitySign1	0.046	0.037	0.022	1.648
group1:condition1:crossedBaseline	−0.057	−0.046	0.067	−0.685
group1:condition2:crossedBaseline	0.099	0.080	0.057	1.397
group1:disparitySign1:crossedBaseline	0.013	0.010	0.039	0.259
condition1:disparitySign1:crossedBaseline	0.015	0.012	0.056	0.214
condition2:disparitySign1:crossedBaseline	0.014	0.011	0.053	0.211
group1:condition1:uncrossedBaseline	0.106	0.085	0.102	0.839
group1:condition2:uncrossedBaseline	−0.200	−0.161	0.088	−1.829
group1:disparitySign1:uncrossedBaseline	0.048	0.038	0.059	0.644
condition1:disparitySign1:uncrossedBaseline	−0.017	−0.014	0.084	−0.164
condition2:disparitySign1:uncrossedBaseline	−0.072	−0.058	0.082	−0.708
group1:condition1:disparitySign1:crossedBaseline	−0.068	−0.054	0.056	−0.968
group1:condition2:disparitySign1:crossedBaseline	−0.014	−0.011	0.053	−0.204
group1:condition1:disparitySign1:uncrossedBaseline	−0.050	−0.041	0.084	−0.483
group1:condition2:disparitySign1:uncrossedBaseline	−0.016	−0.013	0.082	−0.159

Table B.3: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including baseline stereoacuity and presence of ASD diagnosis), occlusion cues, and sign of disparity, and the effect of these predictors upon the slope of the psychometric function.

	F	df	F scaling	p
group	0.179	1, 39.169	1.000	1.000
condition	67.370	2, 37.869	0.975	**<0.001**
disparitySign	2.501	1, 39.732	1.000	0.487
crossedBaseline	8.182	1, 41.423	1.000	**0.026**
uncrossedBaseline	18.038	1, 41.406	1.000	**<0.001**
group:condition	2.403	2, 37.869	0.975	0.416
group:disparitySign	0.693	1, 39.732	1.000	1.000
condition:disparitySign	6.862	2, 73.846	1.000	**0.007**
group:crossedBaseline	0.044	1, 41.423	1.000	1.000
condition:crossedBaseline	3.978	2, 40.754	0.977	0.106
disparitySign:crossedBaseline	0.777	1, 45.089	1.000	1.000
group:uncrossedBaseline	3.442	1, 41.406	1.000	0.283
condition:uncrossedBaseline	3.268	2, 40.088	0.976	0.194
disparitySign:uncrossedBaseline	0.396	1, 44.816	1.000	1.000
group:condition:disparitySign	1.329	2, 73.846	1.000	1.000
group:condition:crossedBaseline	3.120	2, 40.754	0.977	0.219
group:disparitySign:crossedBaseline	0.251	1, 45.089	1.000	1.000
condition:disparitySign:crossedBaseline	0.759	2, 77.213	1.000	1.000
group:condition:uncrossedBaseline	2.289	2, 40.088	0.976	0.458
group:disparitySign:uncrossedBaseline	0.097	1, 44.816	1.000	1.000
condition:disparitySign:uncrossedBaseline	1.193	2, 75.2	1.000	1.000

	F	df	F scaling	p
group:condition:disparitySign:crossedBaseline	0.403	2, 77.213	1.000	1.000
group:condition:disparitySign:uncrossedBaseline	0.503	2, 75.2	1.000	1.000

Table B.4: Raw output from linear mixed-model analysis of participant characteristics (including crossed and uncrossed baseline stereoacuity and presence of ASD), disparity sign, and occlusion configuration, and the effect of these predictors upon the slope of the psychometric function.

