Sailing the Ocean of Faces:

Unravelling Individual Differences in Face Recognition Abilities

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Abstract

Even though it has generally been assumed that humans are experts in face recognition, the ability to learn and recognize faces varies considerably across individuals. However, it is still unclear to what extent the use of facial information and/or underlying processes differs across individuals. This dissertation consists of four empirical chapters that aimed to explore the role of low-level visual processing to higher-level processes in face recognition ability (FRA) at an individual level. In the first empirical chapter (Chapter 2), we examined how the use of different bands of spatial frequency (SF) information influences FRA at different stages of face recognition. While studies have found that low SF information is important for accurate face recognition, whether it facilitates individual differences in FRA remains unexplored. In our study, we found that low and high SF information are equally important and informative in face learning and face recognition. However, no significant association was found between the recognition performance of low and high SF-filtered faces with FRA, this argues that SF processing does not contribute to individual differences in face recognition.

In Chapter 3, we aimed to gain further insight into the role of holistic processing in FRA, particularly between Western and Eastern societies. Although it is generally assumed that face recognition relies on holistic processing, whether face recognition ability can be predicted by holistic processing is currently under debate. The mixed findings from past studies could be the consequence of cultural differences across studies, as well as the use of different measures of holistic processing that showed a poor association between each other: the composite task, the part-whole task, and the inversion task. We found that FRA is associated with the part-whole and inversion effect, but not the composite effect. This was true for both Easterners and Westerners. This suggests that FRA is facilitated by similar underlying cognitive mechanisms of holistic

processing across different societies. Despite that, our factor analysis revealed cultural differences in the loading patterns of holistic mechanisms into FRA. This argues that holistic face processing is not universal, wherein underlying construct in holistic face processing is culture-specific.

Accordingly in Chapter 4, we examined the role of holistic processing in Developmental Prosopagnosics (DPs) and Acquired Prosopagnosics (APs). Similar to the preceding chapter, several tests measuring the holistic processing of faces and non-face objects were used. However, the current chapter recruited groups of DPs (Experiment 1), APs (Experiment 2), and neurotypicals. At a group level, DPs showed diminished inversion and part-whole effects, but comparable magnitudes of the composite effect and global precedence effect. Interestingly, single-case analyses showed that these holistic processing deficits in DPs are *heterogeneous*, wherein holistic impairments are distinct across individual DPs. On the other hand, our single-case analyses revealed that two APs were both impaired in holistic processing, as measured with the face inversion effect, but not the part-whole or composite effects. This suggest that holistic processing deficits in APs are consistent. Together, the findings challenge the view that the concept of holistic processing is unitary, as well as highlight the importance of single-case analyses in characterizing neurodevelopmental profiles.

In Chapter 5, we aimed to further investigate the role of holistic processing, as well as featural processing, in face identification abilities by incorporating the *fixed trajectory aperture paradigm* (FTAP) during face learning and recognition. While it is generally accepted that holistic processing facilitates face recognition, recent studies suggest that poor recognition might also arise from the imprecise perception of local features in the face. Our results showed that participants recognised faces more accurately in conditions where holistic information was preserved than when it is impaired. We also show that the better use of holistic processing during face learning and face recognition was associated with better FRAs. However, enhanced featural processing during recognition, but not during learning, was related to better FRAs. Together, our findings demonstrate that good face recognition depends on distinct roles played by holistic and featural processing, at different stages of face recognition.

Altogether, across four empirical chapters, the results of this thesis showed that individual differences in face recognition abilities can be explained by high-level (i.e., holistic and/or featural processing), but not low-level (i.e., spatial frequency) processes. In the first study, we found that low and high SF processing does not facilitate face learning and face recognition. In contrast, the following studies indicated that higher-level cognitive mechanisms involving holistic and/or featural processing underlie individual differences in face recognition. These associations between holistic face processing and face recognition abilities are also found across both Western and Eastern cultures. However, holistic processing does not seem to predict face recognition deficits in prosopagnosics. Interestingly, the concept of holistic face processing is (1) not unitary, (2) nor is it universal across cultures, and presumably (3) has distinct roles during face learning and face recognition.

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Declaration

I declare that this thesis is my own work carried out under the normal terms of supervision.

Publications

Chapter 5 has been published. Chapter 3 is ready to be submitted for publication. Chapter 2 and 4 are being prepared for submission.

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CHAPTER 1: General Introduction

While seated at a café, savouring your favourite drink, you catch a glimpse of a familiar face. After taking a few moments to observe them, you are certain that this person is one of your high school classmates, whom you have not seen in 20 years. How can you be sure that the person before you today is the same individual you saw many years ago? How can you discern if the person is indeed the one you had in mind? It is possible that the person you are looking at is someone you have encountered elsewhere, at another time. This raises the question: why is it often simpler to recognize a close friend you met decades ago, yet more challenging to identify a stranger you saw at a bus stop just yesterday?

For most humans, associating with others extends beyond mere factors like name, race, ethnicity, or occupation; it hinges on recognizing their unique faces. Although time has passed, certain distinct facial features associated with your high school friend are likely etched in your memory, enabling you to confidently identify them. However, the task of connecting each individual we know with a unique face can be taxing for the human brain, especially when most human faces share common features such as eyes, nose, and mouth. The ability to recognize faces is, therefore, one of the most crucial skills that allow us to form a sense of self, distinguish ourselves from other human beings, and differentiate between others.

1.1 Significance of Face Recognition

The human face – arguably human’s richest source of information about the people around us – has been a significant focus in computer science, contemporary cognition, and neuroscience over the years (Wilmer, 2017). Identity is not the only information conveyed by a face. The face can also signal an individual’s underlying emotion and attentiveness. Therefore, a face is a crucial cue for non-verbal social communication (Little et al., 2011; Todorov et al., 2005). Face recognition enables us to identify and remember individuals, providing a foundation for establishing and maintaining relationships, as well as navigating through various social contexts (Bruce & Young, 1986). Among its many benefits, face recognition enables us to establish trust and cooperation, facilitating meaningful relationships with others.

Furthermore, face recognition also acts as a medium for interpreting subtle facial cues and extracting emotional information that we might overlook when encountering unfamiliar faces. For instance, face recognition allows us to access stored information about that person, including their emotional expressions. This prior knowledge about the individual's emotions allows us to interpret and understand their current emotional state more quickly and accurately (Adolphs, 2006). Thus, recognizing a person and their emotions from non-verbal cues not only facilitates effective communication but also allows one to empathize and comprehend the state of mind of others. Moreover, face recognition is crucial for self-perception or consciousness, where humans can adopt another's perspective onto themselves (Chakraborty & Chakrabarti, 2018; Lee et al., 2022b). As opposed to other forms of personal information, such as names, a face is often unique and distinct to an individual (Devue & Brédart, 2011). Therefore, our ability to recognize our own face forms the basis for self-referential processes and a unified self-concept, which is essential for establishing self-identity and regulating behaviour, like self-esteem (Estudillo & Bindemann, 2017; Gallup, 1970; McNeill, 1998).

In several real-life situations, recognising the identity of faces plays a pivotal role in security monitoring and even danger detection (Estudillo, 2012; Robinson et al., 2014; Tolba et al., 2006). By comparing faces with a database of known individuals, face recognition allows the identification of suspicious individuals, wanted criminals, or persons of interest (Bowyer, 2004). In forensic investigations, face recognition is instrumental in identifying suspects and establishing connections between suspects and evidence. For example, police officers may rely on image or video comparisons obtained from crime scenes to identify criminals (Turk & Pentland, 1991). Here, face recognition can enhance the accuracy and efficiency of an investigative process, and reduce the risk of misidentification that could lead to wrongful convictions. Additionally, by monitoring and recognising facial expressions and reactions, security personnel can identify potential threats or individuals showing suspicious behaviour (Al-Modwahi et al., 2012).

It is also widely believed that our ability to recognise faces was bestowed from an evolutionary advantage, and therefore, preserved through the processes of natural selection (Kennett & Wallis, 2019). As shown in studies by Hershler and Hochstein (2005), using a visual search paradigm, human faces were found to “pop-out” from an array of non-face objects. Notably, this effect was not replicated with schematic or animal faces. This "pop-out" effect is thought to result from threat and predatory detection (Adolphs, 2008). For instance, being able to differentiate an enemy from a friend, or identify those who may pose a potential threat, allows an individual to respond quickly and even proactively prior to an attack. Nonetheless, given the great importance of face identification, it should not come as a surprise that humans are effortlessly good at discriminating between familiar faces (Felisberti & Musholt, 2014; Johnston & Edmonds, 2009).

1.2 Domain-specificity of Face Recognition

1.2.1 Are faces special?

Considering the significance of face recognition, there may be something "special" about the representation of faces and their underlying cognitive mechanisms in the human brain (for detailed discussion, see review by McKone & Robbins, 2011). Accordingly, studies have shown that humans process human faces differently from other classes of complex visual stimuli (e.g., animal faces, man-made objects). For example, the processing of faces was found to be more sensitive towards contrast reversal (Galper, 1970) and orientation inversion (Yin, 1969) than non-face objects, arguing that the processing of faces is dissociable from non-face objects. Explicitly, reversing the contrast or inverting faces and other objects (from their canonical orientation) disrupts our ability to recognize them, but these effects are relatively stronger for faces. Moreover, in line with evolutionary perspectives, humans can instinctively detect the presence of novel faces faster and more accurately than non-face objects (Crouzet & Thorpe, 2011; Hershler & Hochstein, 2005; Simpson et al., 2014). These perceptual advantages for faces persist even when these faces and objects are embedded in natural scenes (Burton & Bindemann, 2009).

There is some evidence showing that the human brain has neural mechanisms that selectively respond to faces. Specifically, neuroimaging studies have found clusters of face-selective neurons located in the temporal lobe, collectively known as the fusiform face area (FFA; Haxby et al., 2000; Kanwisher et al., 1997), the occipital face area (OFA; Gauthier et al., 2000; Rossion et al., 2003), the posterior superior temporal sulcus (pSTS; Hoffman & Haxby, 2000), and the anterior inferotemporal cortex (aIT; Evans et al., 1995), that are engaged during face processing. This face-specific network is active exclusively when people detect and perceive attributes of faces (de Souza et al., 2008). The FFA, OFA, and aIT were shown to be involved in complex computational tasks, such as the representation of facial identities (Zhu et al., 2011), related to the perception of faces at an individual level (Gauthier et al., 2000; Huang et al., 2014; Kriegeskorte et al., 2007). Other studies have found that the pSTS processes the dynamic (e.g., gaze direction) and emotional aspects (e.g., facial expressions) of facial information (Hoffman & Haxby, 2000).

Activations in FFA and OFA have been associated with the recognition of faces, but not of non-face objects or more complex scenes (Zhu et al., 2011; Huang et al., 2014). For instance, studies have revealed that the FFA is activated more strongly when participants are asked to discriminate between human faces than between animal faces (Carmel & Bentin, 2002) or between other classes of objects (e.g., cars, flowers; Kanwisher et al., 1997), while similar levels of activation are found in other brain areas (e.g., lateral occipital complex) that are involved in object processing in a more general way (Kanwisher & Yovel, 2006). Evidently, lesions to face-selective areas can lead to face-specific recognition impairments (Della Sala & Young, 2003; Barton, 2008a). Further, studies have also shown that face-selective neurons were present in other non-human primates (de Souza et al., 2005; Tsao et al., 2006). For example, Tsao et al. (2006) identified a brain region in macaque monkeys that is activated more strongly for human and/or macaque faces than other non-face objects.

Furthermore, some studies have also shown comparable face selectivity in newborns and early infants. Traditionally, it has been suggested that newborns have an innate representation of a “face template” (Morton & Johnson, 1991). Consequently, studies have found that less than one-day-old newborns prefer looking at face-resembling shapes and pictures of real faces over other non-face shapes (e.g., black and white stripes) or complex visual objects (Mondloch et al., 1999; Johnson et al., 1991). Within hours after birth, newborns also prefer to look at their mother's face over other unfamiliar female faces (Bushnell, 2001). Overall, these studies suggest that face recognition has a strong innate component, enabling humans to recognize and discriminate faces from other objects despite little to no visual experience (e.g., Bushnell, 2001; Turati et al., 2006).

1.2.2 The 'expertise hypothesis'

While the evidence discussed above largely supports the existence of specialized brain mechanisms for faces (i.e., domain-specific hypothesis; Wilmer et al., 2010), some studies have argued that faces may not be "special", and that face recognition is an acquired ability. In fact, there are studies that question the specificity of neural systems to faces. One example is Rossion et al. (2012), who showed that low-level visual features of a face, such as colour, also contribute to FFA activation, suggesting that the so-called face-selectivity of the FFA may not be as exclusive to higher-level, meaningful attributes of faces as previously thought. Further, faces are not the only meaningful image category selectively encoded by the brain. For instance, the parahippocampal place area was found to respond more strongly to visual scenes (e.g., topographical information; Epstein et al., 1999) than other visual stimuli (e.g., faces), while other studies have shown neural specificity for non-face objects, such as buildings (Aguirre et al., 1998) in the right lingual sulcus. Together, these findings argue that faces may not be as "special" as presumed.

Consequently, the expertise hypothesis has often been proposed as a challenge to the notion that faces are processed differently from other objects. This hypothesis argued that face recognition may be the result of our expertise with a specific class of objects (Diamond & Carey, 1986). Here, the argument is that humans are good at face recognition because faces are one of the most extensively and frequently encountered classes of objects, leading to the development of better face processing abilities compared to other classes of objects. Contrary to the domain-specific hypothesis, these face-selective visual mechanisms are not specific to faces per se but are engaged in recognizing or discriminating any object classes in which an individual has extensive experience (i.e., expertise). For instance, if someone is an expert in dogs (e.g., dog judges), their visual mechanisms would be engaged by exemplars of dogs (e.g., dog breeds) (see Gauthier & Tarr, 1997). Following this logic, these face-specific visual mechanisms are instead expertise-specific visual mechanisms. Accordingly, research has shown that expertise in novel objects (i.e., Greebles) led to increased activation of the FFA (Gauthier et al., 1999). More importantly, the strength of FFA activation increases with participants' level of visual expertise, suggesting that face specialization actually reflects participants' expertise with faces.

This hypothesis is also supported by one of the most heavily investigated phenomena in face recognition literature – the own-race advantage. The own-race advantage has been replicated by multiple studies examining cultural differences in face recognition, where individuals were found to discriminate and recognize faces from their own race more accurately than faces from other races (i.e., races that the viewer does not belong to; hereon referred to as "other-race faces") (Meissner & Brigham, 2001; Tanaka et al., 2004; Zhao & Bentin, 2008, 2011). Studies showed that recognition accuracy, as well as FFA activation, is poorer for other-race faces compared to faces from a viewer's race (Liu et al., 2015; Tanaka et al., 2004). Accordingly, we have more experience with faces from our own race or ethnicity, resulting in heightened sensitivity and greater perceptual expertise in distinguishing subtle differences between faces of an individual's own group. Kelly et al. (2007) found that 3-month-old

Caucasian and Asian infants, but not newborns, exhibit preferential looking for own-race faces. This preferential looking persisted even when these infants were exposed to other-race faces. Kelly et al. propose that the human face recognition system develops *prototypes* based on the encoded faces they frequently experience to make face recognition more efficient. As a result, the face recognition system tunes out the ability to recognize other-race faces, termed "perceptual narrowing" (Kelly et al., 2007).

However, the expertise hypothesis has also been challenged (e.g., McKone & Robbins, 2011). Accordingly, the finding of innate ability to recognize faces in newborns, but not other non-face objects (e.g., Mondloch et al., 1999; Johnson et al., 1991), is inconsistent with the notion that the face processing mechanisms are the result of experience and expertise. Additionally, multiple studies have found that perception of the object-of-expertise seems to activate non-face selective brain regions more strongly than the FFA (Grill-Spector et al., 2004; de Beeck et al., 2006; Rhodes et al., 2004), implying that the underlying mechanisms coding for objects-of-expertise and faces are indeed dissociable. Overall, while it remains an ongoing debate on whether faces are "special" or not, particularly concerning the mechanisms underlying face recognition, what is clear is that humans are often experts in recognising faces compared to other non-face objects. This brings us to the question of whether humans are always good at face recognition regardless of their familiarity with the face.

1.3 Face Recognition Ability

1.3.1 Familiar and unfamiliar face recognition

As mentioned, face recognition holds significant importance in supporting various social aspects of life, including interactions with both familiar and unfamiliar people. Several lines of research have shown that recognizing *familiar* faces is generally very quick and reliable, wherein we can identify individuals despite ageing, varying lighting conditions, or viewpoints (Bindemann & Hole, 2020; Bindemann & Johnston, 2017; Ellis et al., 1979). For example, familiar face recognition remains highly accurate even under challenging conditions such as low-resolution videos or poor lighting, and even when other identity cues like gait, body shape, and clothing are obscured (Burton et al., 1999; Lander et al., 2001) or distorted (Bindemann et al., 2008). Additionally, familiar faces can be recognized without conscious awareness (Morrison et al., 2000). The reliability of familiar face recognition also extends to real-life scenarios, such as eyewitness testimonies, where reports show that when the witness is familiar with the perpetrator, false identifications are uncommon (Memon et al., 2011).

In contrast to familiar face recognition, recognizing unfamiliar faces is highly unreliable and error-prone (Bindemann & Hole, 2020; Bindemann & Johnston, 2017; Ellis et al., 1979; Young & Burton, 2018). Studies have demonstrated that poor recognition of unfamiliar faces persists even under optimal conditions, such as viewing faces under clear lighting and a frontal view (Bindemann & Johnston, 2017; Bruce et al., 1999; Kemp et al., 1997; White et al., 2014). Even trained passport officers, who regularly attempt to recognise new identities, are equally poor as untrained control participants in matching unfamiliar faces (White et al., 2014). Furthermore, this difficulty is not limited to matching static photographs but persists even when observers are required to match in-person identities to photographs (as passport officers would normally have to do; Kemp et al., 1997; Megreya & Burton, 2006, 2008) or dynamic videos (Davis & Valentine, 2009). Given that most human faces adhere to a common template and feature configuration—such as eyes, nose, and mouth—it is unsurprising that distinguishing between unfamiliar faces is challenging.

Consequently, the implications of poor unfamiliar face recognition present significant challenges in practical or applied contexts (e.g., border control, criminal identification). Russ et al. (2018) argued that poor unfamiliar face recognition may be the primary factor contributing to false identification in eyewitness testimonies. This is perhaps unsurprising as individuals in a suspect line-up likely share similar-looking facial features, making accurate identification between multiple identities difficult. This can lead to false positives, where an individual is incorrectly identified as someone else with a similar appearance. This poses a significant risk in eyewitness identification, potentially leading to the misidentification of innocent individuals. For instance, Russ et al. (2018) simulated multiple line-up identifications in which participants are required to consistently recognise the same target identity in each line-up. Russ et al. found that only approximately 45% of participants could identify the target face in the first line-up, and this percentage decreased further when similar-looking faces were included in subsequent line-ups (28%). In short, unfamiliar face recognition is significantly more challenging compared to familiar face recognition.

Studies have proposed that familiarity with a face can be understood as a continuum (Bindemann & Hole, 2020). At one end of the continuum, individuals become familiar with faces due to extended exposure duration (Bornstein et al., 2012) and within-person variations (e.g., different instances of a person; Burton et al., 2016; Murphy et al., 2015). Conversely, at the other end of the continuum, faces that are never seen result in individuals being unfamiliar with novel faces. A practical example of this is evident when individuals can easily identify monozygotic twins in their family, while non-family members unfamiliar with the twins may struggle to distinguish between them. Overall, it is crucial for one's representation of a face (e.g., via distinct underlying neurocognitive mechanisms) to transition from unfamiliar to familiar faces during face recognition (Bindemann & Johnston, 2017; Young & Burton, 2018). Nonetheless, it is unclear if the capacity to transition from unfamiliar to familiar faces differs at an individual level. Specifically, are there individual differences in how one learns an unfamiliar face and how this face is later recognized?

1.3.2 Individual differences in face recognition

Most of the mentioned research on face processing adopts a group-based approach, wherein the recognition performance of participants is averaged to draw conclusions. However, this conventional approach tends to overlook the differences in performance between individual participants. Indeed, *Individual A* might be better at recognizing unfamiliar faces compared to *Individual B*, while *Individual C* might surpass *Individual A* at recognizing unfamiliar faces and so on. It is widely believed that each person's unique genes and environment contribute to a wide range of individual differences in specific complex cognitive processes, including face perception (Wilmer, 2008). While some people may naturally excel in face recognition, others may require more effort or have difficulty recognizing even familiar faces. Hence, even though face recognition seems effortless on a daily basis, the ability to learn and recognize faces may vary considerably across individuals.

To assess whether there are individual differences in the recognition of unfamiliar faces, it is important to use a systematic and objective measure of (unfamiliar) face recognition ability

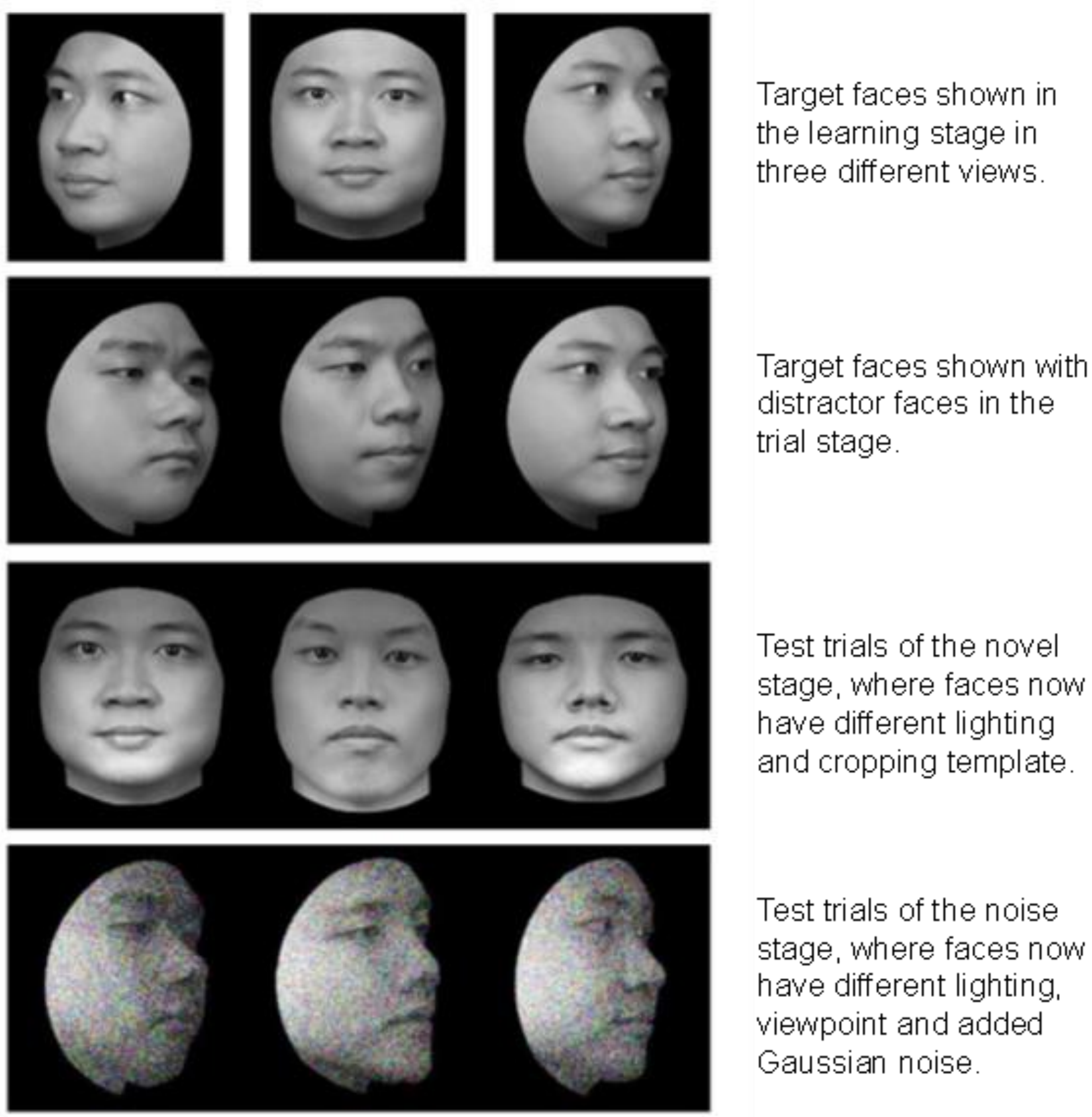
(FRA). This led to the development of early standardized face recognition tests such as the Benton Facial Recognition Test (BFRT; Benton et al., 1983) and the Recognition Memory Test for Faces (RMF; Warrington, 1984). These measures have been widely used in neuropsychological settings to test recognition of novel faces (Duchaine & Nakayama, 2006; Murray et al., 2022) due to their ease of administration and minimal demands on other cognitive functions (i.e., attention, motor functioning). The BFRT is a face-matching task used to assess face perception ability (Murray et al., 2022), wherein participants are required to match target faces to a face in a simultaneously presented array of six test faces. On the other hand, the RMF was designed as a test of non-verbal memory to evaluate the lateralization of brain damage (Warrington, 1984). In the RMF, participants are required to learn a set of faces in a sequential fashion. In the subsequent test trials, participants must choose the target face from two options (one learnt and one distractor).