	β	B	B Std. Error	t value
(Intercept)		14.604	0.856	17.051
group1	0.015	0.364	0.856	0.425
condition1	0.284	6.772	0.727	9.317
condition2	0.141	3.378	0.695	4.859
disparitySign1	0.037	0.891	0.559	1.593
crossedBaseline	−0.248	−5.926	2.057	−2.881
uncrossedBaseline	−0.573	−13.693	3.201	−4.278
group1:condition1	−0.023	−0.543	0.727	−0.747
group1:condition2	0.065	1.546	0.695	2.224
group1:disparitySign1	−0.020	−0.469	0.559	−0.838
condition1:disparitySign1	0.091	2.179	0.586	3.720
condition2:disparitySign1	−0.041	−0.990	0.582	−1.700
group1:crossedBaseline	0.018	0.433	2.057	0.210
condition1:crossedBaseline	−0.131	−3.139	1.771	−1.772
condition2:crossedBaseline	−0.135	−3.219	1.679	−1.918
disparitySign1:crossedBaseline	−0.051	−1.225	1.375	−0.891
group1:uncrossedBaseline	−0.250	−5.981	3.201	−1.869
condition1:uncrossedBaseline	−0.279	−6.663	2.716	−2.454
condition2:uncrossedBaseline	−0.053	−1.275	2.629	−0.485
disparitySign1:uncrossedBaseline	0.057	1.363	2.146	0.635
group1:condition1:disparitySign1	−0.040	−0.962	0.586	−1.643
group1:condition2:disparitySign1	0.016	0.390	0.582	0.669
group1:condition1:crossedBaseline	0.094	2.240	1.771	1.265
group1:condition2:crossedBaseline	−0.170	−4.050	1.679	−2.413
group1:disparitySign1:crossedBaseline	0.029	0.696	1.375	0.506
condition1:disparitySign1:crossedBaseline	−0.025	−0.588	1.455	−0.404
condition2:disparitySign1:crossedBaseline	−0.061	−1.447	1.422	−1.018
group1:condition1:uncrossedBaseline	−0.223	−5.324	2.716	−1.960
group1:condition2:uncrossedBaseline	0.141	3.370	2.629	1.282
group1:disparitySign1:uncrossedBaseline	0.028	0.674	2.146	0.314
condition1:disparitySign1:uncrossedBaseline	−0.045	−1.070	2.216	−0.483
condition2:disparitySign1:uncrossedBaseline	0.146	3.482	2.235	1.558
group1:condition1:disparitySign1:crossedBaseline	0.028	0.666	1.455	0.458
group1:condition2:disparitySign1:crossedBaseline	−0.052	−1.251	1.422	−0.880
group1:condition1:disparitySign1:uncrossedBaseline	0.054	1.282	2.216	0.578

	β	B	B Std. Error	t value
group1:condition2:disparitySign1:uncrossedBaseline	0.061	1.461	2.235	0.654

B.3.2 Reaction time measures

Table B.5: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including baseline stereoacuity and presence of ASD diagnosis), occlusion cues, and sign of disparity, and the effect of these predictors upon reaction speed.

	F	df	F scaling	p
group	9.003	1, 39.049	1.000	**0.019**
condition	5.240	2, 38.467	0.975	**0.039**
disparitySign	1.314	1, 39.258	1.000	1.000
crossedBaseline	2.962	1, 39.174	1.000	0.373
uncrossedBaseline	17.644	1, 39.152	1.000	**<0.001**
group:condition	2.695	2, 38.467	0.975	0.321
group:disparitySign	8.297	1, 39.258	1.000	**0.026**
condition:disparitySign	2.985	2, 38.456	0.975	0.250
group:crossedBaseline	0.152	1, 39.174	1.000	1.000
condition:crossedBaseline	0.751	2, 39.664	0.975	1.000
disparitySign:crossedBaseline	0.403	1, 39.926	1.000	1.000
group:uncrossedBaseline	4.887	1, 39.152	1.000	0.132
condition:uncrossedBaseline	1.189	2, 39.473	0.975	1.000
disparitySign:uncrossedBaseline	1.991	1, 39.814	1.000	0.664
group:condition:disparitySign	0.273	2, 38.456	0.975	1.000
group:condition:crossedBaseline	0.300	2, 39.664	0.975	1.000
group:disparitySign:crossedBaseline	0.011	1, 39.926	1.000	1.000
condition:disparitySign:crossedBaseline	0.277	2, 39.76	0.976	1.000
group:condition:uncrossedBaseline	0.849	2, 39.473	0.975	1.000
group:disparitySign:uncrossedBaseline	0.011	1, 39.814	1.000	1.000
condition:disparitySign:uncrossedBaseline	0.356	2, 39.611	0.975	1.000
group:condition:disparitySign:crossedBaseline	1.807	2, 39.76	0.976	0.710
group:condition:disparitySign:uncrossedBaseline	0.393	2, 39.611	0.975	1.000

Table B.6: Raw output from linear mixed-model analysis of participant characteristics (including crossed and uncrossed baseline stereoacuity and presence of ASD), disparity sign, and occlusion configuration, and the effect of these predictors upon reaction speed.

	β	B	B Std. Error	t value
(Intercept)		1.262	0.038	32.782
group1	0.189	0.116	0.038	3.001
condition1	0.044	0.027	0.017	1.533

	β	B	B Std. Error	t value
condition2	0.044	0.027	0.015	1.801
disparitySign1	0.031	0.019	0.016	1.147
crossedBaseline	−0.256	−0.157	0.091	−1.721
uncrossedBaseline	0.973	0.594	0.141	4.201
group1:condition1	−0.013	−0.008	0.017	−0.458
group1:condition2	0.055	0.034	0.015	2.243
group1:disparitySign1	−0.077	−0.047	0.016	−2.883
condition1:disparitySign1	−0.051	−0.031	0.014	−2.209
condition2:disparitySign1	0.047	0.029	0.015	1.899
group1:crossedBaseline	−0.058	−0.036	0.091	−0.391
condition1:crossedBaseline	−0.073	−0.045	0.042	−1.076
condition2:crossedBaseline	−0.002	−0.001	0.036	−0.034
disparitySign1:crossedBaseline	0.040	0.025	0.039	0.636
group1:uncrossedBaseline	0.512	0.313	0.141	2.211
condition1:uncrossedBaseline	−0.141	−0.086	0.065	−1.333
condition2:uncrossedBaseline	0.124	0.076	0.056	1.357
disparitySign1:uncrossedBaseline	−0.139	−0.085	0.060	−1.413
group1:condition1:disparitySign1	0.008	0.005	0.014	0.348
group1:condition2:disparitySign1	−0.019	−0.011	0.015	−0.747
group1:condition1:crossedBaseline	0.052	0.032	0.042	0.770
group1:condition2:crossedBaseline	−0.014	−0.008	0.036	−0.231
group1:disparitySign1:crossedBaseline	0.007	0.004	0.039	0.104
condition1:disparitySign1:crossedBaseline	−0.032	−0.020	0.033	−0.593
condition2:disparitySign1:crossedBaseline	0.039	0.024	0.036	0.660
group1:condition1:uncrossedBaseline	−0.134	−0.082	0.065	−1.266
group1:condition2:uncrossedBaseline	0.086	0.052	0.056	0.938
group1:disparitySign1:uncrossedBaseline	0.010	0.006	0.060	0.104
condition1:disparitySign1:uncrossedBaseline	0.049	0.030	0.052	0.578
condition2:disparitySign1:uncrossedBaseline	−0.075	−0.046	0.057	−0.807
group1:condition1:disparitySign1:crossedBaseline	−0.043	−0.027	0.033	−0.794
group1:condition2:disparitySign1:crossedBaseline	0.115	0.070	0.036	1.928
group1:condition1:disparitySign1:uncrossedBaseline	−0.036	−0.022	0.052	−0.429
group1:condition2:disparitySign1:uncrossedBaseline	−0.052	−0.032	0.057	−0.561

Table B.7: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including baseline stereoacuity and presence of ASD diagnosis), occlusion cues, and sign of disparity, and the effect of these predictors upon reaction speed variability.