Despite that, these initial attempts to objectively measure face recognition were criticised to be problematic because their test scores did not consistently reflect the FRA of the general population (Duchaine & Nakayama, 2004, Duchaine & Weidenfeld, 2003). For example, some individuals with lifelong or trauma-induced difficulties in recognizing faces were able to score normally on these two tests. Additionally, studies also argued that the BFRT present the test and target faces simultaneously for an unlimited duration, allowing performances to rely solely on back-and-forth matching of facial features (Duchaine & Nakayama, 2006). In this sense, it has been shown that participants could score at the expected level in the BFRT even when only external features of the faces are visible (Duchaine & Weidenfeld, 2003), indicating that performance may reflect the processing and matching of external facial features. This is because the stimuli presented in the BFRT contain other non-facial information that can be diagnostic of identity (e.g., clothing, hairstyles, posture) that are not considered internal features of a face.

Capitalizing on the strengths and overcoming the limitations of those early measures, the Cambridge Face Memory Test (CFMT; Duchaine & Nakayama, 2006; refer to Figure 1) was developed as a tool that can reliably assess individual differences in FRA (e.g., Corrow et al., 2018; Croydon et al., 2014; Kho et al., 2022; McKone et al., 2012b), and has also been widely used for the diagnosis of conditions with face recognition deficits, such as Developmental Prosopagnosia (DP) and Acquired Prosopagnosia (AP) (Bowles et al., 2009; Esins et al., 2016). DP is a lifelong condition characterized by severe deficits in face recognition, yet normal object recognition (Fry et al., 2020; Hendel et al., 2019). Individuals with DP (hereon referred to as Developmental Prosopagnosics; DPs) fail to develop face recognition skills despite having normal vision and memory, and with no obvious brain damage (Susilo & Duchaine, 2013). Many studies have proposed that face processing impairments in DPs extend even to familiar faces, such as those of families and close friends (Kennerknecht et al., 2008). Although attempts have been conducted to improve face recognition skills, the effectiveness of these training programmes has been quite limited (Bate & Bennetts, 2014). Contrary to DP, poor face recognition in AP results from brain damage or structural lesions (Corrow et al., 2016). AP can arise from many different pathologies, including trauma, stroke, encephalitis, tumours, degenerative atrophy, or temporal lobe resections (Barton, 2008b; Corrow et al., 2016). When screening with the CFMT, individuals are often *diagnosed* as Prosopagnosics if their scores on the task fall within the impaired range, generally around two to three standard deviations below the mean score of healthy control participants (Barton & Corrow, 2016; Dalrymple & Palermo, 2016; Duchaine & Nakayama, 2006).

Figure 1.

An example of the format used in the Cambridge Face Memory test (image adapted from Kho et al., 2023).



Note. None of the faces shown in the sample figure is those in the CFMT or those in the original task (CFMT-Malaysia; Kho et al., 2023).

Briefly, the CFMT is an unfamiliar face recognition memory test that employs a three-alternative forced-choice paradigm. The original test is comprised of 72 trials, subdivided into three stages of increasing difficulty. In the first stage (i.e., Learning stage), Caucasian participants were instructed to study six unique Caucasian target faces that are shown in three different views. During the subsequent recognition trials, the presented target faces match those from the study stage, and participants were required to identify the studied faces among two other distractor faces. In the second and third stages, participants study the same six target faces in frontal view simultaneously. In the recognition trials of the Novel stage, target and distractor faces were presented with different lighting and viewpoints. Subsequently, in the Noise stage, additional visual noise was applied to the faces. Visual noise was added to force observers to rely on "special mechanisms" of face recognition (Duchaine & Nakayama, 2006). In addition, the CFMT is also highly versatile, as there are multiple versions of the CFMT created that can reliably test face recognition abilities of different groups, such as in children (Croydon et al., 2014), as well as other ethnicities (CFMT-Australian; McKone et al., 2011), and races (CFMT-Chinese; McKone et al., 2012b; CFMT-Malaysian; Kho et al., 2023).

In comparison to other standardized tests that were available before the CFMT, this measure is considered a relatively well-validated measure of individual differences in FRA (Duchaine & Nakayama, 2006; Kho et al., 2023). The CFMT can reliably reflect the broad nature of face recognition abilities in the general population (Duchaine & Nakayama, 2006; Hendel et al., 2019; Russell et al., 2009), even in online settings (Bobak et al., 2023). More specifically, Duchaine and Nakayama (2006) found that the average score on the CFMT was far from the ceiling and the floor, and only six participants scored around ± 1 standard deviation from the mean. This show that the CFMT can discriminate the high and low ranges of normal

FRA as well (see also Hendel et al., 2019). Further, Duchaine and Nakayama (2006) showed that the CFMT correctly classified 75% of the DPs, unlike the BFRT and RMF, which classified DPs with well below chance accuracy (< 40%). Furthermore, studies have shown that performance in the CFMT is dissociable from general intelligence and object recognition ability (Shakeshaft & Plomin, 2015; Wilmer et al., 2014). This observation implies that the CFMT predominantly assesses face-specific cognitive processes, allowing researchers to also investigate different aspects of face recognition (e.g., heritability, development) (Wilmer et al., 2010; Germine et al., 2011).

The CFMT also mimics the real-life demands of face recognition, requiring recognition from varying viewpoints and different lighting conditions. Additionally, unlike other face recognition tasks (e.g., Before They Were Famous test; BTWF; Rizzo et al., 2002), the CFMT avoids probing the sense of familiarity and controls for variance in participants' familiarity with faces, using anonymous faces rather than celebrities (Corrow et al., 2016). As none of the faces is familiar to participants before learning, all participants taking the CFMT have the same degree of short-term familiarity with the faces seen during the test (Corrow et al., 2016). Here, the use of repeated distractor faces with different viewpoints and lighting conditions also serves to control for any familiarity that may be induced by target repetition (Richler et al., 2015). Overall, the CFMT offers a reliable and valid objective measurement of individual differences in unfamiliar face recognition.

Nonetheless, if the CFMT can objectively measure face recognition abilities and diagnose those at the low extreme end of the general population, it is thus plausible that the CFMT can also identify individuals with superior FRA at the opposite, top end of the *spectrum*. In view of this, Russell et al. (2009) employed an extended version of the CFMT (Cambridge Face Memory

Task – Long Form; CFMT+) to examine how broad the distribution of face recognition abilities (FRAs) is. They added additional trials (e.g., 30 trials with full profile faces with expressions and more visual noise, that were uncropped or retained external features) to the original test to make the task more demanding, to identify people with exceptional FRA (e.g., three neurotypical participants who were performing at ceiling on the original CFMT). Similar to previous studies (e.g., Duchaine & Nakayama, 2006) that found DPs scoring two to three standard deviations below the mean scores of neurotypicals (NTs) on the original CFMT, Russell et al. (2009) found three participants with exceptional FRA (i.e., super-recognizers; SRs) scoring around two standard deviations above the mean of NTs on the CFMT+. This suggests that SRs are about as good at face recognition as DPs are bad, and the range of face recognition and face perception ability is wider than previously acknowledged (for discussion, see Bate et al., 2018). Furthermore, studies also demonstrate that SRs, as classified by the CFMT+ scores, excel in recognizing faces even in applied settings (i.e., recognizing faces from closed-circuit television footage; Bobak et al., 2016), or when faces were unfamiliar (Davis et al., 2016; Robertson et al., 2016), compared to NTs. This suggests that CFMT scores can successfully measure the range of FRAs in the real world too.

Now that we have established that there are individual differences in FRA, and that CFMT and its variants are reliable tools to capture variability in FRA, the next question is the source of this variability. Variability in FRA can stem from qualitative or quantitative differences (see Yovel et al., 2014). For instance, there could be certain features of the face that are more useful for recognition, i.e., more diagnostic of identity. Some individuals may rely on these diagnostic features when recognising faces and as a result, they may be good at it face recognition. Some others may rely on features that are less diagnostic of identity, and as a result, they are poor at recognition. That is an example of a qualitative difference. An alternative possibility is that all individuals use the same facial features for recognition, but they differ in the extent to which these features can be processed efficiently. That is an example of a quantitative difference. As discussed below, many past studies have attempted to identify the sources of variability in FRA, and they have focused on features of the face that are processed at various levels of the visual information processing hierarchies in the human brain.

1.4 Selectivity to Low-level Features in Face Recognition

As with many other objects in our surroundings, a two-dimensional image of a face also contains visual features of varying complexity. At the most basic level, there are simple edges and contours that define the geometrical structure of a face, and these edges/contours can vary in low-level features such as their orientation, spatial frequency, luminance, and contrast (Jeantet et al., 2018; Westheimer, 2001). Within the context of image processing, orientation refers to the spatial arrangement or direction of elements within an image (Hubel & Wiesel, 1968), while spatial frequency (SF) refers to the variation in luminance over a distance unit and is conventionally measured in cycles per degree (cpd) of visual angle (Jeantet et al., 2018). Processing these fundamental features, even when they are not coherently arranged to form the structure of a face, may be sufficient for the human perceptual system to rapidly detect the presence of a face (Crouzet & Thorpes, 2011; Pongakkasira, 2015; Ruiz-Soler & Beltran, 2006). In general, the human visual system is not uniformly sensitive to all levels of a feature. If we consider the orientations of edges, we are more sensitive to edges near the cardinal axes (vertical and horizontal lines) compared to those near the oblique axes (e.g., edges oriented 45° clockwise from vertical) when edges are presented on backgrounds with uniform luminance (Appelle, 1972; Heeley et al., 1997). However, this sensitivity profile reverses (i.e., we are more sensitive to edges near the oblique axes) when edges are embedded in naturalistic backgrounds (e.g., a scene of a forest; Bex et al., 2009). Regarding spatial frequencies (SFs) of edges, sensitivity peaks at around 2-6 cpd, measured using sine-wave gratings as stimuli (Campbell & Robson, 1968; De Valois & De Valois, 1990).

While the sensitivity profiles to various orientations and SFs of the contours reflect people's ability to detect the presence of the edges, they do not tell us which orientations or spatial frequencies are informative to the viewer and help them recognise faces. Some past studies have attempted to answer this question. For instance, Dakin and Watt (2009) selectively retained edges within specific bands of orientations in faces using image processing techniques. Participants' recognition was best when the edges closer to the horizontal axes were retained by the filter, indicating that horizontal information conveys more diagnostic facial information than edges near the vertical and oblique axes. Importantly, they also showed that horizontal information is specifically more useful for identifying faces compared to other classes of objects such as flowers and scenes, indicating specialized low-level processing for faces. This is because the horizontal structures of faces are always represented as vertically-aligned clusters, which generates distinct barcodes as a cue that a face is present, while non-face objects often consist of an irregular arrangement of structures (Dakin & Watt, 2009; Goffaux & Dakin, 2010). Dakin and Watt (2009) proposed that these "biological barcodes" arise from the physical structure of faces and our perception of lighting cues. Facial features such as the forehead, cheeks, eye, and mouth regions have specific reflectance properties, wherein they reflect light (often from above) in distinct ways. For example, the forehead and cheeks tend to be bright, while the eyebrows and lips are often darker. Importantly, these generated structures of barcodes from faces do not vary between different individuals, which makes them reliable and easy to detect (Dakin & Watt, 2009).

Additionally, the arrangement of the structures of biological barcodes from horizontal information could also facilitate the discrimination of homogeneous faces. The coarse-scale bars (i.e., stripes) within the barcode not only facilitate face detection but also act as a direct index of facial features at a finer-scale (Dakin & Watt, 2009). Since the contrasting stripes in the barcodes reliably correspond to different parts of the face, the sequences of barcodes should also convey distinct information about that part of the face. For instance, as facial information becomes more visible at a finer scale, the sequence of barcodes becomes more detailed (e.g., more stripes). Accordingly, inverting faces in their canonical orientation would change the horizontal structure of these barcodes, which is in line with our inability to correctly recognise faces that are inverted in their canonical view (Goffaux & Dakin, 2010), or with inverted features (i.e., Thatcher illusion; Thompson, 1980).

Nonetheless, it is unclear whether individual differences in face recognition can be explained by the use of horizontal information. Recent studies found that FRA, as measured with the CFMT, was correlated to the use of horizontal information in NTs during face recognition (Duncan et al., 2019; Little & Susilo, 2023). However, this association of horizontal preference was also replicated with non-face object recognition (e.g., cars) (Little & Susilo, 2023). This indicates that horizontal information processing is not limited to faces and can be better explained by a general preference for the horizontal structure of complex visual stimuli. Moreover, if horizontal information processing underlies FRA, one would expect DPs to have deficits in utilizing horizontal information during face recognition compared to NTs. In contrast, Little and Susilo (2023) found that the use of horizontal information in DPs was comparable to

NTs, suggesting that face recognition deficits cannot be explained by low-level processing of orientational information of faces. When examined at the opposite end of the spectrum, Nador et al. (2021) found that SRs and NTs did not show any differences in horizontal selectivity during face recognition. However, they did find that SRs were more consistent in their performance, such that SRs could better recognize filtered faces retaining varying degrees of horizontal information than NTs. Together, these findings suggest that although horizontal information is necessary for face recognition, it is neither sufficient nor informative to explain individual differences in FRA.

As far as SFs of edges are concerned, there is evidence showing that there are differences across people in the utilization of various SF bands, when learning and recognising a face (Bar et al., 2006; Gao & Bentin, 2011; Schyns & Olivia, 1994; Ruiz-Soler & Beltran, 2006). Studies have argued that the ability to recognise faces seems seem to rely on SF information within a specific range (see Chapter 2 for a detailed description), wherein face recognition is thought to be largely biased towards the middle (Costen et al., 1996) and low SFs (Gao & Bentin, 2011; Peters & Kemner, 2017; Schyns & Oliva, 1999; Yip & Sinha, 2002). For instance, face recognition performance was comparable between unfiltered faces and those filtered to retain only low SFs (low SF filtered; Yip & Sinha, 2002), but recognition falls below chance when faces were filtered to retain high SFs (high SF filtered; Davies et al., 1978; Sinha et al., 2006). Visual perception often prioritizes low SF features to extract the “gist” of a scene, followed by high SF features for finer details (Bar et al., 2006; Schyns & Olivia, 1994). By quickly attending to the coarse layout, the brain activates scene schemas in memory, and then attention to fine information refines this rough estimate (Schyns & Oliva, 1994). This coarse-to-fine approach minimizes cognitive resources and improves the efficiency of face perception (Leonard et al., 2010; Peter & Kemner, 2017). Together, these studies may indicate that low SFs are more useful for face recognition, but does this mean that low SF processing can also account for variability in FRA?

To explore the role of SF processing in the context of individual differences in face recognition, Nador et al. (2021) also varied the availability of spatial frequency information from images of faces to the retina and compared the performances of SRs and NTs. Nador et al. manipulated the viewing distance by reducing the size of the face image isotropically, ranging from 8 to 512 pixels, simulating the facial information that would be available to the retina at different viewing distances by effectively removing high SF information. For example, when faces are simulated to be at a larger viewing distance, high SF content becomes less available, and low SF information becomes more available. Nador et al. found that SRs consistently outperformed NTs in face matching, but both groups depended on the same range of SF information. Across various simulated viewing distances, the difference in face matching performance between NTs and SRs was consistent, suggesting that SRs had a higher sensitivity to a wide range of SF information. If FRA is predicted by low SF processing, we should see an increase in the magnitude of differences between SRs and NTs as low SF information becomes more available, but this was not the case. In brief, those who are good at face recognition were more consistent and better at extracting low-level facial information but did not rely on a specific range of SF information (e.g., low SF), suggesting that the ability to recognize faces is quantitatively (but not qualitatively) different along the FRA spectrum.

Despite that, it is important to note that low-level information alone may not be sufficient for accurate face identification, as it lacks distinct semantic information about a face. For instance, everyday face recognition often requires humans to identify faces at the subordinate (e.g., This is Alice), rather than at the basic level (e.g., this is a person). If low-level visual features in faces are sufficient for recognition, we should be able to recognise the identities of phase-scrambled faces that retain all low-level features but distort the geometrical structure of higher-level features. In contrast, studies showed that participants were impaired at detecting phase-scrambled faces (Näsänen, 1999; Tyler & Chen, 2006), indicating that face recognition would be too. In another study using event-related potentials (ERPs), Rossion and Caharel (2011) found that the N170 component, associated with face-specific processes, to be virtually non-existent for phase-scrambled faces. This further highlights the importance of higher-level structural information in face recognition. Furthermore, it is still uncertain whether the visual system exhibits heightened sensitivity towards specific bands of SF information. Rather, it is possible that the tuning of SF processing occurs precisely because the information conveyed within these bands of SF is the most informative. Overall, further research is needed to reach clearer conclusions regarding the role of SF processing in face recognition and its relationship to individual differences in FRA.

1.5 Higher-level Visual Processing in Face Recognition

1.5.1 Visual sampling of faces

When faces are processed at a higher level, more diagnostic information can be extracted, such as identity-specific facial features (i.e., eyes, nose, and mouth) and the associated semantics (i.e., personal information). Research has demonstrated that during face recognition, observers tend to focus their gaze on critical regions such as the eyes and eyebrows during face recognition, highlighting their importance (Abudarham & Yovel, 2016; Schyns et al., 2002).

Abudarham and Yovel (2016) found that manipulating the size and shape of the eyes impaired face identification. In contrast, face recognition was less affected when non-critical regions, such as the nose, were manipulated. These findings suggest that face recognition is dependent on higher-level processing of distinct facial features, particularly, the eyes. Consequently, we would expect that the more that individuals utilise information from the eye region during face recognition, the better their FRA are. However, it remains uncertain whether FRA is related to the mere sampling behaviour of facial features or the extent to which individuals are able to process the extracted information from sampling critical features.

Two hypotheses have been frequently proposed concerning individual differences in FRA and visual sampling of faces (Barton & Corrow, 2016). In the first hypothesis, individuals across the spectrum process and recognise faces in a quantitatively different way (e.g., Russell et al., 2009; Tardif et al., 2019). This hypothesis argues that there are predictable variations in the use of facial information from DPs to SRs, wherein DPs and SRs are merely the extreme representation of normal face processing. In statistical terms, the differences observed in FRA are due to variations within the normal distribution curve rather than separate clusters for each group (Barton & Corrow, 2016). Alternatively, the second hypothesis posits that DPs, NTs, and SRs process faces in qualitatively different ways. This hypothesis proposes that SRs and DPs are not merely individuals at the extreme ends of the spectrum, rather, they may possess (or lack) specific qualities that separate them from each other and NTs. For example, atypical eye movements observed in DPs are not necessarily observed in SRs and/or NTs (e.g., Bobak et al., 2017).

One of the earliest pieces of evidence of a quantitative difference between SRs and poor recognisers at this level was proposed by Tardif et al.'s (2019) psychophysical study. They found that individuals across the FRA spectrum relied on the same facial features during face recognition, but how this information is sampled differs dimensionally from DPs to SRs as a function of FRA (measured with the CFMT and CFMT+). When face recognition is obscured by an aperture, wherein only fixated regions of faces are visible (e.g., regions outside of fixations are blurred), both SRs and NTs sampled from similar critical features (e.g., eyes, eyebrows, and mouth). Notably, SRs sampled these critical features more frequently than NTs. In contrast, DPs exploited information from only a small portion of the mouth region, and none from the eyes. This impaired processing of the eyes in DPs has also been reported before (DeGutis et al., 2012; Fisher et al., 2016). In short, Tardif et al. (2019) found that the better the participants' FRA, the more time spent by participants fixating on the eye region, followed by the mouth region.

In contrast, Dunn et al. (2022) found that sampling the eye regions was not linearly associated with the FRA. Similar to Tardif et al. (2019), they restricted the amount of facial information visible using an "aperture", but the region outside of fixation was completely occluded. Dunn et al. found that SRs had fewer fixations on the eye region compared to NTs but had more fixations overall across the face. Further, SRs exhibited a broader gaze distribution, particularly during face learning. Dunn et al. argued that SRs' exceptional FRA stem from the enhanced encoding of facial information, in which SRs have a better accumulation of facial information across successive eye movements sampling from different features. Interestingly, a U-shape distribution of the sampling was found across the spectrum, with both DPs and SRs spending less time fixating on the eyes compared to NTs. Accordingly, Dunn et al. (2022) proposed that this pattern of visual sampling seems to facilitate SRs' superior function and compensates for DPs' deficits during face recognition. For instance, SRs can efficiently extract facial information and thus spend less time on the eyes, while DPs have difficulties with extracting information from the eyes and thus compensate by sampling from other regions. Despite disparities between the findings of Dunn et al. (2022) and Tardif et al. (2019), both studies indicate that DPs and SRs are merely individuals at extreme ends of the FRA spectrum, in which the sampling (or absence of sampling) on specific critical regions seems to contribute to individual differences in FRA.

Qualitative differences between SRs, NTs, and DPs at higher-level face processing have also been found (Bobak et al., 2017). Explicitly, supporting the qualitative view, studies have reported that individual differences across the FRA spectrum can be explained by the processing of specific facial features. For instance, Bobak et al. (2017) found that DPs spend less time than NTs examining internal facial features typically diagnostic of identity, particularly the eyes. Instead, DPs tended to fixate more on other regions, such as the lower part of the face, which are believed to contain less identity-related information (e.g., the Poor Information Hypothesis; see the review by Peterson et al., 2019). In contrast, SRs were found to rely more on extracting information from the nose region compared to NTs. This suggests that SRs and DPs do not merely represent opposite extreme ends of a single spectrum. Bobak et al.'s findings support the idea that these groups have qualitatively distinct face processing strategies, with the time spent sampling specific facial regions predicting FRA for SRs and DPs in non-standard ways. In other words, the utilization of facial information by individuals across the spectrum does not follow a predictable pattern of variation. Rather, atypical exploitation of facial information seems to characterize DPs.

However, interpreting fixation patterns is rather complex, wherein oculomotor behaviour does not always reflect the type of facial information extracted (Arizpe et al., 2012; Lee et al., 2022b; Miellet et al., 2013). For instance, a recent eye-tracking study found that SRs, NTs, and

DPs relied on similar facial features during face recognition. Abudarham et al. (2021) found that individuals across the FRA spectrum fixated on similar regions, yet DPs were more likely to misidentify familiar faces. This suggests that observers from different points on the spectrum may use the same information but with varying degrees of *effectiveness*. In this view, FRA increases systematically with the observer's ability to effectively exploit critical local features, like eyes and mouth.

Nonetheless, the effectiveness of feature exploitation may not be fully explained by fixation patterns. It remains uncertain whether visual sampling reflects the processing of individual facial features, the configural relations between these features, or the face as a whole (i.e., holistic). Miellet et al. (2013) demonstrated that some participants may rely on extrafoveal information during face recognition, which is not reflected by the fixation patterns (i.e., foveal processing). Briefly, foveal information refers to the specific details perceived from central fixations, while extrafoveal information pertains to the details perceived in our periphery. Miellet et al. (2013) found that participants who fixated on the nose of faces were still able to accumulate facial information from the eyes and mouth regions that are present in their extrafoveal regions. In the context of low-level processing, low SF information, but not high SF information, is often preserved in extrafoveal vision, arguing that interpretations of fixation patterns as a direct reflection of face processing may sometimes be misleading. In short, this emphasizes the need for further research using complementary methods.