	F	df	F scaling	p
group	0.184	1, 39.045	1.000	1.000
condition	13.932	2, 38.367	0.975	**<0.001**
disparitySign	0.554	1, 39.279	1.000	1.000
crossedBaseline	0.175	1, 39.373	1.000	1.000

	F	df	F scaling	p
uncrossedBaseline	5.916	1, 39.253	1.000	0.079
group:condition	5.472	2, 38.367	0.975	**0.032**
group:disparitySign	0.095	1, 39.279	1.000	1.000
condition:disparitySign	0.845	2, 38.419	0.975	1.000
group:crossedBaseline	3.166	1, 39.373	1.000	0.332
condition:crossedBaseline	2.323	2, 41.287	0.977	0.443
disparitySign:crossedBaseline	3.914	1, 41.313	1.000	0.218
group:uncrossedBaseline	0.054	1, 39.253	1.000	1.000
condition:uncrossedBaseline	2.511	2, 40.427	0.976	0.375
disparitySign:uncrossedBaseline	4.355	1, 40.592	1.000	0.173
group:condition:disparitySign	1.091	2, 38.419	0.975	1.000
group:condition:crossedBaseline	0.243	2, 41.287	0.977	1.000
group:disparitySign:crossedBaseline	0.082	1, 41.313	1.000	1.000
condition:disparitySign:crossedBaseline	1.567	2, 41.61	0.977	0.883
group:condition:uncrossedBaseline	1.085	2, 40.427	0.976	1.000
group:disparitySign:uncrossedBaseline	0.001	1, 40.592	1.000	1.000
condition:disparitySign:uncrossedBaseline	2.798	2, 40.587	0.976	0.291
group:condition:disparitySign:crossedBaseline	1.500	2, 41.61	0.977	0.940
group:condition:disparitySign:uncrossedBaseline	0.307	2, 40.587	0.976	1.000

Table B.8: Raw output from linear mixed-model analysis of participant characteristics (including crossed and uncrossed baseline stereoacuity and presence of ASD), disparity sign, and occlusion configuration, and the effect of these predictors upon reaction speed variability.

	β	B	B Std. Error	t value
(Intercept)		0.396	0.011	36.652
group1	0.028	0.005	0.011	0.429
condition1	−0.029	−0.005	0.004	−1.274
condition2	−0.098	−0.016	0.003	−4.640
disparitySign1	0.018	0.003	0.004	0.746
crossedBaseline	−0.065	−0.011	0.026	−0.418
uncrossedBaseline	0.588	0.097	0.040	2.433
group1:condition1	0.011	0.002	0.004	0.508
group1:condition2	−0.070	−0.012	0.003	−3.329
group1:disparitySign1	−0.008	−0.001	0.004	−0.308
condition1:disparitySign1	0.000	0.000	0.004	−0.009
condition2:disparitySign1	0.028	0.005	0.004	1.121
group1:crossedBaseline	0.277	0.046	0.026	1.780
condition1:crossedBaseline	0.047	0.008	0.009	0.878
condition2:crossedBaseline	0.088	0.014	0.008	1.722
disparitySign1:crossedBaseline	0.117	0.019	0.010	1.985
group1:uncrossedBaseline	−0.056	−0.009	0.040	−0.232
condition1:uncrossedBaseline	−0.047	−0.008	0.014	−0.555

	β	B	B Std. Error	t value
condition2:uncrossedBaseline	−0.155	−0.026	0.013	−1.977
disparitySign1:uncrossedBaseline	−0.190	−0.031	0.015	−2.093
group1:condition1:disparitySign1	−0.016	−0.003	0.004	−0.691
group1:condition2:disparitySign1	0.037	0.006	0.004	1.494
group1:condition1:crossedBaseline	0.035	0.006	0.009	0.645
group1:condition2:crossedBaseline	0.006	0.001	0.008	0.123
group1:disparitySign1:crossedBaseline	−0.017	−0.003	0.010	−0.288
condition1:disparitySign1:crossedBaseline	−0.015	−0.002	0.009	−0.265
condition2:disparitySign1:crossedBaseline	−0.083	−0.014	0.010	−1.408
group1:condition1:uncrossedBaseline	0.014	0.002	0.014	0.167
group1:condition2:uncrossedBaseline	−0.116	−0.019	0.013	−1.478
group1:disparitySign1:uncrossedBaseline	−0.004	−0.001	0.015	−0.039
condition1:disparitySign1:uncrossedBaseline	−0.056	−0.009	0.014	−0.638
condition2:disparitySign1:uncrossedBaseline	0.211	0.035	0.015	2.312
group1:condition1:disparitySign1:crossedBaseline	0.049	0.008	0.009	0.878
group1:condition2:disparitySign1:crossedBaseline	0.052	0.009	0.010	0.883
group1:condition1:disparitySign1:uncrossedBaseline	−0.051	−0.008	0.014	−0.579
group1:condition2:disparitySign1:uncrossedBaseline	−0.015	−0.003	0.015	−0.170