1.5.1 Whole-face processing

There is a general consensus that one of the properties that make faces "special" is that they are processed and represented as a "whole" rather than as a collection of individual features, termed as *holistic processing* (Sergent, 1984; Maurer et al., 2002). Face recognition has been shown to rely on holistic processing, an automatic and seemingly effortless process (Jacques & Rossion, 2010; Nakabayashi & Liu, 2014; McKone & Robbins, 2011), which is defined as the integration of all facial features into a unified, gestalt representation of the face (Piepers & Robbins, 2012; Rossion, 2008, 2013; Tanaka & Farah, 1993). The counterpart of holistic processing, featural processing, explained as the part-based processing of local facial features information (e.g., eyes, nose, mouth), is often used to show the contrast between face recognition advantage gained from processing faces more holistically (Piepers & Robbins, 2012). For instance, face recognition is often more accurate for whole faces compared to individual features (Tanaka & Farah, 1993). Studies have also consistently shown greater activation of face-specific areas of the brain (e.g., FFA) when participants were relying on holistic processing than featural processing during face recognition (Zhang et al., 2012). In brief, efficient and accurate face recognition seems to be mainly facilitated by specialised higher-level processes involving holistic processing.

While most face researchers agree that faces are perceived holistically, developing behavioural methods to measure holistic processing has presented empirical challenges. One of the earliest approaches was through the investigation of the face inversion effect (FIE). This effect simply shows the impairment in the recognition of inverted faces (i.e., upside down), as opposed to their upright canonical orientation (McKone & Yovel, 2009; Rossion, 2008; Tanaka et al., 2019; Yin, 1969). The FIE is believed to result from holistic processing being hindered by inversion, forcing observers to rely on featural processing (Maurer et al., 2002; Rossion, 2008). For example, Maurer et al. (2002) found that subjects were similarly slow and inaccurate at recognizing inverted full faces and individual parts, even when the individual parts were shown upright. Studies also revealed that the FIE is stronger for the recognition of faces compared to other non-face objects (Bruyer, 2011; Rossion & Gauthier, 2002; Yin, 1969), suggesting its specificity to face processing. Nonetheless, the validity of the FIE has been challenged in recent years as to what aspect of face recognition was really captured by the task (Gerlach et al., 2023; Gerlach & Mogensen, 2023). While it is generally believed that the FIE reflects holistic processing, inverting faces does not manipulate holistic processing directly (Piepers & Robbins, 2012). For instance, inverting faces affects the spatial arrangement and overall configuration of facial features, but it does not directly affect the integration of these features *per se*. Recent studies have shown that even when recognizing inverted faces, observers still exhibit a reliance on holistic processing, albeit to a lesser extent (e.g., Gerlach & Mogensen, 2023; Murphy & Cook, 2017), suggesting that the FIE may not fully capture the complexities of holistic processing.

Consequently, other authors have quantified holistic processing using more direct measures, such as the composite face effect (CFE; Hole, 1994; Rossion, 2013; Young et al., 1987) and the part-whole effect (PWE; Estudillo et al., 2022; Tanaka & Farah, 1993; Tanaka & Simonyi, 2016). The CFE, measured with the composite task, involves the use of composite face stimuli created by combining complementary top and bottom halves of two different face identities, split at the horizontal meridian (Rossion, 2013; Young et al., 1987). In the composite task, participants are presented with two consecutive composite faces that are either aligned or misaligned in every trial. The initial stage requires participants to learn only the top half of a composite face. In the following recognition stage, participants are presented with another composite face and are asked to determine whether the top (or bottom) half of the composite faces are the same or different. Participants perform faster and more accurately when composite faces are misaligned than when the faces are aligned. This is because aligning the top half of one identity with the bottom half of another identity creates the illusion of a new identity, making it hard to attend to one half of the face while ignoring the other. However, misaligning both halves would eliminate such an effect. In other words, the CFE reflects the interference caused by holistic processing when participants are required to process individual features. Nonetheless, it remains unclear if the CFE reflects face-specific mechanisms as the composite effect has also been observed with non-face object-of-expertise (for detailed discussion, see Murphy et al., 2017).

The PWE, measured with the part-whole task, reflects the advantage to recognise a facial feature when it is presented in the context of a whole compared to a single individual feature (Tanaka & Farah, 1993). In the part-whole task (DeGutis et al., 2013b; Estudillo et al., 2022), participants are first given a target face to learn, followed by the recognition stage, in which participants have to identify which of the two test faces (or face parts) shown is the previously learnt target face. In one condition, the test faces are presented as whole faces: one of these test faces is the same as the target face, and the other test face matches the face of a learnt identity but differs by one feature (e.g., the nose). In another condition, test faces are presented as individual features: one of these features is from the target face, and the other feature is from a different identity. Observers discriminate between whole faces more accurately than individual features (Estudillo et al., 2022; Tanaka & Farah, 1993; Tanaka & Simonyi, 2016). This is because facial features are integrated into a holistic figure, and therefore any new features lead to an illusion of a new identity, making it easier to tell the learnt target and test faces apart. Conversely, when facial features are presented individually, the identification process becomes more challenging as faces must be discriminated based on those specific features. Similarly, like

FIE, the PWE was observed for faces but not non-face objects (e.g., houses), implying that the PWE reflects face-specific mechanisms (Tanaka & Farah, 1993). Nonetheless, when participants had to learn face parts instead of whole faces (as in the original part-whole task), recognition of the learnt parts in the context of whole faces was worse than when parts were shown in isolation (Leder & Carbon, 2005). Consequently, it remains unclear whether the PWE reflects the integration of facial features or the disruption towards the processing of face parts (Tanaka & Simonyi, 2016).

Moreover, the specific role and mechanisms of holistic processes involved in individual differences in unfamiliar face recognition remain ambiguous. As assessed with these three gold-standard measures, differences were found in the extent to which faces are processed holistically across the FRA spectrum (Avidan et al., 2011; Belanova et al., 2021; DeGutis et al., 2012; Russell et al., 2009). Similar to the findings involving visual sampling, studies have shown evidence of both quantitative and qualitative differences in holistic processing along the spectrum. For instance, DPs and SRs may qualitatively differ in the way they process faces, wherein holistic processing does not predict the FRA of individuals. Accordingly, some studies have reported a complete absence of holistic processing in DPs (Behrmann et al., 2005; Bennetts et al., 2022) and SRs (Belanova et al., 2021), while other studies found comparable holistic processing in DPs (Bennetts et al., 2022; Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017) and SRs (Belanova et al., 2021) with NTs. Conversely, quantitative differences were also found in other studies, wherein the magnitude of holistic processing corresponds to DPs' and SRs’ ability to recognize faces. For example, multiple studies found reduced (but not absent) holistic processing in DPs (Avidan et al., 2011; DeGutis et al., 2012;

Klargaard et al., 2018) and increased holistic processing in SRs (Belanova et al., 2021; Russell et al., 2009), compared to NTs.

Holistic processing has frequently been associated with individual differences in FRA among typical recognizers (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012). In a study conducted by Richler et al. (2011a), they found that the CFE was positively correlated with FRA, as measured with CFMT. Similarly, DeGutis et al. (2013b) found a positive correlation between holistic processing, as measured with the PWE and CFE, and participants' CFMT scores. This notion is also supported by recent neuroimaging evidence using ERPs, in which Marzi et al. (2021) found that good recognisers rely more heavily on holistic processing compared to poor recognisers, as indicated by a higher amplitude of the N170 potential. Nevertheless, contrasting results have also been reported in other studies (Konar et al., 2010; Richler et al., 2014; Verhallen et al., 2017). Indexing holistic processing with the composite face task, Konar et al. (2010) found that face matching accuracy did not correlate with CFE. In fact, Verhallen et al. (2017) revealed that the construct underlying holistic processing, as measured with the CFE, and FRA is distinct, as supported by their factor analysis. Consequently, despite playing an essential role in face recognition, holistic processing contribution to the individual differences in FRA remains unclear.

The mixed findings regarding the role of holistic processing in face recognition might be due, at least partially, to the existence of different measures of holistic processing. Previous research has predominantly considered one of the three holistic measures, a limitation highlighted by recent studies demonstrating that these measures tap into distinct underlying cognitive mechanisms (Boutet et al., 2021; Lee et al., 2022a; Rezlescu et al., 2017). Rezlescu et al. (2017) found that these traditional measures were only weakly associated with each other. A more recent study by Boutet et al. (2021), using factor analysis, revealed that these measures also load onto distinct components. For instance, the variability in CFE and PWE loaded onto different factors, and the FIE did not load onto either of the two factors. Boutet et al. (2021) proposed that the PWE appears to be linked to integrating face parts and their configuration, while the CFE is related to utilizing a whole-face template and engaging in configural processing (e.g., Rossion, 2013). As for FIE, they postulated that it might be associated with inefficient processing of facial information. In any case, these findings suggest that holistic processing is not a *unitary* process. Thus, given that these measures likely underlie distinct holistic mechanisms, their relationship with FRA may depend on other intra- and between-subject factors.

It is also possible that both qualitative and quantitative differences may exist along the FRA spectrum, as evidenced by the *heterogeneous* nature of both DPs (Bennetts et al., 2022; Bobak et al., 2017; Corrow et al., 2016; Lee et al., 2010) and SRs (Belanova et al., 2021; Ramon et al., 2019; Ramon, 2021). On the one hand, some DPs' impairment(s) may extend to non-face objects (Gerlach et al., 2018a), while other DPs may be impaired in only certain measures of face recognition (Corrow et al., 2016). As shown by Bennetts et al. (2022), heterogeneity in DP persists even when only one measure (e.g., face inversion task) was used. Specifically, among individual DPs, differences were observed not only in the extent of their holistic impairments but also in the presence of idiosyncratic perceptual deficits, such as impaired processing of inverted faces. On the other hand, heterogeneity was also evident in SRs (Belanova et al., 2021). Belanova et al. (2021) found that some SRs have enhanced integration of the nose into a holistic representation (as measured with the PWE), while others showed superior integration of other features (i.e., eyes), and yet others did not show any superior integration at all. Surprisingly, a small subset of SRs even displayed reduced holistic processing. Here, Belanova et al. (2021) postulated that SRs (with reduced holistic processing) are superior in face recognition because they possess enhanced processing of features (i.e., featural processing). This argues that FRA cannot be fully attributed to holistic processing. As a whole, there is mixed evidence in the literature, particularly pertaining to the processes underlying individual differences in FRA.

1.6 Cultural Differences in Face Recognition

Up until now, we have delved into the processes contributing to the variability in FRA. However, the potential influence of complex and multifaceted social factors, such as *culture*, on these processes, has largely been overlooked. Culture has frequently been used to describe the unique behaviours, traditions, and beliefs that define a specific social or ethnic community, which profoundly influences perception and cognition (Segall et al., 1986). Thus, it is plausible that culture may also impact the processing and perceptual representation of faces. Evidently, even in low-level processes, cultural differences in the processes underlying face recognition have been found (Blais et al., 2021; Estéphan et al., 2018; Tardif et al., 2017). For instance, Tardif et al. (2017) found that Eastern-Asians (EAs) rely on lower SF information than Western-Caucasians (WCs) during face recognition.

Accordingly, if EAs and WCs are attuned to different low-level information, we would expect sampling strategies to be distinct across cultures. For example, we should observe that EAs tend to fixate at the centre of faces (nose region) as means to facilitate the efficient spread of attention, which enhances the processing of low SF information (Belanova et al., 2021). In fact, numerous investigations into visual sampling have demonstrated significant cultural differences in face perceptual strategies (Blais et al., 2008; Caldara, 2017; Kelly et al., 2010, 2011; Miellet et al., 2013; Rodger et al., 2010). For example, Blais et al. (2008) observed that during the learning and recognition of a set of faces, EAs consistently fixated on the centre of faces, reflecting a global perceptual strategy. Conversely, WCs tended to adopt a triangular fixation pattern, reflecting a more analytical perceptual strategy. Together, these findings propose that the processes underlying face recognition are not *universal*.

Presumably, these cultural differences should also manifest in complex higher-level processes. Yet, cultural differences in higher-level processes have mostly been found with non-face stimuli. For example, using the Navon's paradigm (Navon, 1977), McKone et al. (2010) showed that Eastern-Asians (EAs) exhibited a significantly larger global processing advantage compared to Western-Caucasians (WCs) (i.e., global precedence effect; GPE). Strikingly, this advantage, although weaker, was also evident in second-generation EAs who were not born in Asian countries (i.e., Australian-born Asians). While McKone et al.'s (2010) findings suggest that cultural differences persist even in higher-level visual processing, it is unclear whether these variations extend to special classes of stimuli, such as faces, given the scarcity of studies on this subject.

As far as our understanding goes, only one study has indirectly examined this. Miyamoto et al. (2011) compared WC and EA participants' sensitivity towards changes in individual features and the configural relationship of these features. In the first experiment, they presented participants with a set of four target faces, followed by two prototype faces. One prototype was a morphed face derived from all four target identities, preserving the overall configuration of these faces (configural prototype), while the other prototype comprised the shape of one target face with facial features substituted from the three other target identities (featural prototype). When asked which of the prototype faces were shown earlier, Miyamoto et al. (2011) found that EAs were more likely to select configural prototypes than WCs, suggesting that EAs rely more on the overall configuration than facial features. In the second experiment, Miyamoto et al. created an array of test faces by either manipulating the distance between facial features or replacing the features of target faces with those of another identity. Participants were then shown the target and test faces sequentially and asked to determine if they were the same or different. They found that EAs were more accurate than WCs when the configural relation of target faces was manipulated, but both groups were comparable when features were replaced. This implies that EAs have a higher sensitivity towards changes in the configuration of faces.

Overall, the study by Miyamoto et al. (2011) argues that cultural differences in visual perception extend to higher-level face processing. While this study provides evidence that EAs exhibit stronger sensitivity towards configural changes of faces, it does not inherently suggest that holistic processing is stronger in EAs than WCs. Nonetheless, how could individuals from one culture process a face more holistically than those from another, considering that holistic processing is a fundamental aspect of face recognition? In other words, if holistic representation is indeed what sets faces apart as a “special” class of stimuli, a culture-specific approach to face recognition could challenge this notion.

Further, expanding on the cultural differences in the factors contributing to face recognition, it remains unclear how these differences might also affect the variations in FRA across cultures. For example, DeGutis et al. (2011) found that Caucasian DPs did not show any holistic advantage for own-race and other-race faces, arguing that race-effect might have minimal impact on the individual differences in holistic processing. While previous studies have examined cultural differences in holistic processing, it is still ambiguous whether these differences influence the overall variability in FRA between cultures. This uncertainty is further exacerbated by evidence suggesting that holistic processing may not be a unitary process (e.g., see Rezlescu et al., 2017). Hypothetically, if holistic processing is neither universal nor unitary, it is possible that, across cultures, these holistic processing indexes have different weights as predictors of FRA. Thus, even when holistic processing is utilized during face recognition across different cultures, the underlying mechanisms of holistic processing influencing FRA could be culture-specific. However, to the best of our knowledge, no study has directly tested this hypothesis.

1.7 Thesis Structure

The current thesis, which consists of four empirical chapters, aims to explore the roles of low-level and higher-level processes underlying face recognition, and the extent to which these processes can account for individual differences in people's ability to learn and recognize unfamiliar faces. The central focus is on determining whether individual differences in face recognition ability can be explained by (1) differences in the utilization of low-level visual information, specifically spatial frequency, during face learning and recognition, and (2) the extent to which cognitive mechanisms related to holistic processing underlie individual differences in face recognition. If so, are these higher-level processes universal or unitary? Alternatively, are there other high-level processes that facilitate face recognition (e.g., featural processing)? For the former, in Chapter 2, we examined how visual information at different spatial frequency bands is utilised during face learning and recognition. For the latter, we examined whether processing a face as a whole facilitates face recognition ability, from typical observers from different societies (Chapter 3) to atypical observers (e.g., suspected developmental prosopagnosics) at the low-extreme end of the spectrum (Chapter 4). Lastly, using a recently developed paradigm, we also examined the extent to which face recognition abilities can be explained by the processing of individual features (Chapter 5). Through these interconnected chapters, our objective is to understand how low-level and higher-level processes work together in face recognition, shedding light on their potential contribution to explaining individual differences within this essential cognitive domain.

CHAPTER 2: Individual Differences in Spatial Frequency Processing during Face Learning and Recognition

2.1 Spatial Frequency Processing

Spatial frequency (SF), within the context of image processing, refers to the variation in luminance over a distance unit and is conventionally measured in cycles per degree (cpd) of visual angle (Jeantet et al., 2018). The sensitivity of the human visual system to fundamental, low-level features such as edges or contours within different SF bands is typically measured using a contrast sensitivity function. The CSF, often measured with sinusoidal luminance gratings, tells us how well our eyes can detect changes in contrast for different types of patterns or stimuli. By varying the spatial frequency of these gratings (i.e., spaces between alternating light and dark bars), we can assess how sensitive the visual system is. According to the CSF, sensitivity to different spatial frequencies follows a non-linear function, with sensitivity peaking between 2-6 cpd and reducing as SFs deviate further from this peak range. However, this contrast sensitivity profile does not directly translate to people's ability to recognise objects or scenes composed by these low-level features. In other words, when recognising objects or scenes by assigning meaningful semantic labels to them, we do not necessarily prioritise the processing of SFs that we are highly sensitive to, or those that we are less sensitive to.

When processing a scene for the purpose of recognition, we seem to follow a coarse-to-fine strategy (Bar, 2004; Hegdé, 2008). Features at low spatial frequencies (LSF) that reveal the course layout of a scene are temporally prioritised to rapidly extract a "gist" and this is followed by the processing of information at high spatial frequencies (HSF) that provide the finer details of the scene (Schyns & Olivia, 1994). According to Bar et al. (2006), the gist facilitates the subsequent HSF processing by initiating top-down predictive processes. In other words, by attending to the coarse layout of an image, the visual system can get a quick and rough estimate of the input to activate scene schemas in memory; attending to fine information allows refinement of the raw estimate (Schyns & Oliva, 1994). What at first seems a limitation could, therefore, be viewed as an asset to minimize the use of cognitive resources and improve efficiency (Leonard et al., 2010; Peter & Kemner, 2017). Nevertheless, the coarse-to-fine processing strategy is not mandatory. For instance, when observers are cued with the location of faces, they were found to process HSF first (Bachmann & Kahusk, 1997). Thus, the strategy used for extracting SF information is flexible and is dependent on the constraints imposed by task demands.

Our natural environment consists of many objects organized into coherent scenes, and faces are one of the most frequently encountered objects. Our ability to detect and perceive faces also seems to be best when facial features are visible at specific SF bands. Accordingly, Pongakkasira (2015) measured participants' ability to detect faces embedded within complex natural scenes when faces were presented unfiltered or filtered to preserve one of three bands of SFs quantified in cycles per face width (c/fw): LSF (< 5 c/fw), HSF (> 15 c/fw) and middle spatial frequency (MSF; between 5-15 c/fw). Detection accuracy was best for unfiltered faces, followed by MSF, LSF and HSF faces. LSF faces were detected as quickly as MSF faces but less accurately. In addition, LSF faces showed a clear advantage over HSF faces in terms of detection speed and accuracy. This indicates that MSF and LSF structures are of greater importance for face detection, which is consistent with the notion that detection is facilitated by face-shape information which is largely represented by lower SFs (Bindemann & Burton, 2009; Bindemann & Lewis, 2013; Halit et al., 2006; Hershler & Hochstein, 2005).

Face perception is another aspect of face processing that is dependent on the SF content of the face. In contrast to face recognition, face perception is defined as a process of representing the properties of a face with minimal memory constraints (see discussion by Dalrymple et al., 2014). Gao and Bentin (2011) employed a face-matching task that required participants to match SF-filtered faces to a simultaneously presented unfiltered face. When the faces were presented for 250 ms, matching accuracy was better with LSF (2.8–13 c/fw) than HSF faces (13–64 c/fw). However, when they were presented for 500 ms, matching accuracy was similar between LSF and HSF faces. This demonstrated that LSF information is extracted earlier than HSF information during face perception, although they are both equally informative at longer presentations. Neural evidence also supports this LSF precedence in face perception (e.g., Goffaux et al., 2011). By measuring neural responses using functional magnetic resonance imaging, Goffaux et al. (2011) demonstrated that faces containing LSF information (2–8 c/fw) activated face-selective brain regions (e.g., face fusiform area) earlier (e.g., 75 ms after presentation) compared to HSF (32–128 c/fw) faces (e.g., >150 ms). Therefore, behavioural and neural evidence both suggest a LSF precedence during face perception.

2.2 Spatial Frequency and Face Recognition Ability

In addition to detection and perception, the ability to recognise previously learnt faces also seems to rely more on a specific SF range. While recognition and perception of faces are related, the underlying processes could be sensitive to different SF bands (Peters & Kemner, 2017). On the one hand, we have evidence in favour of the coarse-to-fine strategy. Schyns and Oliva (1999) demonstrated that face identification is largely biased towards LSFs. They showed participants hybrid images made by superimposing two faces they had previously learnt. One face was filtered to retain only LSFs (< 8 c/fw) while the other was filtered to retain only HSFs (> 24 c/fw). When asked to identify the learnt face in the hybrid, participants' identifications were more accurate for the identity depicted by the LSFs. Moreover, in Gao and Bentin's (2011) second experiment, they demonstrated that LSF test faces were more accurately recognized than HSF test faces across different retention intervals when learnt unfiltered faces were shown briefly (500ms). However, recognition of LSF and HSF filtered faces was comparable when exposure time to unfiltered faces during learning was high (800ms). Since forming an accurate perceptual representation for LSF and HSF faces in memory were not comparable at 500ms, this LSF advantage must be due to the precedence of low spatial frequency processing, especially in terms of the order in which spatial frequency information is encoded into memory (Gao & Bentin, 2011). More recently, it has been shown that adult and adolescent observers were more accurate in recognising unfiltered faces when these faces were learnt (with an exposure duration of 2s) in LSFs (≤ 9 c/fw) than HSFs (≥ 27 c/fw) (Peters & Kemner, 2017). Their findings suggest that the availability of LSF information during face encoding facilitates long-term face memorization.

On the other hand, some studies have found evidence constraining face recognition to a specific band of SFs that does not necessarily contain only LSFs. Fiorentini et al. (1983) found an optimal SF range of 5 to 12 c/fw when recognizing SF-filtered test faces that were always learnt unfiltered. Contrary to what is expected in general from coarse-to-fine processing, the range was somewhat closer to MSFs. Subsequently, four different studies found optimal SFs for face recognition in the range of 4.5 to 14 c/fw (Costen et al., 1996; Gold et al., 1999; Näsänen, 1999; Parker & Costen, 1999), despite differences in methods used to selectively present specific bands of SFs to participants. A review by Jeantet et al. (2018) highlighted that these methods (e.g., spatial filtering of faces, masking) may alter the critical band. For instance, applying low and high-pass filters on the faces revealed a lower optimal SF average (e.g., upper limit below 16 c/fw; Costen et al., 1996; Gold et al., 1999; Parker & Costen, 1999), while noise masking (e.g., Gao & Maurer, 2011; Näsänen, 1999) yielded a higher optimal SF average (upper limit above 16 c/fw). In general, Jeantet et al. (2018) suggested that the critical band is fluid within the range of 4.5 to 23 c/fw. This is in line with the importance of the eyes and brows in face recognition (Sekuler et al., 2004), as studies have argued that the structures at or near the eyes are represented by a narrow range of SFs near 10 c/fw, reflected by MSF information (Gaspar et al., 2008; Keil, 2008).

Even though face recognition seems effortless on a daily basis, the ability to recognize faces is not uniform but presents substantial differences across individuals in the general population (Russell et al., 2009; Bate et al., 2018; Estudillo & Bindemann, 2014). On one side of the distribution, there are individuals such as Developmental Prosopagnosics (DPs), who in the absence of brain damage and despite normal visual experience, have great difficulties recognising faces (Duchaine & Nakayama, 2006). In contrast, on the other side of the distribution, we find individuals, known as Super-recognizers (SRs) who have exceptional face recognition abilities, despite having normal general cognitive abilities (e.g., working memory; Russell et al., 2009). This suggests that there may be specific perceptual processes that influence the ability to identify faces. In the context of low-level processing, if face recognition is dependent on a narrow range of SFs, we would expect that those who are better at face recognition would rely on this distinct range during face processing more than those who are poor at face recognition. However, whether individual differences in face recognition ability can be explained at least partially by SF processing is underexplored.