APPENDIX C

Chapter 6

C.1 Tables for omnibus type-III tests

Table C.1: F-test of fixed terms in a linear mixed model analysis of age, motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	F	df	F scaling	p
view	88.642	1, 70	1.000	**<0.001**
activity	0.000	2, 69	0.986	1.000
age	49.255	1, 70	1.000	**<0.001**
view:activity	17.927	2, 140	1.000	**<0.001**
view:age	0.456	1, 70	1.000	1.000
activity:age	2.482	2, 69	0.986	0.273
view:activity:age	0.802	2, 140	1.000	1.000

Table C.2: Raw output from Linear mixed-model analysis of age, motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	β	B	B Std. Error	t value
(Intercept)		0.000	0.063	0.000
view1	0.345	0.255	0.027	9.415
activity1	0.000	0.000	0.073	0.000
activity2	0.000	0.000	0.055	0.000
age	0.318	0.236	0.034	7.018
view1:activity1	−0.172	−0.127	0.036	−3.505
view1:activity2	0.292	0.216	0.036	5.957
view1:age	−0.013	−0.010	0.014	−0.675
activity1:age	−0.101	−0.075	0.039	−1.913
activity2:age	0.009	0.006	0.030	0.213
view1:activity1:age	−0.001	−0.001	0.019	−0.048
view1:activity2:age	−0.028	−0.021	0.019	−1.072

	β	B	B Std. Error	t value

Table C.3: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including age and crossed stereoacuity), motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	F	df	F scaling	p
view	82.827	1, 68	1.000	**<0.001**
activity	0.052	2, 67	0.985	1.000
crossedStereoacuity	8.785	1, 68	1.000	**0.013**
age	43.016	1, 68	1.000	**<0.001**
view:activity	15.479	2, 136	1.000	**<0.001**
view:crossedStereoacuity	0.253	1, 68	1.000	1.000
activity:crossedStereoacuity	1.030	2, 67	0.985	1.000
view:age	0.302	1, 68	1.000	1.000
activity:age	2.216	2, 67	0.985	0.351
crossedStereoacuity:age	1.756	1, 68	1.000	0.569
view:activity:crossedStereoacuity	0.843	2, 136	1.000	1.000
view:activity:age	0.470	2, 136	1.000	1.000
view:crossedStereoacuity:age	0.054	1, 68	1.000	1.000
activity:crossedStereoacuity:age	0.983	2, 67	0.985	1.000
view:activity:crossedStereoacuity:age	1.581	2, 136	1.000	0.629

Table C.4: Raw output from Linear mixed-model analysis of participant characteristics (including age and crossed stereoacuity), motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	β	B	B Std. Error	t value
(Intercept)		−0.019	0.062	−0.305
view1	0.275	0.257	0.028	9.101
activity1	−0.022	−0.021	0.075	−0.277
activity2	0.018	0.017	0.057	0.301
crossedStereoacuity	−0.424	−0.396	0.134	−2.964
age	0.231	0.216	0.033	6.559
view1:activity1	−0.120	−0.112	0.037	−3.010
view1:activity2	0.221	0.206	0.037	5.558
view1:crossedStereoacuity	0.033	0.031	0.061	0.503
activity1:crossedStereoacuity	−0.149	−0.139	0.163	−0.853
activity2:crossedStereoacuity	0.190	0.178	0.123	1.446
view1:age	−0.009	−0.008	0.015	−0.549
activity1:age	−0.083	−0.077	0.040	−1.922
activity2:age	0.013	0.013	0.030	0.413