To our knowledge, very few studies have examined individual differences in processing SF content in faces and how that affects their ability to recognize facial attributes. One such study is that of Awasthi et al. (2012) who examined the influence of SF information on the perception of gender in DPs and a control group of typical adults. They found that DPs process LSF information later than controls. To do this, Awasthi et al. (2012) presented two hybrid images to participants, one named the target and other the non-target. Each hybrid contained an LSF (≤ 8 c/fw) and an HSF (≥ 16 c/fw) face superimposed on each other. At viewing distance, only the HSF faces were clearly visible. Participants were instructed to reach towards the hybrid containing the face of a specific sex (e.g., male) and this face was always the HSF face in the target. The HSF face in the non-target was always the opposite sex (e.g., female). When the HSF in the target was paired with a congruent LSF face of the same sex (e.g., male with male), reaching trajectories were straighter than when they were paired with an incongruent LSF face of the opposite sex (e.g., male with female). This was interpreted as evidence for facilitation of reaching due to early LSF processing. This congruity effect was larger in controls than in DPs when the non-target's LSF face differed in sex to the HSF in the target. Here, control participants benefit more from an early processing of LSF information in the target. In contrast, when the non-target's LSF face has the same sex as the HSF in the target (i.e., a distractor), the congruity effect was larger in DPs. Analyses of reaching movements revealed that this resulted from a delayed processing of the LSF distractor in the non-target by DPs. Overall, DPs do utilize low SF information, but there are delays in processing them compared to control participants.

A different study by Nador et al. (2021), slightly more relevant to our context, examined perception of identity from faces in super-recognisers and control participants. They varied viewing distance of face stimuli during a face matching task. Here, with increasing viewing distance, the availability of high SF information reduces and low SF information increases. Irrespective of the extent of shifts in the SF bandwidths visible to the retina, super-recognisers were consistently better at utilising the available SFs for face perception than control participants. At higher viewing distances, this could imply that super-recognisers are better at utilising LSFs than controls in face perception, but these findings do not speak for the relative importance of HSF and LSF information for face recognition (i.e., face memory).

To our knowledge, there is no study directly examining whether people's ability to process information from facial structures in different SF bands is associated with face recognition at an individual level. While some studies have indeed examined whether individuals with and without face recognition deficits show differences in contrast sensitivity to the SFs of simple features such as edges (Barton et al., 2004; Behrmann et al., 2005), we know that those contrast sensitivity profiles do not translate directly to the sensitivity to facial structures. Therefore, the experiments in this chapter aim to explore whether recognising unfiltered, LSF, and HSF filtered faces is related to individual differences in FRA. Here, we were interested in finding out whether recognition based on specific SFs is quantitatively different across the FRA spectrum. To measure recognition based on SFs retained, we used an old/new recognition memory task. To measure face recognition ability, we employed the CFMT – Chinese (CFMT-Chi; McKone et al., 2012b).

We were also interested in how this potential relationship between SF processing and FRA manifests at different stages of face recognition, i.e., when learning the identity (learning stage) and when recognising a learnt identity (recognition stage). Accordingly, we conducted two experiments that differed only in how the recognition memory test was administered. In Experiment 1, faces that were learnt were manipulated to retain predetermined bands of SFs

(LSF, HSF or broadband), but the faces to be recognised were always unfiltered. In Experiment 2, faces that were learnt were always unfiltered, but the faces to be recognised were manipulated to retain predetermined bands of SFs.

2.3 Experiment 1: Face Learning

Experiment 1 examined if face recognition ability was related to differences in people's ability to use information from distinct SF bands during *face learning*. Given that studies have found a narrow band of SFs, near those of MSF and LSF information, that is most useful during face learning (Peters & Kemner, 2017), we expect sensitivity in the recognition memory test to be best for faces that are learnt unfiltered (i.e., retaining all SFs), followed by LSF-filtered faces (i.e., faces largely retaining LSF information), and worst for HSF-filtered faces (i.e., faces largely retaining HSF information). Given that individuals with face recognition deficits may have potential impairments in processing low SF information in faces (Awasthi et al., 2012), we expect that FRA, as measured by the CFMT-Chi, will positively correlate with the increased ability to recognise faces learnt as unfiltered and LSF- (but not HSF-) filtered.

2.4 Methods

2.4.1 Participants

We recruited 54 Malaysian Chinese participants (31 females), with a mean age of 22.74 years (*SD* = 2 years). Participants received either five Malaysian Ringgits in cash or course credits as compensation for their time. All participants reported normal or corrected-to-normal vision. Written informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ191119).

2.4.2 Stimuli/Apparatus

The experiment was conducted using the PsychoPy software (Peirce et al., 2019). Participants were seated in a quiet and dimly lit room at approximately 57 centimetres (cm) from a 20-inch Hewlett-Packard ProDisplay P201 LED Backlit TN LCD monitor (60 Hz refresh rate, 1280 x 720 pixels (px) resolution). To keep participants at a constant viewing distance, a chinrest was used.

Old/New Recognition Memory Task (RMT)

One hundred and twenty pairs of full-frontal faces were taken from the CAS-PEAL-R1 Face Database (Gao et al., 2007) for the RMT (120 identities). These faces consisted of 60 male and 60 female identities, each with either a neutral or a happy expression (i.e., each identity with two expressions from the same viewpoint). All faces in the learning stage had neutral expressions, while all faces in the recognition stage had happy expressions. This was done to avoid recognition based on pictorial coding (see Bruce, 1983; Estudillo, 2012; Estudillo & Bindemann, 2014). The allocation of faces to this RMT was counterbalanced across participants; each face image was presented once throughout the entire experiment in random order. Using Adobe Photoshop, all faces were cropped from the chin down (external facial features were kept, e.g., hair and ears), resized and embedded in a uniformly grey background of 480 × 480 px. Within the background, all cropped faces measured approximately 190 px (175 to 210 px) in width and 250 px in height.

To create our low and high SF-filtered faces, face images were spatially filtered in the frequency domain by multiplying their amplitude spectra with a Gaussian low-pass (LP; largely preserving frequencies below a certain spatial frequency) or a high-pass (HP; preserving frequencies above a certain spatial frequency) spatial frequency filter using Matlab R2019b (Mathworks, Version 9.7.0.1247435; refer to Figure 2.1). The LP filter was a two-dimensional Gaussian function with a standard deviation of 14.25 cycles per face width (c/fw) and the HP filter was the inverse of a Gaussian function with a standard deviation of 106 c/fw.

Figure 2.1.

Examples of face stimuli used in the learning stage of the RMT in Experiment 1.

Note. (From left to right) unfiltered, low SF-filtered, and high SF-filtered faces.

In the literature on face processing, especially where SF-filtered faces are presented to participants, variants of face stimuli are generally equated for root-mean-square contrast (Collin et al., 2006; Ojanpää & Näsänen, 2003; Jeantet et al., 2018). However, this does not guarantee that images are equated for low-level visibility (e.g., “visible energy” of spatially filtered images may vary). Here we followed an approach used by Hussain Ismail et al. (2019) to equate face stimuli for their low-level visibility. According to Hussain Ismail et al., the “visible energy” of any grey-scale image can be calculated as the dot-product between an image’s power spectrum and a two-dimensional filter that considers non-uniformities in people's contrast sensitivity to different spatial frequencies and orientations spatial frequencies. Using this method, we calculated the visible energy of each of the 120 images (both filtered and unfiltered) to be used in this RMT and obtained the mean visibility across all. The amplitude spectra of all images were then uniformly adjusted (i.e., clipping pixels) to reach this mean, thereby equating all images for low-level visibility. The adjusted spectra were used to regenerate images using inverse Fourier transformation. In the resulting images, a few pixel values were outside the displayable range of grey levels (0 to 255). These pixels were clipped to the displayable range (values below 0 set to 0, and values above 255 set to 255). Across all images, the mean percentage of image pixels clipped was way less than 1% (0.17% to be exact, with the maximum being 0.25%), and therefore, we believe that clipping would have negligible effects on the amplitude spectra, as far as visibility is concerned.

Cambridge Face Memory Task – Chinese

We used the Chinese version of the Cambridge Face Memory Task (e.g., CFMT-Chi), and all faces were the same as those used in the original paper (McKone et al., 2012b). Face images were those of men in their 20s and early 30s in neutral expressions, and each individual was photographed in the same range of poses and lighting conditions. For this task, six unique target identities and 46 unique distractor identities were used. For each identity, three face images from three different viewpoints (one left 1/3 profile, one full-frontal and one right 1/3 profile) were used. Only male faces were used because people perform equally well with male faces whereas women show a recognition advantage over female faces (Lewin & Herlitz, 2002). These faces did not contain external features (e.g., hair) and no facial blemishes were visible. They were greyscale faces (160 px in width and 195 px in height) embedded in the centre of a uniformly grey background that is 200 px wide and 240 px tall (4 x 4.8 cm; see McKone et al., 2012b for further details).

2.4.3 Procedure

Each participant had to complete two tasks: The RMT and the CFMT-Chi. The order of these tasks was counterbalanced across participants.

Old/New Recognition Memory Task (RMT)

The RMT consisted of five blocks, each starting with an initial "learning stage", followed by a filler task and finally a "recognition stage". These five blocks were randomized across participants. In the initial learning stage, any single trial contained a white central fixation cross (17 × 17 px; 0.6° × 0.6°) shown for 500 ms, followed by a unique face stimulus (190 × 250 px; 6.7° × 8.8°) presented in the centre of the screen for 3000 ms. Faces were presented equally often as either unfiltered, LSF-filtered, or HSF-filtered. Twelve such trials were presented, and participants were asked to learn and memorize all 12 faces for a subsequent recognition stage. This led to a total of 60 unique faces (e.g., 12 faces from five blocks) that needed to be learnt throughout the entire task.

Following the learning stage, participants were given a short filler task that involved simple number calculations (e.g., count seven numbers backwards from 93 and divide that number by three) or a word search task (e.g., write down three words that rhyme with 'face'), which took approximately one minute to complete. This was followed by the recognition stage. During this stage, a total of 24 faces were sequentially presented to participants (over 24 trials), where the 12 learnt faces ("old") were randomly intermixed with 12 novel faces that participants had not seen previously in the experiment ("new"). New faces were always presented as unfiltered. Similar to the learning stage, each trial began with a 500 ms presentation of a white central fixation cross. This was followed by the presentation of a face that remained at the centre of the screen until a response was recorded. The participants were required to indicate whether they had previously seen this face in the learning stage, by pressing the key “Q” on the keyboard if they have seen it and the key “P” if they have not seen it before. Participants were instructed to respond as accurately as possible.

Cambridge Face Memory Task – Chinese (CFMT-Chi)

The CFMT-Chi (refer to Figure 1) consists of a total of 72 trials across three different stages (i.e., 18 Learning, 30 Novel and 24 Noise). In all trials that test face memory, there were three simultaneously presented faces (one target and two distractors) and participants were required to select which of them was the learnt face, by pressing the key ‘1’ for the left, ‘2’ for the middle, ‘3’ for the right image.

During the initial “Learning” stage, participants were presented briefly with a single target identity in all three views, for 3000 ms each (learning stage). In the subsequent stage (trial stage), participants must discriminate the learnt target faces (same as those shown in the learning stage) from two distractors. This is then repeated for the subsequent target identity until a total of six identities are completed. In this stage, all faces are presented in the same lighting and viewpoint. In the following “Novel” stage, participants will be presented with a single review image with the same six target identities in frontal view for 20 seconds (learning stage). This was followed by a series of 30 trials where three faces (one target and two distractors) were presented in each trial (trial stage). Participants had to discriminate a learnt target identity from the distractors. However, the trial now consists of a novel image of the previously studied identities. This new image differs from the studied faces in viewpoint, lighting, or both (six target identities

× five different presentations = 30 trials). The final “Noise” stage uses the same format as the novel stage. However, the trial now consists of another new set of face images of the six target identities with added visual noise (30% Gaussian Noise, see Duchaine & Nakayama, 2006) and varying presentations (different viewpoints and lighting). This stage contains a total of 24 trials, i.e., six targets with four different presentations.

2.5 Data Analysis

Our main measure of individual differences in face recognition ability was the CFMT-Chi score, which denoted the sum of correct responses. The mean hit rates and false alarm rates in the RMT were recorded and separated based on the filtering condition: UF, LP filtered, and HP filtered faces. Hit rates and false alarm rates were used to calculate *d*-prime scores (i.e., a measure of sensitivity; see Tajika, 2001). This approach was employed to effectively differentiate between signal and noise in a memory task and mitigate the influence of response biases, thus providing a more objective and quantitative assessment of recognition memory performance (Stanislaw & Todorov, 1999). Accordingly, a one-way repeated-measures analysis of variance (ANOVA) was conducted for *d*-prime scores of the RMT, with filtering conditions as the within-subjects factor. Following this, we correlated the *d*-prime scores of each condition in the RMT with the participant’s respective CFMT scores, as well as with the remaining conditions of RMT.

Potentially, one could argue that significant associations (if any) between FRA and reliance towards LSF information might be due to the “noise” stage in the CFMT-Chi. In fact, the visual noise added in this stage forces participants to rely on “special mechanisms” of face recognition (Duchaine & Nakayama, 2006), particularly the processing of holistic information

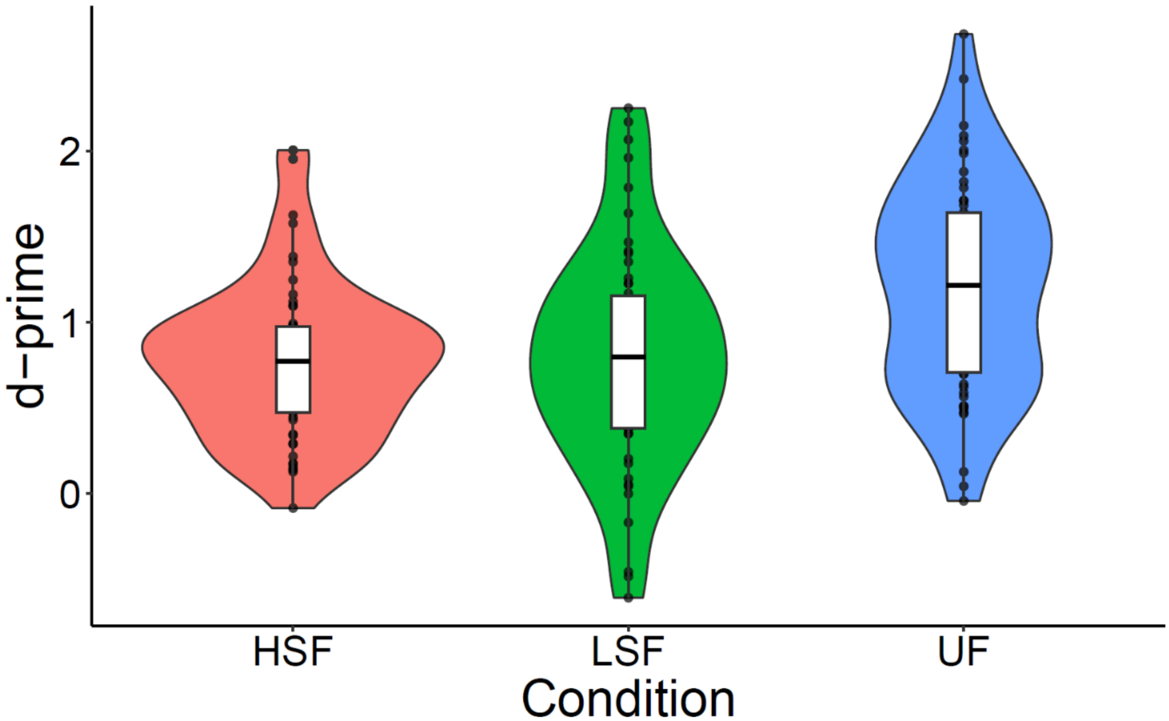
(Corrow et al., 2018; McKone et al., 2012b), which has been found to be conveyed mainly by LSF information (Goffaux et al., 2005; Goffaux & Rossion, 2006). Thus, to further examine the relationship between the individual differences in face recognition and SF processing, additional analyses were carried out on the CFMT scores calculated based on the first two stages (e.g., learning and novel stages). Some evidence has indeed shown that running the first two stages (i.e., excluding the noise stage) of the CFMT is sufficient to detect individual differences in face recognition (e.g., Corrow et al., 2018).

2.6 Results

The maximum achievable score for the CFMT-Chi is 72, in which our current sample had a mean score of 56.07 (*SD* = 10.87). The maximum achievable score in the CFMT excluding the noise trials (i.e., CFMT-short) is 48, and our sample had a mean of 38.61 (*SD* = 6.50). Our ANOVA on *d*-prime scores for the RMT revealed a significant main effect of filtering condition, $F(2,106) = 23.957$, $p < .001$ (refer to Figure 2.2). Holm Bonferroni-corrected paired samples *t*-tests found that *d*-prime in the UF ($M = 1.214$, $SD = .615$) condition was significantly higher than LSF ($M = .796$, $SD = .644$; $t(53) = 5.836$, $p < .001$) and HSF ($M = .774$, $SD = .446$; $t(53) = 6.142$, $p < .001$) conditions. However, participants' performance was comparable in both LSF and HSF conditions, $t(53) = .306$, $p = .760$. In addition, the *d*-prime scores were significantly above chance (i.e., more than zero) for both LSF-filtered ($t(53) = 9.085$, $p < .001$) and HSF-filtered ($t(54) = 12.737$, $p < .001$) conditions, respectively, as revealed by one-sample *t*-tests.

Figure 2.2.

Sensitivity (d-prime) scores for each of the three conditions: HSF (red), LSF (green), and UF (blue).

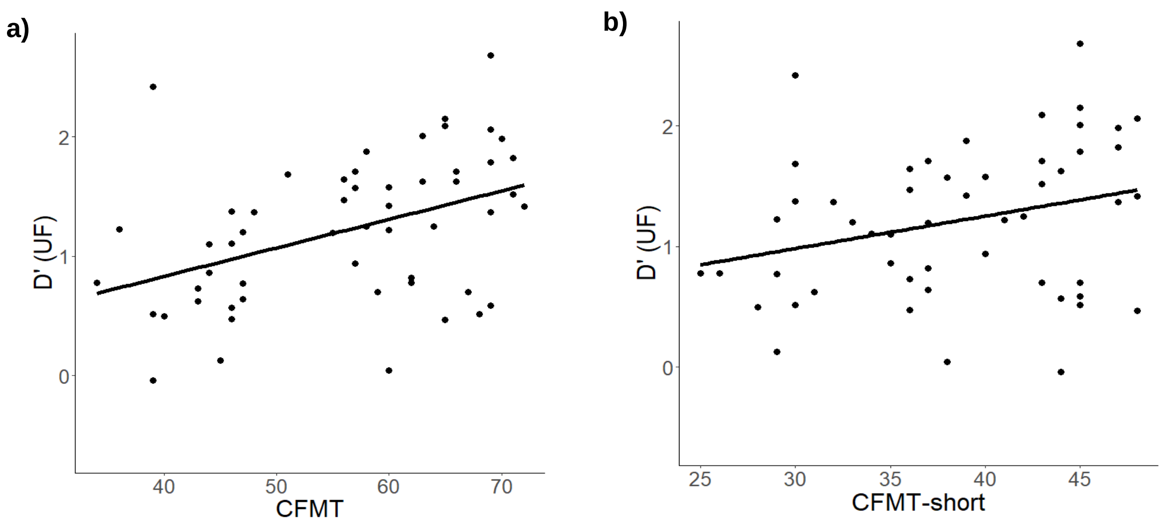


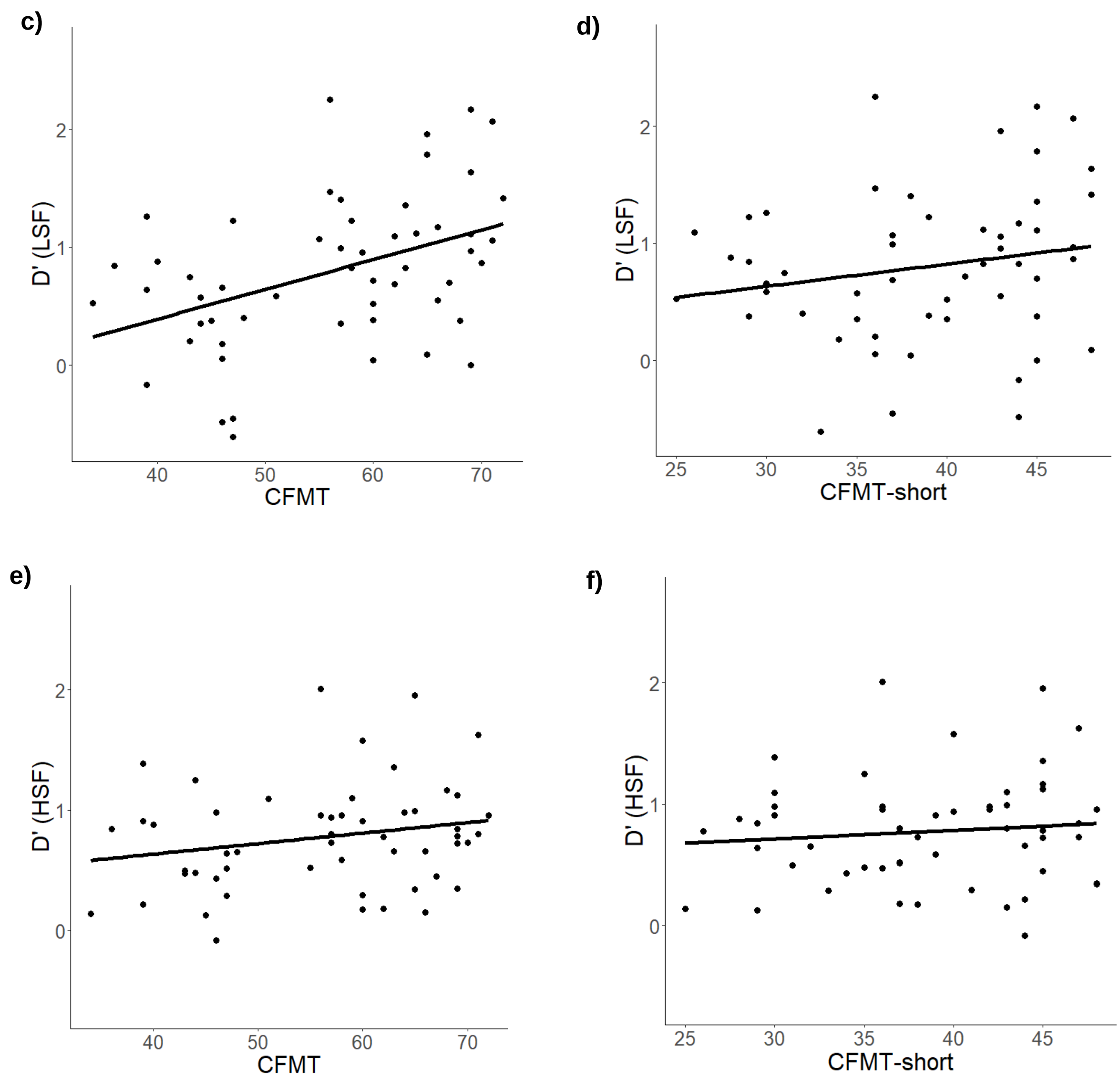
Note. The violin plot represents the density distribution of *d*-prime in each condition. Black circles represent scores from individual participants. The horizontal line within the boxplot represents the mean scores, whilst the top and bottom hinge of the boxplot represent the first and third quartiles. The vertical black line outside of each boxplot represents the 95% confidence interval.

Furthermore, we carried out multiple Pearson's product-moment correlation tests to analyse the relationship between *d*-prime scores in the RMT (for each filtering condition, separately) and the scores in the CFMT-Chi. We found a significant positive correlation between the score in the CFMT-Chi and sensitivity to UF faces in the RMT ($r(52) = .422$, $p = .001$, see Figure 2.3a), and this association remained significant even for the CFMT-short ($r(52) = .284$, $p = .037$, see Figure 2.3b). Similarly, there was also a significant positive correlation between the score in the CFMT-Chi and sensitivity to LSF faces in the RMT ($r(52) = .426$, $p = .001$, see Figure 2.3c), however, this association was not significant when the noise stage was not included ($r(52) = .191$, $p = .166$, see Figure 2.3d). Further, the correlation between the use of HSF information in the RMT and their respective CFMT-Chi scores did not reach significance, $r(52) = .213$, $p = .123$ (see Figure 2.3e). This nonsignificant association remained true when noise trials were excluded from the CFMT too, $r(52) = .102$, $p = .463$ (see Figure 2.3f).

Figure 2.3.

CFMT-Chi scores with (left column) and without (right column) the noise trials correlated against against *d*-prime scores of participants in the unfiltered (UF; a and b), low-spatial frequency (LSF; c and d) and high spatial frequency (HSF; e and f) conditions.



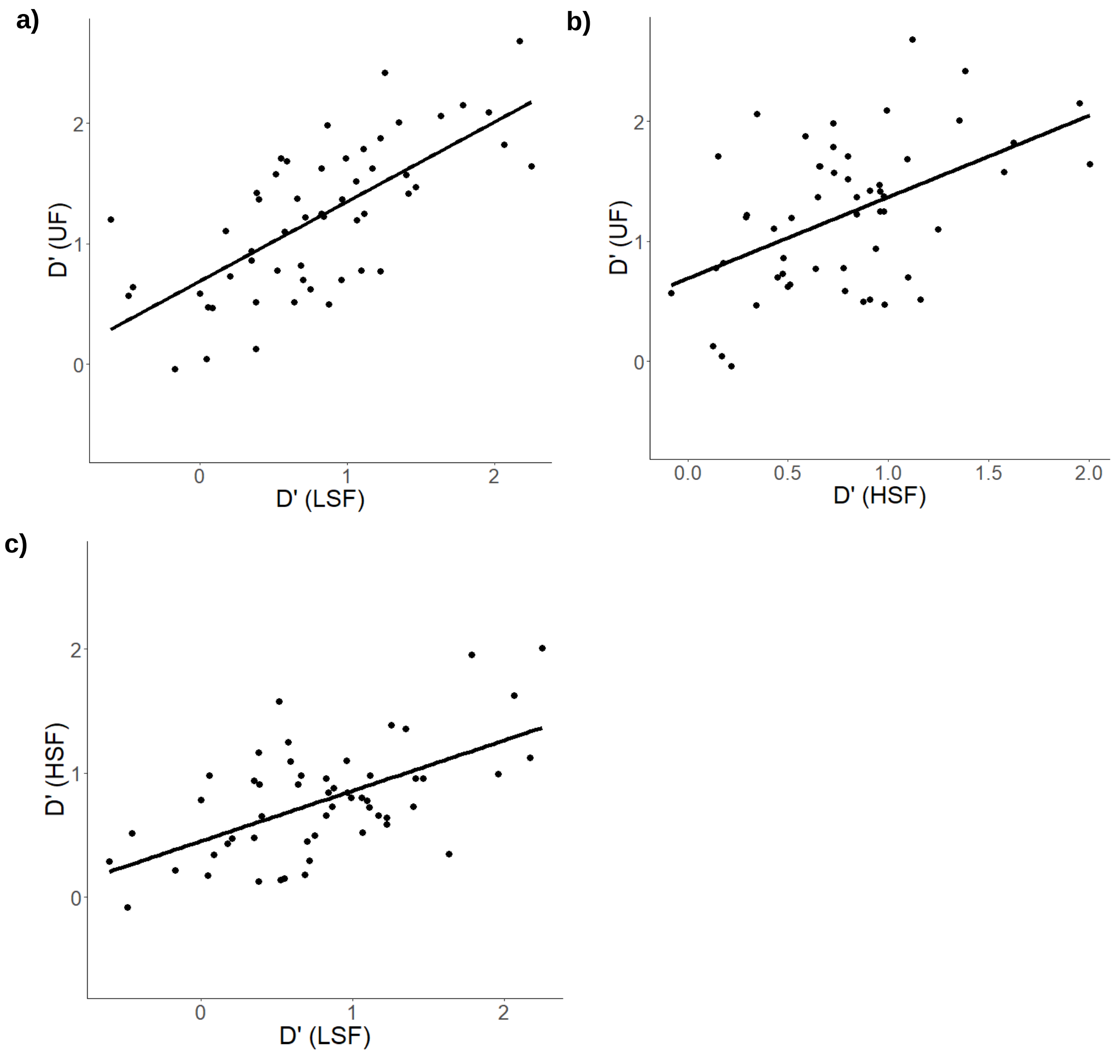


Note. Black circles represent scores from individual participants. Black solid lines are least-squares regression fits to individual data.

Moreover, we also carried out three Pearson's product-moment correlations to analyse the relationship between the three conditions of the RMT (see Figure 2.4). We found significant positive correlations between UF with LSF conditions ($r(52) = .691$, $p < .001$, see Figure 2.4a), UF and HSF conditions ($r(52) = .491$, $p < .001$ see Figure 2.4b), as well as HSF and LSF conditions ($r(52) = .586$, $p < .001$, see Figure 2.4c).

Figure 2.4.

Sensitivity (*d'*) performances between the three (UF, LSF and HSF) conditions in the RMT.



Note. Black circles represent scores from individual participants, and black solid lines are least-squares regression fits to individual data.

2.7 Discussion

The purpose of experiment 1 was to explore the role of spatial frequency (SF) processing during face learning and individual differences in face recognition abilities, and we did this by manipulating the spatial frequency content in faces that were learnt. First, we found a reduced recognition performance in both low spatial frequency (LSF) and high spatial frequency (HSF) filtered conditions compared to the unfiltered (UF) condition. This shows that retaining only (or removing) specific bands of spatial frequency reduces people's ability to learn faces in general. Our findings somewhat contradict previous literature (Peters & Kemner, 2017), as we show that LSF and HSF information are similarly useful for learning unfamiliar faces.

Moreover, the current study shows distinct associations between the CFMT-Chi and the different SF conditions of the RMT, wherein we found significant positive associations between the CFMT-Chi scores and face recognition performances (i.e., *d*-prime) in UF and LSF, but not HSF conditions. This suggest that the use of LSF, but not HSF information, during face learning was associated with individuals' FRAs. This seems to be in line with Awasthi et al.'s (2012) findings who showed that perception of facial attributes (i.e., gender) is determined by an individual's ability to process low SF information. However, when the "noise" trials in the CFMT-Chi were removed from the analysis, FRA was no longer associated with the ability to recognise faces learnt with low SF information. This suggests that the observed association between LSF processing and CFMT-Chi could be driven by the participants' performance in noise trials of the CFMT-Chi. In other words, what we found may not necessarily represent an association between individual differences in face learning and processing of LSF information in faces. Additionally, we also found a significant correlation between recognition performance in the UF condition and CFMT-Chi scores. This indicates that the two face recognition tasks employed were measuring similar constructs.

Lastly, we found that performances in the three conditions of the RMT were positively associated. This suggests that individuals who are better in face learning (UF condition) not only depend more on both low and high SF information but also that those who utilize more low SF information tend to make greater use of high SF information. Theoretically, individuals with better integration of SF information would also mean that they are better in processing both HSF and LSF information. This further supports our claim that people's ability to learn faces is dependent on a broad range of SF information.

2.8 Experiment 2: Face Recognition

While previous studies, and the findings from our Experiment 1, revealed how specific bands of SF information could be important for the initial encoding and formation of memory representations, they do not highlight the importance of specific SF bands in matching perceived faces to facial representations retrieved from memory. LSF has been shown to be important for the initial face learning stage (although our findings from Experiment 1 does not support this), as studies suggest that LSF information conveys global information (Goffaux & Rossion, 2006; Peters & Kemner, 2017), which plays an important role for perceptual encoding and memory consolidation (Henderson et al., 2005; Tanaka et al., 2019; Wang et al., 2022). In fact, learning faces that retained only LSF information were better recognized than faces that retained only HSF information (Peters & Kemner, 2017). While this suggests that LSF is more important during encoding and storage of faces, it does not inform us whether LSF also has an advantage over HSF information during the recovery of faces from memory.

Accordingly, when the SF filtering was applied in the recognition stage, studies have shown that HSF can be not only useful but sometimes even more informative than LSF information (Fiorentini et al., 1983; Gao & Bentin, 2011; Goffaux & Rossion, 2006). For example, when faces only retained SF information above (HSF) or below (LSF) 5 c/fw (with frequencies beyond 15 c/fw not detectable), HSF-filtered faces were significantly better recognized than LSF-filtered faces (Fiorentini et al., 1983). As the cut-off point of the filters were increased (to 8 c/fw and then to 12 c/fw), the number of errors for LSF filtered faces dropped, and the number of errors for HSF-filtered faces increased. However, Wenger and Townsend (2000) showed that learning unfiltered faces and recognizing filtered version of these faces was better for LSF faces (< 12.4 c/fw) than HSF faces (> 12.4 c/fw), and this LSF advantage increased with retention period. Importantly, when the filter was applied during both learning and recognition stages, this LSF advantage persisted even with a 20-second delay in recognition, suggesting that LSF information aids in long-term delayed recognition.

Nonetheless, despite the disparity between these two studies, a consensus emerges when considering the broader context. Specifically, these mixed findings could be attributed to the fact that a substantial portion of MSF information, typically in the range of SFs near 10 c/fw (Gaspar et al., 2008; Keil, 2008), are retained in the band-pass filtered faces that is recognized more accurately. As shown in Fiorentini et al. (1983), when cut-off frequency used was low (5 c/fw), more accurate recognition of HSF faces may be due the faces retained most (if not all) of the MSF information. This rationale is also applicable for LSF advantage observed when the threshold is increased to 12 c/fw (Fiorentini et al., 1983). Similarly in Wenger and Townsend's (2000) study, the relatively high cut-off frequencies for LSF faces (< 12.4 c/fw) likely retained a significant portion of MSF information (see also Gao & Bentin, 2011). This suggests that the recognition advantage observed in these studies is actually a reflection of the importance of a critical band of SFs lying between low and high SF information. Consequently, when researchers carefully controlled for the MSF information retained in their filtering process of faces, the advantage of HSF information became apparent. Even when HSF information was preserved at a higher threshold (> 32 c/fw) for whole faces during the later recognition stage, accuracies were significantly better than faces retaining only low SF information (< 8 c/fw) (Goffaux & Rossion, 2006). This suggests that HSF information is not only sufficient for face recognition but indeed becomes increasingly important during the later recognition stages. However, this HSF advantage could be due to a short retention period (i.e., 300 ms) of the recognition task, which would resemble a discrimination task (e.g., Wenger & Townsend, 2000). As shown by Wenger and Townsend (2000), when the retention interval of a memory task was reduced to one second, HSF information became more crucial.

Together, it is unclear if different bands of SF information have distinct roles in different stages of face recognition. Despite the large number of studies suggesting dominance of LSF processing, it is possible that HSF information is more relevant than LSF information for later recognition than learning of faces. While some studies have shown that participants were able to recognise faces retaining both LSF and HSF information more accurately than faces that only retained LSF information (Halit et al., 2006), this does not speak to the relative importance of HSF over LSF in face recognition. Consequently, we conducted a second experiment in which participants would learn unfiltered faces and will be required to recognise that retained one of three predetermined bands of SFs.

2.9 Methods

2.9.1 Participants

We recruited 55 Malaysian Chinese participants (38 females) from the University of Nottingham Malaysia student population, with a mean age of 22.13 (*SD* = 2 years). Participants received either five Malaysian Ringgits in cash or course credits as compensation for their time.

All participants reported normal or corrected-to-normal vision. Written informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ191119).

2.9.2 Stimuli/Apparatus

The stimuli and apparatus used in the current experiment are identical to those used in Experiment 1 (see p. 57 – 61).

2.9.3 Procedure

The procedural description in the current experiment is identical to the preceding experiment, except for the following changes in the old/new RMT. Similar to Experiment 1, the RMT consisted of five randomized blocks, each starting with an initial "learning stage", followed by a filler task and finally a "recognition stage". However, in the current experiment, faces presented in the "learning stage" were always unfiltered. Faces in the "recognition stage" were presented equally often as either unfiltered, LSF-filtered, or HSF-filtered (e.g., four faces in each condition).

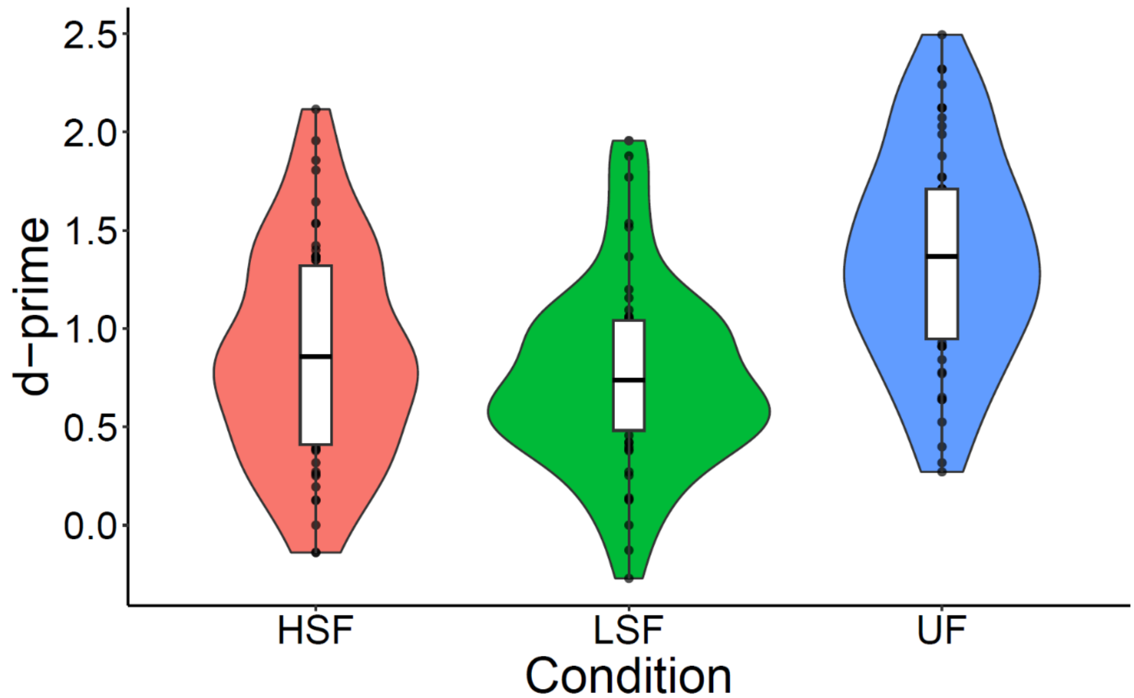
2.10 Results

Our current sample had a mean score of 57.46 (*SD* = 8.05) in the CFMT-Chi and a mean of 38.71 (*SD* = 5.50) excluding the noise trials (e.g., CFMT-short). For the current experiment, both the mean hit and false alarm rates in the RMT were recorded and separated based on the filtering condition.

The one-way repeated-measures analysis of variance (ANOVA) on *d*-prime scores calculated from the RMT revealed a significant main effect of filtering condition, $F(2, 108) = 32.718$, $p < .001$ (see Figure 2.5). Holm Bonferroni-corrected paired samples *t*-tests were used to make post hoc comparisons between the three conditions, in which we found that sensitivity in the UF ($M = 1.366$, $SD = .547$) condition was significantly different from LSF-filtered ($M = .739$, $SD = .467$; $t(54) = 7.617$, $p < .001$) and HSF-filtered ($M = .858$, $SD = .542$; $t(54) = 6.167$, $p < .001$) conditions. Participants were comparable in both LSF and HSF filtered conditions, $t(54) = -1.450$, $p = .150$. The *d*-prime scores were significantly above chance for both LSF-filtered ($t(54) = 11.733$, $p < .001$) and HSF-filtered ($t(54) = 11.741$, $p < .001$) conditions, respectively, as revealed by one-sample *t*-tests.

Figure 2.5.

Sensitivity (d-prime) scores for each of the three conditions of the RMT: HP (red), LP (green), and UF (blue).



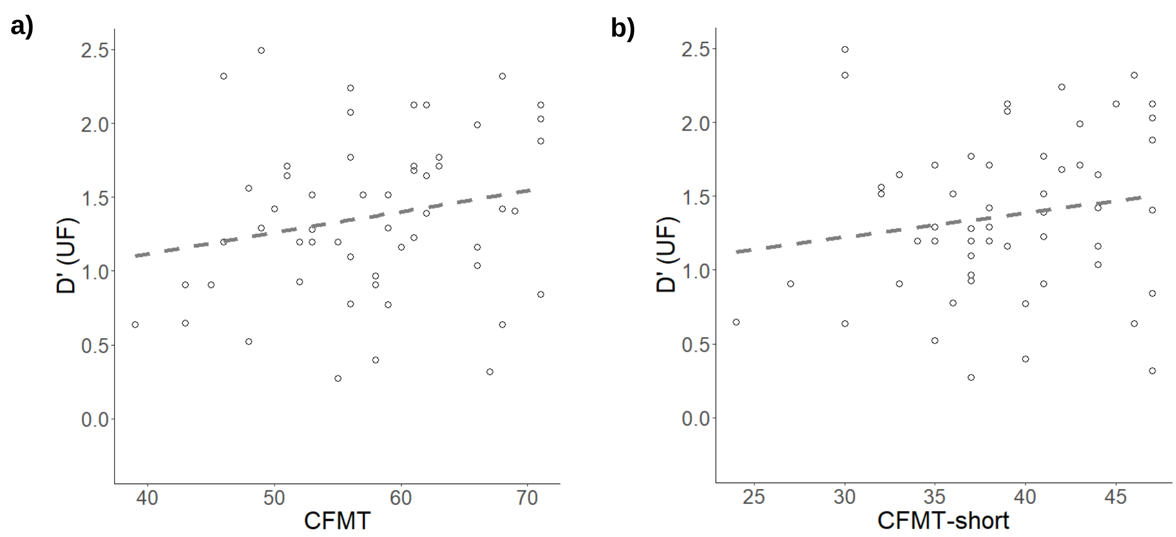
Note. The violin plot represents the density distribution of *d*-prime in each condition. Black circles represent scores from individual participants. The horizontal line within the boxplot represents the mean scores, whilst the top and bottom hinge of the boxplot represent the first and third quartiles. The vertical black line outside of each boxplot represents the 95% confidence interval.

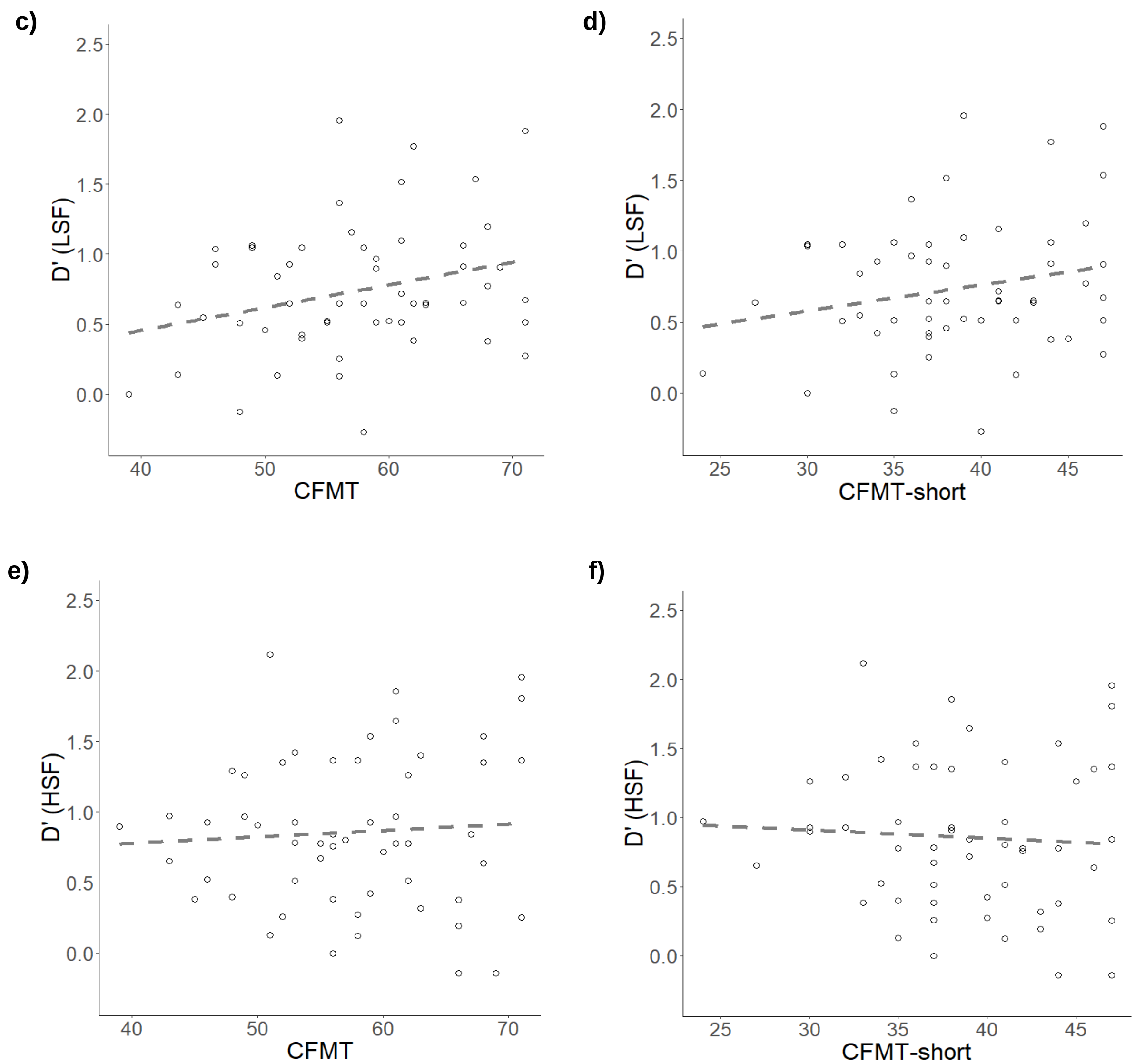
Furthermore, we carried out multiple Pearson's product-moment correlation tests to analyse the relationship between *d*-prime scores in the RMT (for each filtering condition, separately) and the scores in the CFMT-Chi (see Figure 2.6). There was no significant correlation between the scores in the CFMT-Chi and sensitivity to UF faces in the RMT ($r(53) = .211$, $p = .122$, see Figure 2.6a), and this non-significant association was also found when the noise stage was not included to calculate CFMT-Chi scores ($r(53) = .165$, $p = .229$, see Figure

2.6b). However, there was a significant correlation between the scores in the CFMT-Chi and sensitivity to LSF information in the RMT ($r(53) = .280$, $p = .038$, see Figure 2.6c), but this association was not significant when the noise stage was not included ($r(53) = .216$, $p = .113$, see Figure 2.6d). Lastly, there was also no correlation between the use of HSF information and the CFMT-Chi scores ($r(53) = .067$, $p = .626$, see Figure 2.6e), even when the noise stage was excluded ($r(53) = -.060$, $p = .665$, see Figure 2.6f).

Figure 2.6.

CFMT-Chi, with and without the noise trials (left and right), against *d*' scores of participants in the unfiltered (UF), low-spatial frequency (LSF) and high spatial frequency (HSF) conditions.