	β	B	B Std. Error	t value
crossedStereoacuity:age	−0.092	−0.086	0.065	−1.325
view1:activity1:crossedStereoacuity	0.079	0.073	0.081	0.911
view1:activity2:crossedStereoacuity	0.030	0.028	0.081	0.346
view1:activity1:age	−0.001	−0.001	0.020	−0.035
view1:activity2:age	−0.017	−0.016	0.020	−0.822
view1:crossedStereoacuity:age	0.007	0.007	0.030	0.233
activity1:crossedStereoacuity:age	−0.102	−0.095	0.079	−1.205
activity2:crossedStereoacuity:age	0.083	0.078	0.059	1.307
view1:activity1:crossedStereoacuity:age	0.074	0.069	0.039	1.763
view1:activity2:crossedStereoacuity:age	−0.045	−0.042	0.039	−1.080

Table C.5: F-test of fixed terms in a linear mixed model analysis of participant characteristics (including age and uncrossed stereoacuity), motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	F	df	F scaling	p
view	84.807	1, 68	1.000	**<0.001**
activity	0.076	2, 67	0.985	1.000
uncrossedStereoacuity	9.497	1, 68	1.000	**0.009**
age	31.929	1, 68	1.000	**<0.001**
view:activity	14.261	2, 136	1.000	**<0.001**
view:uncrossedStereoacuity	3.266	1, 68	1.000	0.225
activity:uncrossedStereoacuity	0.118	2, 67	0.985	1.000
view:age	0.003	1, 68	1.000	1.000
activity:age	1.674	2, 67	0.985	0.586
uncrossedStereoacuity:age	2.979	1, 68	1.000	0.267
view:activity:uncrossedStereoacuity	0.702	2, 136	1.000	1.000
view:activity:age	0.226	2, 136	1.000	1.000
view:uncrossedStereoacuity:age	0.933	1, 68	1.000	1.000
activity:uncrossedStereoacuity:age	0.584	2, 67	0.985	1.000
view:activity:uncrossedStereoacuity:age	0.424	2, 136	1.000	1.000

Table C.6: Raw output from Linear mixed-model analysis of participant characteristics (including age and uncrossed stereoacuity), motor activity, and viewing condition, and the effect of these predictors upon motor performance.

	β	B	B Std. Error	t value
(Intercept)		−0.040	0.064	−0.622
view1	0.293	0.265	0.029	9.209
activity1	−0.034	−0.031	0.078	−0.390
activity2	0.013	0.012	0.060	0.200
uncrossedStereoacuity	−0.479	−0.434	0.141	−3.082
age	0.216	0.196	0.035	5.651
view1:activity1	−0.126	−0.114	0.039	−2.923
view1:activity2	0.230	0.208	0.039	5.332
view1:uncrossedStereoacuity	0.126	0.114	0.063	1.807
activity1:uncrossedStereoacuity	0.004	0.004	0.172	0.021
activity2:uncrossedStereoacuity	0.055	0.050	0.132	0.379
view1:age	0.001	0.001	0.016	0.053
activity1:age	−0.076	−0.069	0.042	−1.632
activity2:age	0.011	0.010	0.033	0.298
uncrossedStereoacuity:age	−0.118	−0.107	0.062	−1.726
view1:activity1:uncrossedStereoacuity	0.041	0.038	0.086	0.437
view1:activity2:uncrossedStereoacuity	0.070	0.063	0.086	0.735
view1:activity1:age	0.001	0.001	0.021	0.047
view1:activity2:age	−0.014	−0.013	0.021	−0.604
view1:uncrossedStereoacuity:age	0.030	0.027	0.028	0.966
activity1:uncrossedStereoacuity:age	−0.090	−0.082	0.076	−1.082
activity2:uncrossedStereoacuity:age	0.036	0.032	0.058	0.555
view1:activity1:uncrossedStereoacuity:age	0.038	0.034	0.038	0.915
view1:activity2:uncrossedStereoacuity:age	−0.023	−0.021	0.038	−0.547