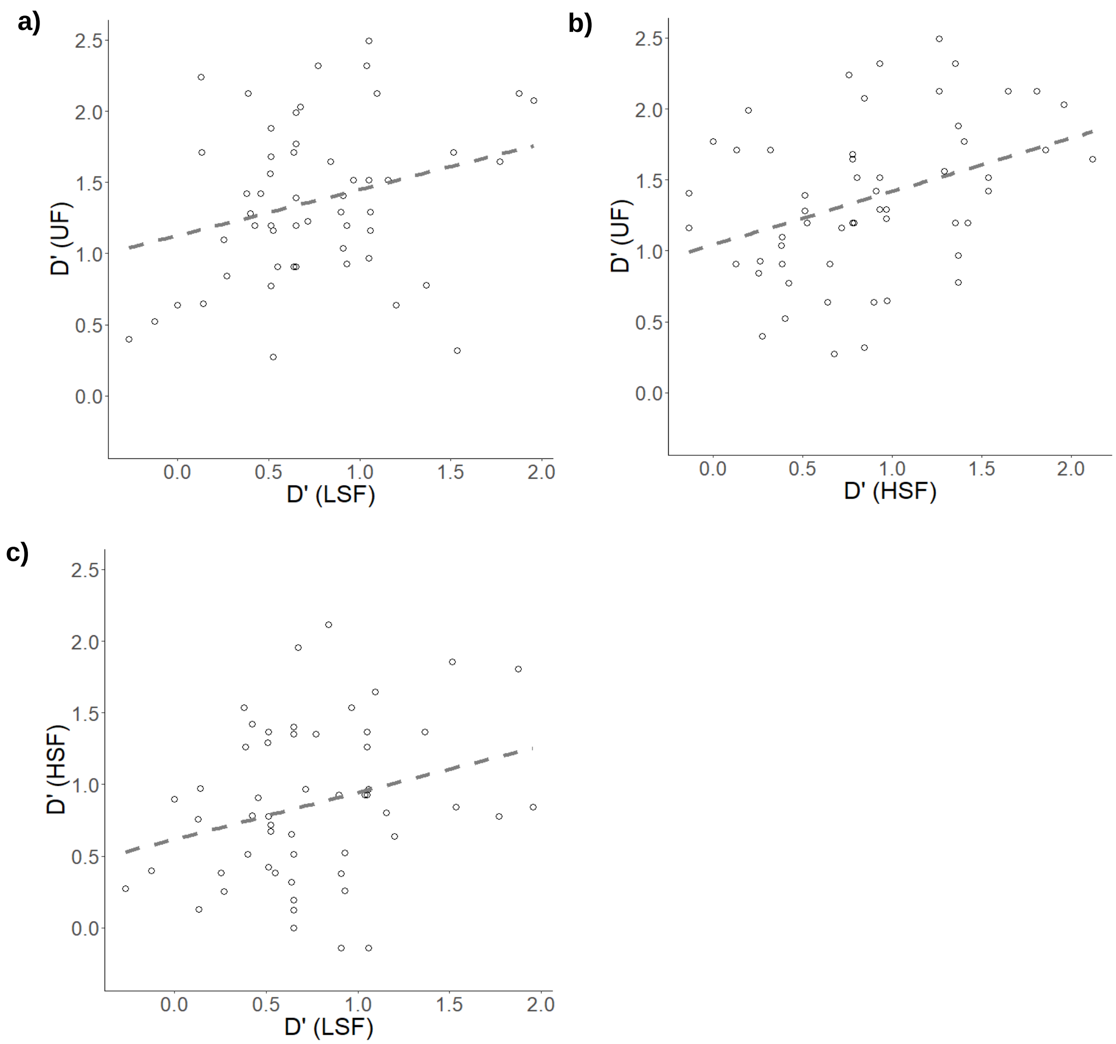
Note. Grey annuluses represent scores from individual participants, and grey-dashed lines are least-squares regression fits to individual data.

We also carried out three Pearson's product-moment correlations to analyse the relationship between the three conditions of the RMT (see Figure 2.7). We found significant positive correlations between UF and LSF-filtered conditions ($r(53) = .276$, $p = .042$, see Figure 2.7a), as well as UF and HSF-filtered conditions ($r(53) = .373$, $p = .005$ see Figure 2.7b).

Additionally, HSF- and LSF-filtered conditions were also positively correlated with each other ($r(53) = .280$, $p = .038$, see Figure 2.7c).

Figure 2.7.

Sensitivity (*d*’) performances between the three (UF, LSF and HSF) conditions in the RMT.



Note. Grey annuluses represent scores from individual participants, and grey-dashed lines are least-squares regression fits to individual data.

2.11 Discussion

The purpose of this experiment was to explore the role of processing specific bands of SFs in faces during recognition on individual differences in face recognition abilities. We found a reduced recognition performance in both low spatial frequency (LSF) and high spatial frequency (HSF) filtered conditions compared to the unfiltered (UF) condition. This shows that retaining only (or removing) specific bands of spatial frequency reduces people's ability to recognise faces in general. Contrary to our hypothesis, we found that HSF processing is important during later face recognition stages, but not more important than LSF information. This suggests that accurate face recognition was not only facilitated by LSF information (Wenger & Townsend, 2000), rather, both LSF and HSF information were found similarly useful for the recognition of learnt faces.

Similar to Experiment 1, the current findings indicate distinct associations between the CFMT-Chi and the different filtering conditions of the RMT, wherein we found significant positive associations between individual differences in FRA (e.g., CFMT-Chi scores) and face recognition performances (i.e., *d*-prime) in the LSF condition. Consistent with our predictions, an individual's face recognition ability is linked to their use of LSF information during the later face recognition stages. However, when the "noise" trials in the CFMT-Chi were removed, this significant association disappeared. This suggest that the observed correlation between LSF processing and individual differences in face recognition is mainly driven by recognition performance in the noise trials of the CFMT. Therefore, individual differences in face recognition may not be associated with processing LSF information in faces. Similarly, we found that the use of HSF information during the recognition stage was not associated with the FRAs (with or without noise stage) of individuals. In other words, the findings suggest that good face recognition skills were not associated with a better utilization of a specific band of SF information at later stages of face recognition.

Surprisingly, we did not find a significant correlation between recognition performance in the UF condition and CFMT-Chi scores. One possibility is that the recognition memory task and CFMT-Chi were measuring distinct constructs of face recognition. For instance, face stimuli in both tasks had different image characteristics. The CFMT-Chi faces do not contain any external facial features, however, faces used in the RMT retained the external features. Therefore, participants may rely on cognitive mechanisms that encodes external facial features in the RMT, particularly when participants were unfamiliar with these faces (c.f. Latif & Moulson, 2022). However, if this was true, we would observe a lack of correlation in Experiment 1 too, which was not the case. Therefore, we speculate that these differences could be the consequence of different perceptual strategies used for recognising SF filtered faces. For example, recognizing faces with different bands of SFs may have influenced the perceptual strategies used to recognize subsequent UF faces. This influence appears to extend to faces presented in the CFMT (which also retains all SF information), potentially explaining the observed disparities.

Similarly, we found that performances in the three conditions of the RMT were positively associated. This suggests that individuals who are better in face recognition (UF condition) not only depend more on both low and high SF information, but also those who utilize more low SF information tend to make greater use of high SF information. This also further supports our claim that people's ability to recognize faces is dependent on a broad range of SF information.

2.12 General Discussion

The purpose of experiments reported in this chapter was to explore the relationship between individual differences in processing SF information in faces and face recognition abilities. Across both experiments, we found a reduced recognition performance in both low spatial frequency (LSF) and high spatial frequency (HSF) filtered conditions compared to the unfiltered (UF) condition. This shows that retaining only (or removing) specific bands of spatial frequency reduces people's ability to learn and recognise faces in general. We show that irrespective of whether people are learning a face or attempting to recognise a learnt face, structures in both low and high SF bands are similarly useful. This finding certainly contradicts with the literature emphasising on a low SF dominance in face recognition (Gao & Bentin, 2011; Peters & Kemner, 2017; Wenger & Townsend, 2000).

While previous studies have consistently shown the dominance of LSF processing in face recognition (Gao & Bentin, 2011; Wenger & Townsend, 2000), our contrasting findings could be attributed to the fact that a substantial portion of MSF information (Gaspar et al., 2008; Keil, 2008) were retained in the SF-filtered faces. The results pertaining to the importance of HSF information provides further evidence of the dissociation between face recognition (i.e., face memory) and face perception and the range of SF information utilised. Even though face memory and face perception may be presumably related, the underlying processes could be biased to different SF bands. For instance, face perception relies on LSF-based configural processing which is useful to monitor rapid and holistic changes. However, memorizing a face might also require an additional focus on featural details (e.g., eye contours, lip shape or skin texture) that contain specific information on facial identity, which is essential for accurate retrieval during face identification. Interestingly, despite findings to the contrary, Peters and

Kemner (2017) argued that such specific details of facial features are conveyed by HSF information. Therefore, unlike face perception, HSF information in faces might be as relevant for face memory as LSF information. Indeed, Gao and Bentin (2011) showed that when unfiltered faces were learned for 800ms, HSF information was as useful as LSF information. Accordingly, our RMT design invites the encoding and retrieval of identity-specific, distinct features that could help to distinguish an unfamiliar identity from other similar-resembling faces. Given that such specific featural details are conveyed by higher SF information, the availability of HSF content might be as important for accurate face recognition here.

It is possible that the results we obtained were influenced by our spatial filtering process. Specifically, all the images in the RMT, both filtered and unfiltered, were adjusted for low-level visibility by uniformly adjusting their amplitude spectra (Hussain Ismail et al., 2019). In simple terms, the visibility of structures preserved in faces after SF filtering was manipulated to make them equally visible across the three filtered conditions (UF, LSF-filtered, and HSF-filtered). Previous studies that measured useful SF bands during face recognition often overlooked differences in low-level visibility. As a result, some filtered face images in previous studies may contain more visible structures than others, such as LSF global structure being more visible than HSF structures. Overall, our current findings argue that HSF is as useful as LSF during long-delayed face recognition, when both LSF and HSF face structures are equally visible.

As far as correlations between CFMT-Chi and LSF conditions are concerned, when the “noise” stage in the CFMT-Chi was removed from calculations of the CFMT-Chi score, processing of LSF information was no longer associated with FRA of participants, across both face learning and recognition stages. This suggests that the contribution of LSF processing to FRA is primarily driven by the “noise” trials in the CFMT-Chi, and it does not actually facilitate

FRA. This also poses a challenge as to what is actually being assessed by the CFMT. One potential explanation is that the CFMT requires observers to learn a limited set of target faces that must be repeatedly discriminated from two distractor faces. Consequently, this would decrease emphasis on whole-face processing and lead to the reliance of processing individual features (Richler et al., 2015). Nevertheless, it is important to note that removing one third (24 out of 72) of the trials in the CFMT-Chi would result in less room for variability in FRA to be observed. Although the shortened version of the CFMT was found to be as sensitive as the original version in the screening of prosopagnosia (Corrow et al., 2018), its reliability in assessing the wide range of FRA in typically-developing adults, particularly from different races or cultures, has not been investigated. Additionally, it should be noted that face recognition impairments in prosopagnosia can vary among individuals (Corrow et al., 2016; Tardif et al., 2019) and may not always reflect the poor recognition abilities of the general population.

These differences also provide evidence that the "special mechanisms" of face recognition prompted during the noise stage of the CFMT, i.e., holistic processing (Duchaine & Nakayama, 2006), are associated with the processing of LSF information. In fact, in addition to the notion that LSF information in faces convey holistic cues (Goffaux et al., 2005; Goffaux & Rossion, 2006; Peters & Kemner, 2017), these observed relationships may also be indicative of the same underlying construct between holistic and LSF processing. In short, our results suggest a potential link between holistic processing and LSF processing as facilitators of FRA, as assessed by the noise stage of the CFMT. Nonetheless, it is possible that positive associations found between holistic processing and FRA in previous studies (e.g., DeGutis et al., 2013b; Richler et al., 2011a) may also be the consequence of the noise stage in the CFMT. In short, we do not argue against the notion that LSF processing facilitates FRA, but rather, we claim that this observed facilitation is dependent on how FRA is measured.

Nonetheless, the current study is not without limitations. It is important to take note that we used an LCD (rather than a CRT) monitor display in both experiments. Previous research has demonstrated that LCD monitor displays have inferior image rendering, such as colour, contrast, and spatial uniformity compared to CRTs (Ghodrati et al., 2015). These factors could potentially impact the visibility of SF-filtered faces (but see Zhang et al., 2018). We did not use a CRT display initially due to their limited spatial resolution compared to modern LCD displays (Hwang et al., 2003). The spatial resolution refers to the number of individual pixels that can be displayed on the screen. In brief, CRT monitors had lower pixel densities, which result in loss of details (conveyed by high SF information) compared to the higher pixel densities found in modern LCD displays. Furthermore, retaining/removing external features has been reported to influence SF processing (Jeantet et al., 2018; Kwon & Legge, 2011). As aforementioned, our contrasting results with those of Peters and Kemner (2017) could be due to participants relying on external facial cues during face learning and face recognition in the RMT, which consequently affect the type of SF information extracted. It is possible that HSF information was shown to be as useful as LSF information due to retaining of external features (e.g., hair, ears) in the RMT. For instance, retaining external features could result in participants to utilize HSF and LSF information equally during both face learning and recognition.

One could argue that our null associations between performances in the CFMT and UF in Experiment 2 are the result of short-term familiarity induced by the face recognition tasks used (Leonard et al., 2010). In the CFMT-Chi, the six target faces were presented repeatedly throughout the task (Duchaine & Nakayama, 2006). In contrast, target faces that were presented in the RMT only appeared once during face learning throughout the entire experiment. As shown in Richler et al. (2015), they found significant correlation between the CFMT and holistic processing, but this was only true when the face parts in their face matching task were repeated. This suggests that the CFMT may instead reflect an underlying construct involving stimulus repetition that is different from what our RMT measures. Additionally, face recognition is suggested to be affected by memory constraints such as the retention duration and memory load (i.e., duration of presentation and number of faces to remember; Fysh, 2018; Ölander et al., 2019; Pertzov et al., 2020; Weigelt et al., 2014). Accordingly, our two face recognition tasks also differed in these two aspects. Despite that, this does not fully explain our contrasting findings, given that what happens in the unfiltered condition in both experiments is identical, wherein both the learning face and the recognising face contained all SF bands. This proposes that the observed differences cannot be explained by task constraints alone.

Possibly, this contrasting association for UF and FRA between both experiments, can be explained by how faces were learnt and recognised in the RMT. In Experiment 2, the faces required to be recognised were a mix of UF, high, and low SF-filtered faces. Here, recognition of SF-filtered faces could cause repulsive face after-effects. For instance, recognition of LSF filtered faces could result in subsequent faces being perceived with a bias towards their finer details (e.g., HSF information) and lesser sensitivity towards coarse details (e.g., LSF information), vice versa (Webster & MacLeod, 2011). As a result, presentation of SF-filtered faces could affect the "strategy" used to recognise subsequent faces in Experiment 2. Nonetheless, it is unclear why these after-effects were more prevalent during face recognition than face learning. One possibility is that presenting faces with varying SF could result in participants to *switch* between perceptual strategies during recognition across each trial (Gold et al., 1999). In contrast, the strategy used in the CFMT and RMT (in Experiment 1) is always consistent because only unfiltered faces are presented during the recognition stage. While this last point remains speculative, it provides a foundation for future studies involving SF processing of faces, particularly between face learning and recognition stages.

2.13 Future Directions: Higher-order Processing of Faces

An alternative explanation for the inconsistent results in our study is cultural differences in face processing, which are often reflected by variations in SF tuning (Estéphan et al., 2018; Tardif et al., 2017). While studies that examine SF processing during face recognition mostly involve Westerners, our study consisted of only Easterners. Previous research has suggested that individuals from Eastern and Western societies differ in the way they allocate their attention over space, with Easterners relying more on global, lower SF information (see review by Blais et al., 2021). Although our findings did not support this previous finding, our task may have constrained participants to rely more on HSF information (i.e., external features). Speculatively, Westerners may show a bias toward HSF information when a similar methodology (to the current experiment) is used. Furthermore, it is also unclear if SF processing has different weights on individual differences in FRA across cultures. For instance, our findings found that Easterners that are better at face learning and recognition did not rely on low SF information more. Consequently, it is possible that these patterns are not replicated in Westerners, wherein the FRA of Westerners may be predicted by the reliance on low and/or high SF information.

Previous studies have argued that holistic processing is often reflected as LSF processing, while featural processing is related to higher SF processing (Goffaux et al., 2005; Goffaux & Rossion, 2006). Based on the cultural differences found in low-level processing (Estéphan et al., 2018; Tardif et al., 2017), it is conceivable that these differences could also manifest in higher-level processes. For instance, we would expect Easterners to also rely on holistic processing more than Westerners. Nevertheless, to the best of our knowledge, this has not been directly tested. It remains uncertain whether (1) the cognitive mechanisms underlying holistic face processing are culture-specific, or (2) individual differences in FRA and higher-order processing (i.e., holistic processing) are influenced by cultural factors. Given that low-level visual information may not be a reliable predictor of FRA, specifically when face recognition is measured with the CFMT, and there is more compelling evidence that holistic processing facilitates face recognition, we will address these points in subsequent chapters to investigate the role of these higher-order processes in FRA.

In conclusion, the findings from the current chapter indicate that both LSF and HSF information are important and informative in face recognition. Removal of SF information reduces sensitivity in face identification, in which removing both LSF and HSF information significantly impairs face learning and long-delayed recognition. Further, we found that individual differences in face recognition cannot be explained by reliance towards SF information during face learning and/or recognition. Lastly, we suggest that the underlying mechanisms of face memory are dependent on task constraints.

CHAPTER 3: Individual Differences in Holistic Processing between Western and Eastern Societies

3.1 Face Processing Strategies Between Cultures

The expression ‘culture’ has often been used to denote the distinct behaviours, customs and beliefs that characterize a social or ethnic group. Representing a powerful deterministic force, culture is responsible for shaping human behaviour and thinking (Segall et al., 1986). Over the years, a steadily growing body of literature has shown evidence suggesting that culture also impacts more basic cognitive processes, such as visual perception (Chua et al., 2005; Nisbett et al., 2001; Nisbett & Miyamoto, 2005; McKone et al., 2010; Segall et al., 1986). For instance, using the Navon’s paradigm (Navon, 1977), McKone et al. (2010) found that Eastern-Asians (EAs) had a significantly larger global processing advantage compared to Western-Caucasians (WCs) (i.e., global precedence effect; GPE). Strikingly, this advantage, although weaker, was also evident in second-generation EAs who were not born in Asian countries (i.e., Australian-born Asians). Despite that, whether these cultural differences are generalized across special, higher-level classes of stimuli such as faces or distinct task constraints (i.e., perceptual, recognition or categorization) remains unknown. The study reported in this chapter aims to examine the role of culture in face recognition abilities and its underlying cognitive mechanisms.

Multiple studies measuring oculomotor behaviour have found cultural differences in face perception strategies, especially between Western-Caucasian (WC) and Eastern-Asian (EA) societies (e.g., Blais et al., 2008; Caldara, 2017; Kelly et al., 2010, 2011; Miellet et al., 2013; Rodger et al., 2010). Early accounts by Blais et al. (2008) found cultural differences in eye movements when participates had to learn and recognize a set of faces from their own races. For instance, EAs were found to consistently fixate at the centre of faces, reflecting a global perceptual strategy, while WCs tend to engage with a triangular fixation pattern, reflecting a more analytical perceptual strategy. Notably, these strategies did not change when categorizing other-race faces too, highlighting the robustness of perceptual mechanism(s) engaged during face processing. A recent eye-tracking study by Caldara (2017) also found similar cultural differences between EAs and WCs in fixation patterns even when identifying facial expressions. Caldara proposed that the face recognition system relies on culture-specific strategies (for further evidence, see Arizpe et al., 2016; DeGutis et al., 2013a).

In consideration of the findings above, whether cultural differences in fixation patterns also reflect on the type of information extracted remains unknown (Lee et al., 2022). Fixating the centre of the face means that most of the featural information (e.g., eyes and mouth) in the face must be processed peripherally under reduced spatial resolution (Balz & Hock, 1997), and in this case one would expect EAs to prioritise low spatial frequency (SF) information more than WCs. For instance, studies have proposed that the nose region allows optimal face processing (Peterson & Eckstein, 2012), potentially because it also allows the efficient spread of attention (i.e., low SF information), which enhances whole-face processing (Belanova et al., 2021). Accordingly, Tardif et al. (2017) compared the range of SFs information used by EAs and WCs during face recognition. Rather than removing or retaining SF information of faces at a cut-off point, they randomized the amount of SF information available in the face stimuli to maintain participants' accuracy at a pre-selected threshold. Across two different face perception tasks, they found that EAs were tuned to lower SF information than WCs. Tardif et al. provide further support that quantitative differences in oculomotor behaviour (i.e., eye movements) are also paired with a qualitative disparity (e.g., different types of visual information utilised), in which EAs are more tuned to global information, while WCs are more tuned to local information (see also Arizpe et al., 2016; Caldara, 2017; Estéphan et al., 2018).

3.2 Holistic Processing and Face Recognition Ability

Face perception is thought to rely on two distinct higher-level processes, namely, featural processing and holistic processing (Diamond & Carey, 1986; Leder & Bruce, 2000). Featural processing refers to the separate processing of isolated facial features as distinct components, whereas holistic processing refers to an integration of all facial features into one meaningful whole (Piepers & Robbins, 2012; Rossion, 2008, 2013). It is widely believed that holistic processing occurs automatically, unconsciously and wherein it is an essential component of face perception (Jacques & Rossion, 2010).

Traditionally, holistic processing has been measured with three classical measures: the face inversion task (Yin, 1969; Rossion, 2008), the part-whole task (Tanaka & Farah, 1993; Tanaka et al., 2004), and the composite task (Young et al., 1987; Rossion, 2013). The face inversion task shows that memory for faces is impaired when they are seen inverted (i.e., upside down) as opposed to upright, in their canonical orientation (Tanaka et al., 2019). This "face inversion effect" (FIE) is particularly stronger for the recognition of faces compared with other non-face objects (Bruyer, 2011; Rossion & Gauthier, 2002; Yin, 1969). Maurer et al. (2002) used the FIE to demonstrate the difference between featural and holistic processing, where participants were similarly slow and inaccurate at recognizing inverted full faces and individual parts that was presented in either orientation, compared to full upright faces. Specifically, the inversion reduced recognition accuracy of full faces (e.g., holistic processing) more than the recognition of individual face parts (e.g., featural processing). Despite that, Piepers and Robbins

(2012) claimed that the FIE does not necessarily constitute to a direct measure of holistic processing. In fact, although the FIE is stronger for faces, this effect is not absent for non-face objects (see Gerlach et al., 2023). In addition, recent evidence suggests that FIE paradigm does not directly manipulate holistic processing and impacts face processing quantitatively (Gerlach & Mogensen, 2023; Tanaka & Simonyi, 2016). For instance, it has been argued both upright and inverted faces are processed holistically, but the inversion effect is stronger for upright faces (i.e., quantitative differences; Gerlach & Mogensen, 2023; Murphy & Cook, 2017). Here, it is unclear whether FIE has a qualitative or quantitative impact on holistic face processing (Boutet et al., 2021; Rossion, 2008; McKone & Yovel, 2009; Gerlach et al., 2023). In other words, it is unclear if FIE reflects the complete disruption of holistic processing, a reduction in holistic processing, or the disruption of processes other than holistic processing.

More direct evidence for holistic processing during face recognition can be observed from the composite face effect (CFE; Young et al., 1987; Murphy et al., 2017; Rossion, 2013) and the part-whole effect (PWE; Estudillo et al., 2022; Tanaka & Farah, 1993; Tanaka & Simonyi, 2016). The composite task (Hole, 1994; Young et al., 1987; Rossion, 2013) involves the use of face stimuli created by combining complementary top and bottom halves of two different face identities, split at the horizontal meridian. Aligning the top half of one identity with the bottom half of another identity creates the illusion of a new identity, making it hard to attend to one half of the face while ignoring the other. However, misaligning both halves would eliminate such an effect. In the part-whole task (DeGutis et al., 2013b; Estudillo et al., 2022; Tanaka et al., 2004), participants are required to recognize a set of “target” faces. They are first shown a target face, followed by two “test” faces. In one case, the “whole” condition, participants are asked to either identify which of two “test” faces, that differ only by one feature (e.g., the nose) matches the face of a learnt identity. In another case, the “part” condition, they are asked to identify which of two isolated facial features belong to the target identity. The part-whole task indexes holistic processing as the advantage to recognise a facial feature when it is presented in the context of the studied face. This is because facial features are integrated into a whole, and therefore any new features lead to an illusion of a new identity, making it easier to tell the two test faces apart (Tanaka & Farah, 1993). However, when the features are presented in isolation, the faces must be discriminated at the level of those individual features, which makes identification harder.

If holistic processing is fundamental for face recognition, one would expect that individual differences in face recognition abilities (FRA) would be associated with holistic processing (Belanova et al., 2021; DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012). However, the results are rather mixed. On the one hand, some studies have found associations between FRA and holistic processing (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012). For instance, DeGutis et al. (2013b) found that holistic processing, as indexed with the PWE and CFE, was positively correlated with FRA, as measured with the Cambridge Face Memory test (CFMT; Duchaine & Nakayama, 2006). However, other studies have found no support for this association (Konar et al., 2010; Richler et al., 2014; Verhallen et al., 2017). For instance, Konar et al. (2010) found that CFE did not correlate with performances in a face-matching task. Supporting the lack of relationship between FRA and holistic processing, Verhallen et al., (2017) found that face processing can be explained by a general factor, termed *f*. Interestingly, they found that *f* did not load onto holistic processing, as measured with the CFE (Verhallen et al., 2017). These findings further challenge the view that holistic processing is necessary for face identification.

Consequently, it is possible that the mixed findings regarding the role of holistic processing on face recognition can be explained, at least partially, by the existence of different measures of holistic processing. For instance, Konar et al. and Verhallen et al's study only included the CFE as a measure of holistic processing. This is problematic as recent studies have shown that the three traditional measures of holistic processing (e.g., FIE, PWE and CFE) are indeed measuring different underlying cognitive mechanisms of holistic processing (Boutet et al., 2021; Lee et al., 2022a; Rezlescu et al., 2017). Accordingly, Rezlescu et al. (2017) found that these three traditional measures of holistic processing were only weakly associated. A more recent examination of the three traditional holistic measures with factor analysis by Boutet et al. (2021) showed that these measures did not load onto similar components. For instance, the variability in CFE and PWE loaded onto different factors, while the FIE, despite its high reliability, did not load onto any of these factors. They proposed that the PWE was linked with the integration of face parts as well as their configural relations, while the CFE was linked to utilizing a whole face template and configural processing (for discussion, see Rossion, 2013). Further, Boutet et al. speculate that the FIE may be linked with inefficient processing of both holistic and featural information, which might explain why it did not load onto any of the factors. In fact, recent studies argued that both upright and inverted faces are processed holistically (Gerlach & Mogensen, 2023; Murphy & Cook, 2017; Murphy et al., 2020; Richler et al., 2011b).).

Accordingly, if these measures are measuring distinct holistic processing mechanisms, their relationship with face identification should also vary. In view of this, Rezlescu et al. (2017) also found that these three traditional holistic measures had varying associations with face perception abilities, as measured with the Cambridge Face Perception Test (CFPT; Duchaine et al., 2007a). For instance, while the inversion and the part-whole effects were moderately correlated with CFPT, the CFE was not associated with CFPT. This suggests that different measures of holistic processing might contribute differently to the wide range of individual differences seen in face identification. Nonetheless, to our knowledge, the relationship between all three holistic measures and FRA, specifically face memory, has yet to be examined together.

3.3 Culture-specific Mechanisms of Holistic Processing

While we know that there are cultural differences in tuning to low-level feature processing in faces (Caldara, 2017; Tardif et al., 2017), we do not know if cultural differences extend to more complex, higher-level cognitive processes such as holistic processing of faces. To our knowledge, only one study has examined this. Miyamoto et al. (2011) compared WC and EA participants’ sensitivity toward changes in facial features and the overall configuration of these features. In their first experiment, participants were presented with four unique target faces, followed by two prototype faces. One of these prototypes preserved the overall configuration of features from all four target identities (configural prototype), while the other prototype comprised the shape of one target face with facial features substituted from the three other target identities (featural prototype). When asked to identify which prototype faces participants had seen previously, Miyamoto et al. (2011) found that EAs were more likely to select configural prototypes than WCs, suggesting that EAs rely more on the overall configuration than facial features for recognition. In the second experiment, Miyamoto et al. created an array of test faces by either manipulating the distance between facial features or replacing the features of target faces with those of another identity. Participants were shown the target and test faces sequentially and asked to determine if they were the same or different. They found that EAs were more accurate than WCs when the configural relation of target faces was manipulated, but both groups performed similarly when features were replaced. This suggests that EAs have a higher sensitivity towards changes in the configuration of faces.

Overall, the research conducted by Miyamoto et al. (2011) supports the notion that cultural differences in visual perception extend to higher-level face processing. While this study provides compelling evidence that EAs exhibit stronger sensitivity towards the configural information of faces, it may only reflect some aspects of holistic processing. Specifically, holistic processing has been described as a higher-level processing encompassing the integration of all facial features and second-order configural relations between these facial features (Piepers & Robbins, 2012). Nonetheless, how could individuals from one culture process a face more holistically than those from another, considering that holistic processing is a fundamental aspect of face recognition? In other words, if holistic representation is indeed what sets faces apart as a "special" class of stimuli, a culture-specific approach to face recognition could challenge this notion. In contrast, if holistic processing is indeed universal, how can an identical holistic mechanism be utilized when there is strong evidence of cultural disparities in the computation of faces?

Recent findings by Wang et al. (2020) provide a possible explanation of why there has not been a consensus on the universality of holistic processing across different cultures. Using event-related potentials (ERP), Wang et al. found that EA participants exhibited a global-to-local (i.e., early P100 to late P200 components) processing bias, contrary to WC participants, who exhibited a local-to-global processing bias, for own-race faces. This suggests that although both EAs and WCs relied on holistic and featural processing during face recognition, cultural disparities were found in the temporal order in which higher-level processes are utilised during face processing. Hypothetically, cultural differences in face processing may be the result of utilizing different holistic mechanisms, as reflected by different holistic processing indexes. In this sense, it is possible that, across cultures, these holistic processing indexes have different weights as predictors of FRA. However, to the best of our knowledge, this has not been directly measured. In brief, it is unclear if holistic processing (1) is associated with individual differences in face recognition ability, or if the concept of holistic processing (2) is unitary and/or (3) is universal across cultures.

The current study aims to answer all the aforementioned questions by systematically examining the relationship between holistic processing and face recognition ability, across Eastern and Western cultures. To achieve this, the current study employs the three traditional measures of holistic processing for faces (the inversion, part-whole and composite face task) and a measure of holistic processing for non-faces (Navon's task), along with objective measures of face (i.e., CFMT; Duchaine & Nakayama, 2006) and non-face (the Cambridge Car Memory test; CCMT; Dennett et al., 2012) recognition abilities. First, to examine if holistic processing facilitates face recognition ability, we correlated performances in holistic measures with the CFMT. Second, to examine if holistic processing is unitary, we correlated the holistic measures with each other. Third, to examine if there are cultural differences in holistic processing and whether they are face-specific, we compared performances between WCs and EAs in the four holistic measures. Consequently, we also compared if the strengths of the associations between holistic measures and FRA are different across cultures.

Although this correlational analysis informs us about the potential relationship between the different tasks, this approach does not tell us whether these mutual associations are due to some common underlying cause (Yong & Pearce, 2013). For example, the fact that face recognition is associated with two or more different indexes of holistic processing would not tell us whether these indexes represent the same, overlapping or distinct cognitive mechanisms underlying FRA. Thus, in this study, we also ran factor analyses to explore the holistic processing structure of face recognition ability and whether this structure is similar across Eastern and Western cultures. A previous study conducted a factor analysis to explore the structure of different mechanisms of holistic processing (Boutet et al., 2021). However, this study did not include a measure of face recognition ability, so it is unclear whether (and if so how) holistic processing skills and individual differences in face recognition share a common structure. In addition to the three gold-standard measures of holistic face processing and one measure of global processing (i.e., Navon's task), in our factor analysis, we included objective measures of face and object recognition. This allows us to examine whether this common structure (if any) is dissociable between faces and non-face objects.

3.4 Methods

3.4.1 Participants

An *a-priori* power analysis using G*Power (Faul et al., 2007) estimated that a sample size of 82 is required to obtain an effect size of 0.3 with a statistical power of 80% (α = .05), for a Pearson's test of correlation. Accordingly, this study recruited 102 British Caucasians (84 females) and 100 Malaysian Chinese young adults (70 females). The age range was similar between British Caucasians (*M* = 21 years, *SD* = 4 years) and Malaysian Chinese (*M* = 22 years, *SD* = 3 years) participants. All participants were recruited through online platforms such as social media, and word of mouth. Participants were compensated with either 15 Malaysian

Ringgits or 1.5 credit hours for their participation. A digital informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of University of Nottingham Malaysia (approval code: BLQZ250920).

3.4.2 Apparatus

All the Western Caucasian participants completed their experiments at a lab based at Bournemouth University. Most Eastern Asian participants completed the experiment at a lab based at University of Nottingham Malaysia. The remaining (N = 22) completed it online in their own computers, through the testing platform “Testable” (www.testable.org; Rezlescu et al., 2020) while being on a conference call with the experimenter, as data collection from them was affected by COVID-19 lockdowns imposed by the Malaysian government. To minimise size differences in displayed stimuli size across different computer screens used by Malaysian participants, participants were required to adjust the length of a yellow line that appeared on their screens to match the width of a debit/credit card they had in possession. This allowed Testable to calculate how many screen pixels (px) mapped on to 1 centimetre (cm) and scale all stimuli based on this conversion. Adobe Photoshop CS6 and Matlab R2019b (Mathworks, Version 9.7.0.1247435) were used to edit stimuli where necessary (refer to Stimuli and Procedure).

3.4.3 Stimuli and Procedure

Each participant was first briefed about the experiment and was informed that they had to complete two different stages: the “evaluation” stage and the “experimental” stage. The “evaluation” stage, which was always completed first, included the CFMT and the CCMT. This was followed by the “experimental” stage, which included the part-whole task, the composite task, the face inversion task and the Navon's task. The order of the face holistic measures was counterbalanced across all participants. However, the Navon's task was always completed last as some research has shown that this task could bias subsequent face processing tasks (e.g., Estudillo et al., 2022; Macrae & Lewis, 2002; Lewis et al., 2009). Accuracy and reaction time (Navon's task only) were measured and recorded. To avoid *other-race effects* (Crookes et al., 2013; Michel et al., 2006; Rossion & Michel, 2011), participants were presented with faces congruent with their own race. To do this, two different versions (one with Caucasian faces, another with Asian faces) of face processing tasks (e.g., Cambridge Face Memory test – Chinese; CFMT-Chi, the inversion, part-whole, and composite task) were created. Here, Caucasian participants engaged in face processing tasks that presented only Caucasian faces, while Asian participants engaged in tasks that presented only Asian faces. Faces of both races in the holistic tasks were taken from identical databases, thus, the faces all had similar characteristics (e.g., lightning, size, cropping). The descriptions of stimuli and procedures mentioned from here on are similar for both groups.

3.4.4 Evaluation Stage

This stage is comprised of the basic evaluation tasks for evaluating participants' recognition abilities for faces and non-face objects (CCMT). For Caucasian participants, we employed the original version of the Cambridge Face Memory test (CFMT, Duchaine & Nakayama, 2006). For Chinese participants, we employed the Chinese version (CFMT-Chi, McKone et al., 2012b) of the CFMT.

Cambridge Face Memory Test (CFMT/CFMT-Chi)

We used the original version (CFMT, Duchaine & Nakayama, 2006) and the Chinese version (CFMT-Chi, McKone et al., 2012b) of the CFMT. Both versions of the CFMT have similar stimuli descriptions and task procedures (for detailed descriptions, refer to Chapter 2, p. 59 – 61).

Cambridge Car Memory Test (CCMT)

The CCMT (Dennett et al., 2012) follows an identical format as the CFMT, with the exception that the stimuli were modified computer-generated images of actual car models (instead of faces), created using 3D Studio Max. To minimize matching based on easily noticeable visual features, all cars are of the same colour, and no identifying badges, logos, or emblems are visible. Car stimuli for the CCMT were sized approximately 465 × 215 px (9.3 × 4.3 cm) (average across cars and viewpoints). Similar to the CFMT, the CCMT also comprises three stages: learning (18 trials), novel (30 trials), and noise (24 trials). The maximum possible score is 72. Any score above 40 denotes normal recognition ability for non-face objects (Dennett et al., 2012).

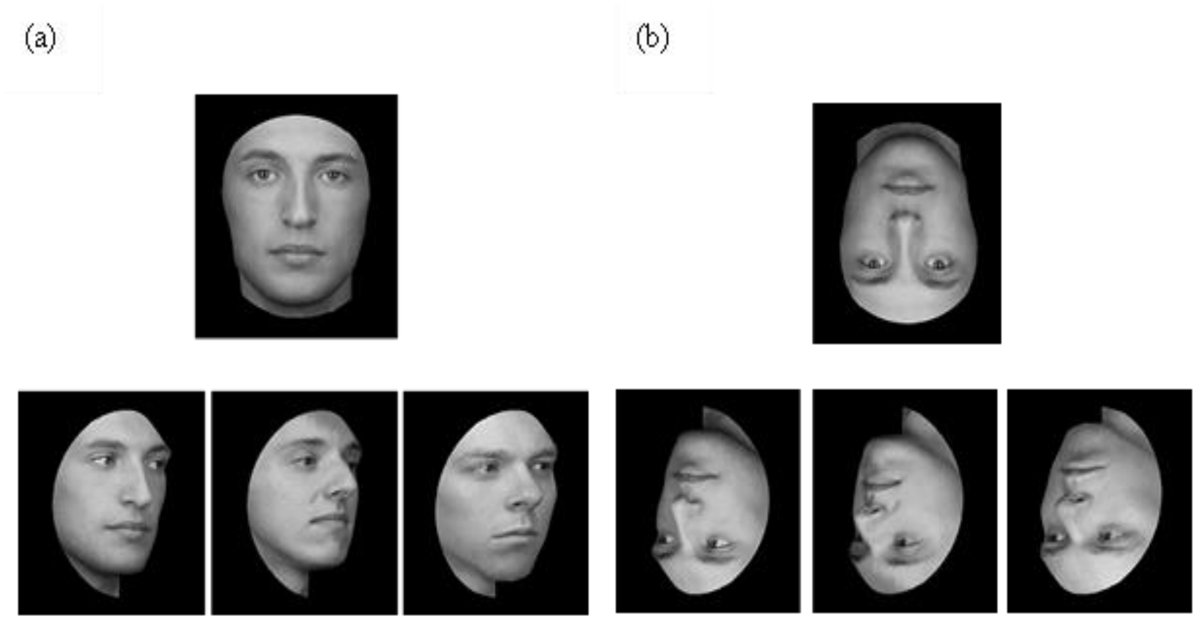
3.4.5 Experimental Stage

Face Inversion Task

Two sets of 30 face identities (15 males) were used for each task (i.e., total of 60 distinct faces). Face images were those of British Caucasian and Malaysian Chinese in their early or mid-20s in neutral expressions. All individuals were photographed in the same range of poses and lighting conditions in the Face Laboratory at the University of Nottingham Malaysia (for full description, see Kho et al., 2023). The external features (i.e., hair, ears) of face stimuli were cropped so that judgements were based on internal facial features only. The faces were also in grey-scale and embedded in a 200 × 250 px (4 × 5 cm) black background (see Figure 3.1).

Figure 3.1.

An example of the (Caucasian) face stimuli used in the inversion task.



Note. A target face (top) followed by three simultaneous test faces (bottom) are shown in each trial: (a) upright and (b) inverted trials.

On any given experimental trial, participants were asked to match one of three test faces (i.e., mid-profile view) with a target face (i.e., frontal view) in terms of identity. Target identities were also used as test faces (i.e., distractor faces) in trials that have a different target identity. Participants first saw the target face for 400 ms, followed by the three simultaneously presented test images for 2000 ms, and a blank screen until the participant response. Participants were required to press ‘1’ for the face on the left, ‘2’ for the face in the middle, and ‘3’ for the face on the right. The test had a total of 80 trials (40 upright and 40 inverted), presented in random order.

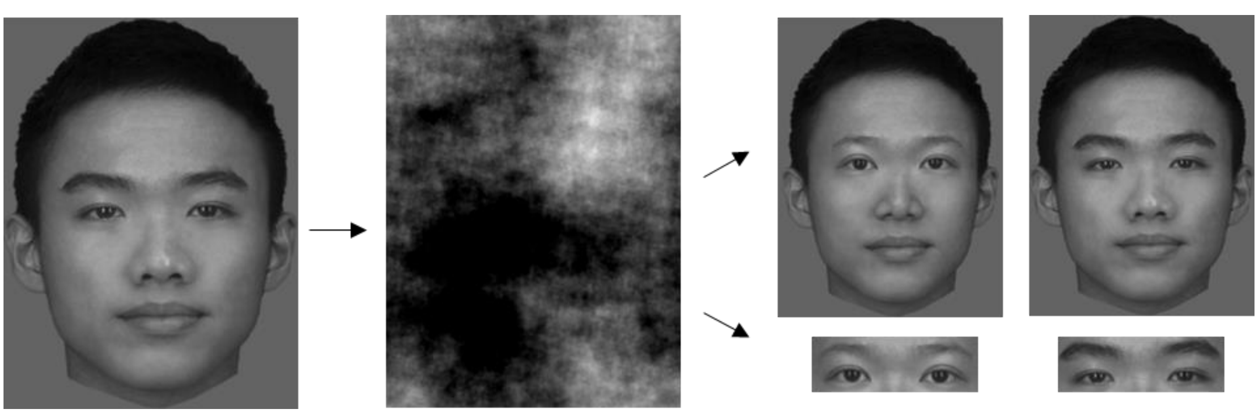
Participants were instructed not to tilt their heads when they see inverted faces. Across all trials, each identity was presented twice – once upright and once inverted.

Part-whole task

Face images for this task were taken from Wong et al. (2021; see also Estudillo et al., 2022) and procedures were similar to those used in Rezlescu et al. (2017) and Estudillo et al. (2022). These images were modified to create new faces with unique combinations of internal features using Photoshop. Target faces were created using either a male or female face template that included the hair and the face outline only. For each (gender) template, six target faces were created by adding internal features such as distinct noses, mouths, and eyes, from six different identities. These six target faces did not share any similar internal features (see Figure 3.2).

Figure 3.2.

An example of the (Asian) stimuli and procedure used in the part-whole task.



Note. A target face is shown on the left-hand side and 4 test stimuli are shown on the right-hand side: the whole condition (top row) and the part condition (bottom row).

Two types of test stimuli were also created. One of this type of test stimuli consisted of isolated features (mouth, nose, or eyes only) taken from the target faces. The other type comprised of full faces ("whole foils") that were created by switching only one of the distinct features of a target face (eyes, nose, or mouth) with that of a different target face. All faces were in grey-scale and embedded in a 370 × 500 px (7.4 × 10 cm) grey background. All isolated features were also cropped similarly (e.g., eyes: 234 × 80 px, 4.68 × 1.6 cm; nose: 97 × 77 px, 1.94 × 1.54 cm; mouth: 138 × 71 px, 2.76 × 1.42 cm) from the original face stimuli and the size was kept constant (i.e., same size as the features in full faces) in the experiment.

In each trial, one target image of a whole face was presented for 1000 ms, followed by a phase-scrambled mask (i.e., Fourier transformed the image and scramble the phase spectrum by multiplying it with a random phase, while maintaining the amplitude spectrum; see Loschky et al., 2007) for 500 ms. The phase-scrambled mask was created using Matlab R2019b (Mathworks, Version 9.7.0.1247435). Two test images were presented side-by-side until the participant responded. The test images were either two whole faces (whole trials) or two isolated features (e.g., two eyes), one from each face (part trials). Participants had to indicate which of the test stimuli matched the target, by pressing one of two allocated keys. There were 144 trials (e.g., 2 conditions × 24 per feature), with an equal number of male and female targets, presented in a randomized order.

Face Composite Task

All stimuli were obtained from the Chicago Face Database (Ma et al., 2015). Composite stimuli (for each race) were made from the faces of 8 identities (4 females). All face images were in grey-scale with neutral expressions. Composite faces have their top and bottom halves separated horizontally by a white gap of five pixels. Of the 4 composites ("aligned composites"), one of them had a combination of the same identity for the top and bottom halves. The other three were a combination of the top half of one identity with the bottom half of one of the other remaining identities, chosen to match them for gender and face width as closely as possible. These composites were duplicated to create “misaligned composites” where the bottom half of the composite was translated to the right by 25% of its width. These aligned and misaligned composites were used as “target” stimuli.

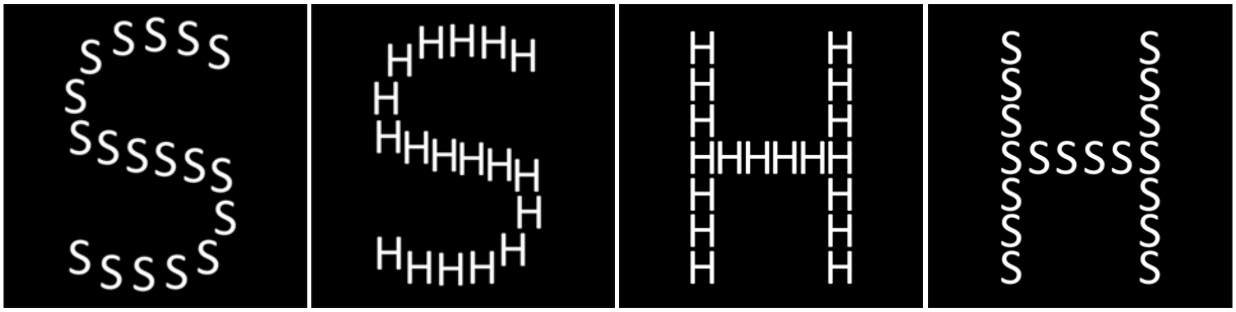
The bottom halves were always different between the two composites, while the top halves were the same in half of the trials and different in the remaining trials. Participants were asked to ignore the bottom halves and decide whether the top halves of the two composites are the same or different. The participants were required to press ‘Q’ for same and ‘P’ for different. The procedure for this task was adopted from Susilo et al. (2013). The test had 120 randomized trials (40 same-aligned, 40 same-misaligned, 20 different-aligned, 20 different-misaligned). Each trial begins with a fixation cross (1000 ms), followed by two composite faces that were presented sequentially (e.g., the first composite for 200 ms and the second composite for 200 ms) and that was separated by a grey blank screen for 500 ms. The composite faces presented sequentially were either aligned or misaligned composite faces.

Navon’s task

Participants were presented with large letters, either ‘H’ or ‘S’, that were made of either smaller ‘H’s or ‘S’s. Congruent stimuli had the same alphabetical character for the large and small letters, whereas incongruent stimuli did not (see Figure 3.3). The large letters were 278 × 162 px (5.56 × 3.24 cm) in size, and the small letters were 37 × 22 px (0.74 × 0.44 cm) in size. A fixation cross (22 × 22 px; 0.44 × 0.44 cm) was always presented before showing a Navon stimulus. All stimuli were in white and were centred on a 6 × 6 cm black background.

Figure 3.3.

Examples of the stimuli used in the Navon's task.



Note. (From left to right) S-congruent, S-incongruent, H-congruent, and H-incongruent.

Each participant was presented with four experimental blocks. In two blocks ("A"), participants were required to report the identity of the global letter (e.g., press the key 'H' if the global letter 'H' is presented). In the other two blocks ("B"), they were to report the identity of the local letters. The blocks were always presented in an ABAB order. Participants performed a total of 96 trials across all blocks, where 48 trials consisted of congruent stimuli (e.g., the same identity of local and global letters) and 48 trials consisted of incongruent stimuli. An equal number of stimulus types were presented within each block. Congruent and incongruent trials were randomized within each block. In all blocks, each trial began with a fixation cross presented in the middle of the screen for 1000 ms, followed by the test stimulus shown for 180 ms and a blank screen which remained until a response was recorded. The participants were also required to perform 16 practice trials (equal amount of all 4 trial types) at the beginning of the experiment.

3.5 Data Analysis

Our main measure of recognition abilities for faces and non-face objects were the scores in the CFMTs and the CCMT. The sum of correct responses in the CFMT/CFMT-Chi and the CCMT was recorded and analysed. Any score above 42 (Caucasian in original CFMT) or 39 (Asians in CFMT-Chi) in the CFMT denotes normal FRA, and any score above 40 in the CCMT denotes normal object recognition ability, respectively (Duchaine & Nakayama, 2006; Dennett et al., 2012; McKone et al., 2017). Preliminary analyses were conducted on both sample groups to observe any differences in face and (non-face) object recognition abilities.