APPENDIX D

Chapter 7

D.1 Per-item normality distribution

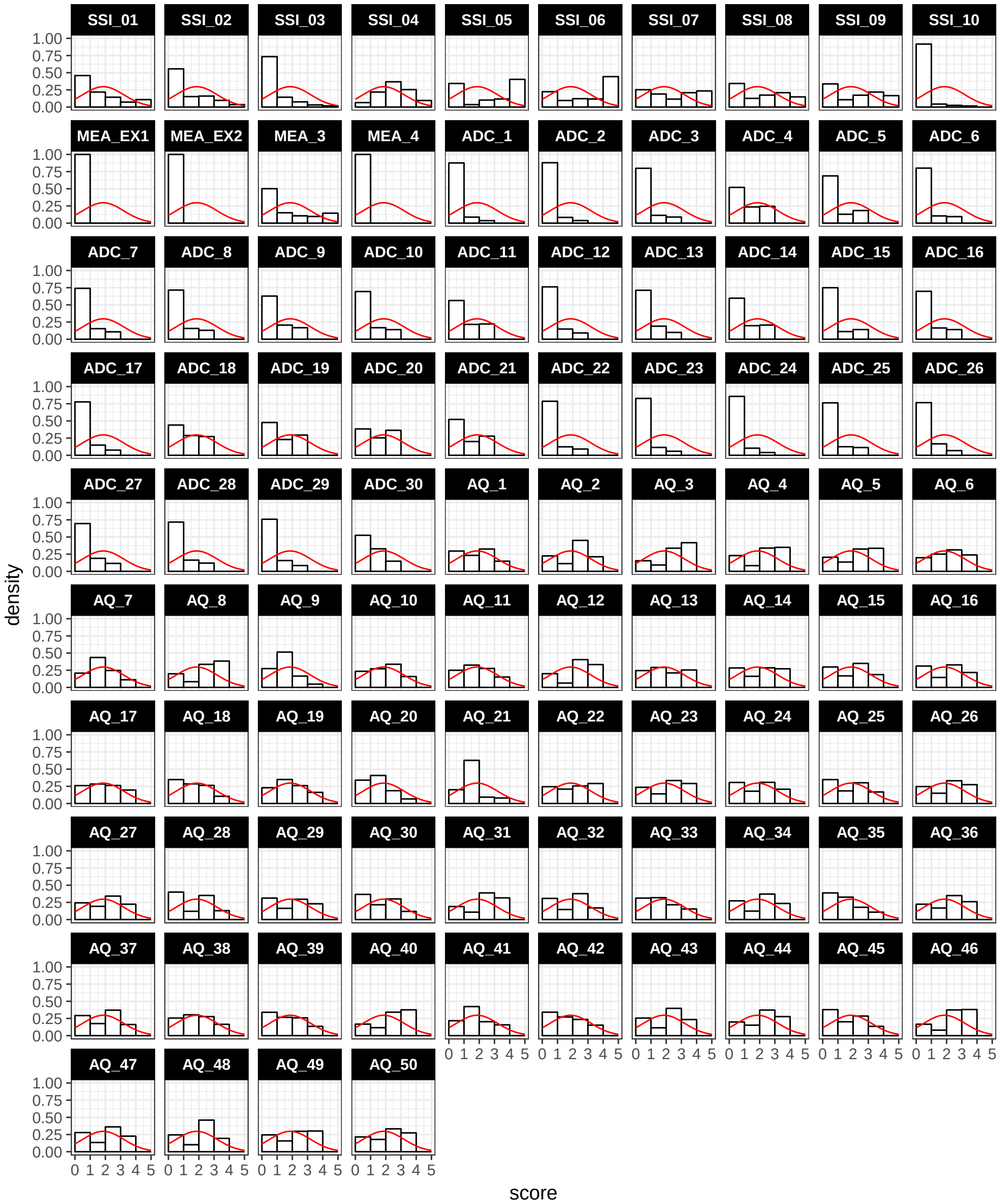


Figure D.1: Distributions of scores across all items from the four measures.

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