Previous studies using the three evaluation tasks here (e.g., CFMT, CFMT-Chi, CCMT) have consistently shown that these measures have high reliabilities (Bowles et al., 2009; McKone et al., 2012b; Murray & Bate, 2020). The reliability of the Navon task (Dale & Arnell, 2013; Hedge et al., 2018) and the global precedence index (Gerlach et al., 2017) were also examined in detail. However, as described by Ramon (2021), reliability should be routinely examined. For this reason, we assessed the reliabilities of our four holistic tasks (face inversion, part-whole, composite face, and Navon's tasks). To test for internal consistency and/or reliability of our tasks, we calculated Guttman's λ_2 and Cronbach's α with the raw scores for each holistic face task, separated by conditions and sample group. The analyses were done using the R package *psych* (Revelle, 2023).

In addition, using Guttman's λ_2, we also calculated the reliability of our tasks in computing holistic advantage using the subtraction (Navon's task) and regression (face inversion, part-whole, and composite face tasks) approach (Malgady & Colon-Malgady, 1991; DeGutis et al., 2013b). We used Guttman's λ_2 due to its robustness in measuring reliability when dealing with measures that includes multiple factors (Callender & Osburn, 1979). Accordingly, traditional calculations of reliabilities (i.e., subtraction) may be problematic as these approaches do not take into consideration the association between constituent variables (Peter et al., 1993). Consequently, we followed the method of calculation in DeGutis et al. (2013b) and Ross et al. (2015), which factors in the association between the conditions within each task.

We ran four different types of main analyses. First, to replicate that our different measures of holistic processing are performed similarly as in other studies, we compared each *condition of interest* (i.e., upright, whole and same-aligned trials in the inversion, part-whole and composite tasks, respectively) to their respective *control conditions* (i.e., inverted, part, same-misaligned trials), irrespective of the groups. Second, we calculated the magnitude of holistic advantage via the regression approach (DeGutis et al., 2013b; Rezlescu et al., 2017), in which the variances of the *control conditions* are regressed from the *condition of interest* to obtain the line of best fit. Using the equation of the line of best fit of the overall scores, each participant's expected score on the condition of interest (i.e., residual scores) was calculated from their performance in the control condition. For the Navon's task, we calculated the global precedence index for correctly responded trials as the standardized mean difference (Cohen's *d*) between RTs of Local congruent and Global congruent trials. Compared to other Navon indexes, this index offers a purer precedence index as it is not confounded with interference effects (for description, see Gerlach & Krumborg, 2014; Gerlach & Starrfelt, 2018b). A higher residual score (for holistic measures) and/or standardized difference (for the Navon's task) represents a stronger holistic advantage. Consequently, we compared the residual scores and standardized differences across both groups using independent *t*-tests to examine if there are any cultural differences in holistic processing.

For the remaining analyses, we used residual scores calculated based on the lines of best fit obtained from each respective group (i.e., group residuals). This was done so to ensure the regression lines were based only on performances within each respective culture, especially since the tasks conducted were different (i.e., race of faces). For our third analysis, we correlated the magnitude of holistic advantage (i.e., residual scores for holistic face measures and effect size for Navon's task) with the participant's respective CFMT scores, as well as with each other.

Fourth, to reveal any factor(s) that emerge from variation in the data and the relationship across the six tasks, we used an Exploratory Factor Analysis (EFA) with a direct Oblimin rotation, using JASP (v0.16.3; JASP Team, 2020). This was because we found moderate to high correlations within each task (i.e., condition of interests and control conditions), but weak associations between tasks (refer below for analyses; see also Boutet et al., 2021 for detailed discussion on factor analysis involving multiple holistic face measures). Based on the overall sample size, the factor loading threshold of .32 was used (Tabachnick & Fidell, 2007). Accordingly, we ran separate EFAs for both groups with the group residuals. However, when examining each culture separately, we used a more conservative loading threshold of .4 since the sample size is reduced (Yong & Pearce, 2013).

We expect the CFMT, FIE and PWE to load onto the same component. Briefly, performances in CFMT and PWE have a common reliance towards face memory (Tanaka & Simonyi, 2016), while the FIE has often been shown to be associated with CFMT and PWE (Rezlescu et al., 2017). In contrast, compared to the other two measures, the CFE has been suggested to reflect a different cognitive process (Boutet et al., 2021; Rezlescu et al., 2017; Wang et al., 2012). Further, CFE and GPE have been demonstrated to rely on selective attention and global interference (Fitousi, 2020; Ventura et al., 2019). Similar to the Navon's tasks, the composite effect has been replicated with word stimuli (Wong et al., 2011) and Chinese characters (Wong et al., 2012). Although this holistic advantage for letters (or words) was found with the PWE in an old study (Reicher, 1969), it was not replicated with the inversion effect (Albonico et al., 2018). Moreover, previous studies also found the Navon's paradigm to augment subsequent performances in the CFE (Gao et al., 2011; Ventura et al., 2021), but not the PWE (Estudillo et al., 2022). Thus, we expect the CFE and Navon's task to load into a second component, which reflects the domain-general attentional processes of holistic processing. Lastly, we expect performances in the Navon's task and CCMT to load onto a third component, reflecting general object recognition processes.

To explore whether the relationship between each of the holistic processing measures and face recognition was comparable across societies, we compared the significant coefficients of correlation (Hinkle et al., 1988). The was done by transforming the Pearson's correlation coefficient values into *z* scores (i.e., Fisher's *z*). The analyses were done using the R package *cocor* (Diedenhofen & Much, 2015).

3.6 Results

First, our initial independent *t*-tests revealed that the FRA of EAs and WCs were comparable, $t(200) = .325$, $p = .746$ (see Figure 3.4). This shows that the FRA are largely similar between the two cultures. However, our analyses revealed that EAs had an overall higher non-face object recognition ability (as measured by CCMT) compared to WCs, $t(200) = 2.728$, $p = .007$. In line with previous studies (Rezlescu et al., 2017), our four holistic measures showed only modest reliability (e.g., .4 to .7; see Table 1).

Table 1.

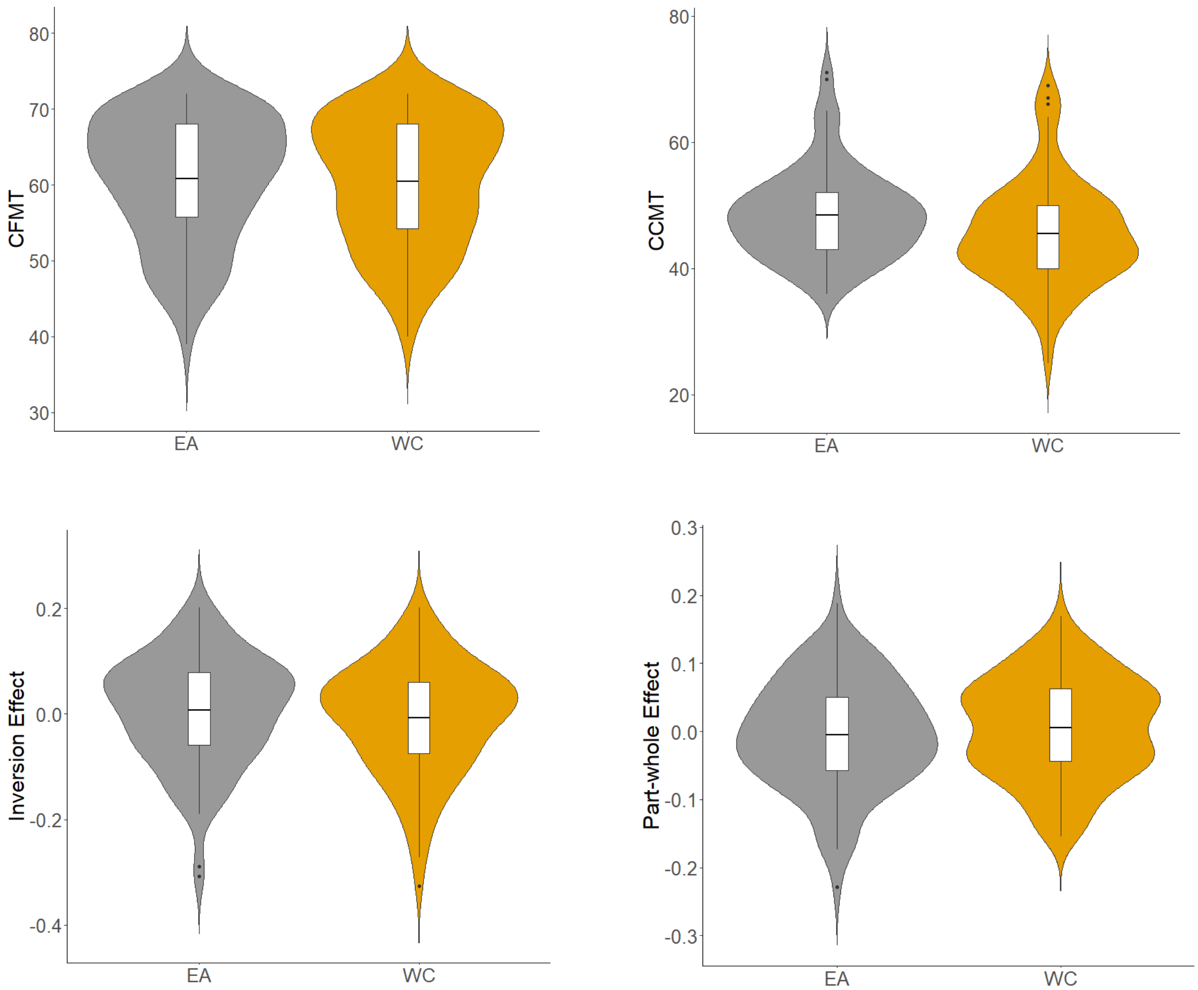
Reliability scores of Western-Caucasians (WCs) and Eastern-Asians (EAs).

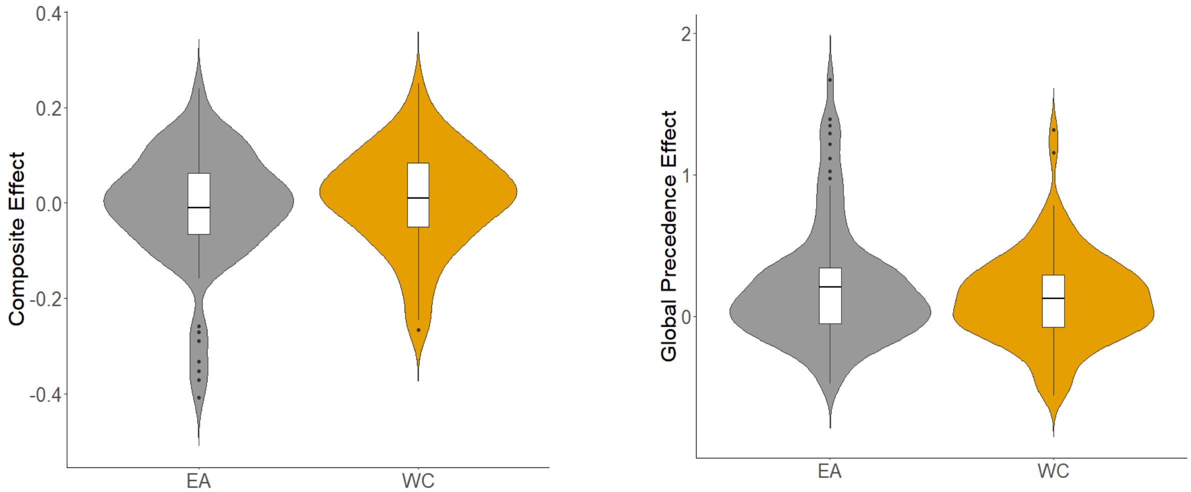
Tasks/Conditions	WCs		EAs	
	Guttman's λ_2	Cronbach's α	Guttman's λ_2	Cronbach's α
Inversion				
Upright	.723	.723	.724	.704
Inverted	.677	.561	.409	.347
FIE residual	.563	-	.674	-
Part-whole				
Whole	.779	.779	.783	.758
Part	.715	.659	.613	.572
PWE residual	.416	-	.681	-
Composite				
Same-Aligned	.834	.834	.866	.868
Same-Misaligned	.820	.820	.873	.834
CFE residual	.442	-	.663	-
Navon				
Global-Congruent	.445	.402	.701	.679
Local-Congruent	.569	.510	.756	.760
GPE subtraction	.469	-	.607	-

Note. *FIE* face inversion effect, *PWE* part-whole effect, *CFE* composite face effect, *GPE* global precedence effect.

Figure 3.4

Mean accuracy (CFMT, CCMT), residuals (FIE, PWE, CFE) and effect size (Navon's task) between EAs (grey) and WCs (orange).





Note. The violin plot represents the density distribution of performance in each group. The horizontal line within the boxplot represents the mean scores, whilst the top and bottom hinge of the boxplot represent the first and third quartiles. The vertical black line outside of each boxplot represents the 95% confidence interval. Black-filled circles represent the accuracy scores of individual participants that are outside the 95% confidence interval.

Face Inversion Task

In general, participants were better with upright (M = .786, SD = .113) compared to inverted (M = .536, SD = .104) trials, $t(201)$ = 29.792, p < .001. This pattern replicates the classic inversion effect reported by previous studies (e.g., Yin, 1969; Rossion, 2008). The group comparison analyses on the residual scores revealed a comparable inversion effect in EAs (M = .008, SD = .102) and WCs (M = -.008, SD = 0.116), $t(200)$ = 1.055, p = .293 (see Figure 3.4). Irrespective of groups, the overall magnitude of the inversion effect was associated with face recognition ability, $r(200)$ = .385, p < .001. Consequently, the magnitude of the inversion effect was also correlated with face recognition ability in both WCs ($r(100)$ = .314, p = .001) and EAs ($r(98)$ = .461, p < .001) sample (see Figure 3.5). The correlation coefficients of the part-whole effect and CFMT were comparable between both groups (z = -1.215, p = .224).

Part-whole task

Irrespective of cultural groups. participants were better with the whole (M = .777, SD = .096) compared to the part (M = .676, SD = .085) trials, $t(201) = 17.393$, $p < .001$. This pattern replicates the classic part-whole effect reported by previous studies (e.g., DeGutis et al., 2013b; Estudillo et al., 2022). The group comparison analyses revealed a comparable part-whole effect in EAs (M = -.005, SD = .080) and WCs (M = .005, SD = .074), $t(200) = -.923$, $p = .357$ (see Figure 3.4). Irrespective of groups, the overall magnitude of the part-whole effect was associated with face recognition ability, $r(200) = .307$, $p < .001$. Consequently, the magnitude of the part-whole effect was correlated with face recognition ability in both WCs ($r(100) = .335$, $p < .001$) and EAs ($r(98) = .281$, $p = .005$) sample (see Figure 3.5). The correlation coefficients of the part-whole effect and CFMT were comparable between both groups ($z = .418$, $p = .676$).

Composite Face Task

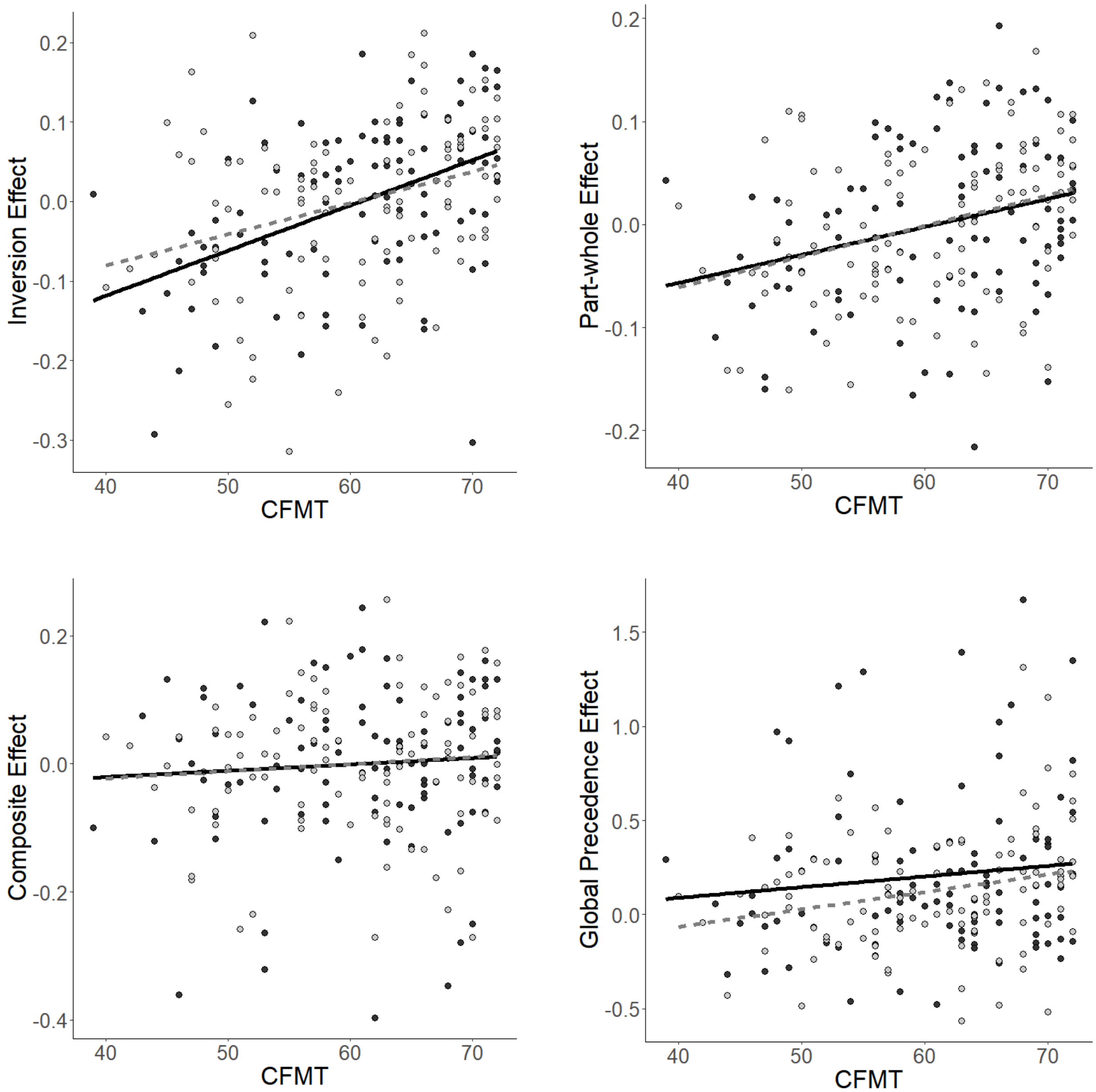
Participants were better with same-misaligned (M = .810, SD = .141) compared to same-aligned (M = .742, SD = .154) trials, $t(201) = 8.232$, $p < .001$. This pattern replicates the classic composite effect reported by previous studies (e.g., Young et al., 1987; Rossion, 2013). The group comparison analyses revealed a comparable composite effect in EAs (M = -.010, SD = .121) and WCs (M = .009, SD = 0.105), $t(200) = -1.206$, $p = .229$ (see Figure 3.4). Irrespective of groups, the overall magnitude of the composite effect was not associated with face recognition ability, $r(200) = .077$, $p = .275$. Consequently, the magnitude of the composite effect was not correlated with face recognition ability in either the WC ($r(100) = .089$, $p = .374$) or the EA ($r(98) = .067$, $p = .505$) sample (see Figure 3.5). The correlation coefficients of the composite effect and CFMT were comparable between both groups ($z = .155$, $p = .438$).

Navon's task

Irrespective of cultural groups, participants were faster with global-congruent (*M* = 479.8 ms, *SD* = 82.4) compared to local-congruent (*M* = 501.6 ms, *SD* = 90.2) trials, $t(201) = -5.592$, $p < .001$. This pattern replicates the classic global precedence effect reported by previous studies (e.g., Estudillo et al., 2022; Navon, 1977). The group comparison analyses revealed a comparable global precedence effect in EAs (*M* = .207, *SD* = .418) and WCs (*M* = .124, *SD* = 0.320), $t(200) = 1.590$, $p = .113$ (see Figure 3.4). Irrespective of groups, the overall magnitude of the global precedence effect was associated with face recognition ability, $r(200) = .168$, $p = .017$. The magnitude of the global precedence effect was correlated with face recognition ability in WCs ($r(100) = .239$, $p = .015$), but not EAs ($r(98) = .112$, $p = .267$) (see Figure 3.5). The correlation coefficients of the global precedence effect and CFMT were comparable between both groups ($z = .919$, $p = .358$).

Figure 3.5

Correlation plots of holistic advantage and face recognition abilities of both Western (grey) and Eastern (black) societies.



Note. The grey annulus and black dots represent individual residuals of Western Caucasians (WCs) and Eastern Asians (EAs), respectively. Grey dashed and black solid lines are least-squares regression fits to individual data of WCs and EAs, respectively.

Exploratory Factor Analysis (EFA)

A summary of the correlation matrix is shown in Table 2. The Kaiser–Meyer–Olkin Measure of Sampling Adequacy (KMO) of the overall scores was .599, above the suggested cut-off value of .50 (Boutet et al., 2021). Bartlett's test of sphericity was significant, $\chi^2(15) = 73.019$, $p < .001$, supporting that our data can be reduced to underlying factors. The exploratory factor analyses identified one main component (i.e., holistic face processing; *HF*) from the scree plot of our six measures that explained the total variance of 18.0% for all participants. This is consistent with past research using factor analysis with multiple face processing tasks (Boutet et al., 2021; McCaffery et al., 2018; Verhallen et al., 2017). When the cultural groups were examined separately, KMO were .527 for WC and .592 for EA. Bartlett's tests of sphericity were also significant for WCs ($\chi^2(15) = 38.465$, $p < .001$) and EAs ($\chi^2(15) = 47.463$, $p < .001$). Similarly, one component was also identified from the scree plot that explained a total variance of 16.9% in WCs, and 20.0% in EAs. The performance loadings, rotated eigenvalues, and the proportion of variance explained are shown in Table 3.

Table 2.

Pearson's correlation analyses between CFMT, CFPT and the four holistic measures of all participants (both EAs and WCs).

Measures	CFMT	CCMT	FIE	PWE	CFE	GPE
CFMT						
CCMT	.130					
FIE	.385***	.114				
PWE	.307***	.081	.193*			

CFE	.077	.066	.012	-.117		
GPE	.168*	.034	.090	.101	-.084	

Note. Values represent the coefficient from overall scores (*N* = 202). Coefficients highlighted in grey represent correlations significant at the level of *p <. 05, **p <.01, or ***p< .001.

The component *HF* was able to explain a modest portion of the variance and loaded strongly on the CFMT, the inversion, and part-whole tasks, but not on the CFE, the CCMT and the Navon's task. The results indicate that the CFMT, FIE, and PWE measure an overlapping mechanism that is distinct from CFE. Factor analysis separated by culture revealed that WCs' performance in the CFMT, the FIE and PWE loaded into *HF*. However, only the CFMT and FIE loaded into *HF* for EAs. This suggest that there are both overlapping and distinct mechanisms of holistic face processing, but they are different across cultures.

Table 3.

Results from the principal component analysis (loading matrix and variance explained).

Measures	**Component *HF***		
	Both	WCs	EAs
CFMT	.769	.726	.823
CCMT			
FIE	.498	.408	.586
PWE	.400	.462	
CFE			
GPE			

Eigenvalues	**1.08**	**1.02**	**1.20**
Variance explained (%)	***18.0***	***16.9***	***20.0***

Note. Only values above the threshold following the rotation are shown. *CFMT* Cambridge face memory test, *CCMT* Cambridge car memory test, *FIE* face inversion effect, *PWE* part-whole effect, *CFE* composite face effect, *GPE* global precedence effect.

3.7 Discussion

The aim of this study was to investigate whether individual differences in face recognition abilities can be explained by holistic processing mechanisms, and if this relationship is modulated by culture. Irrespective of the groups, participants replicated previous effects with the inversion, part-whole, composite and Navon's tasks (Hole, 1994; Rossion, 2008, 2013; Tanaka & Farah, 1993; Tanaka & Simonyi, 2016; Yin, 1969; Navon, 1977). In line with previous literature, we also found positive associations between the overall inversion, part-whole (Belanova et al., 2021; DeGutis et al., 2013b; Wang et al., 2012; Rezlescu et al., 2017), and global precedence effect (Gerlach & Starrfelt, 2018b) with FRA.

For the group comparisons, both societies presented comparable susceptibilities to the inversion, part-whole, composite and Navon's effects. In other words, both EAs and WCs utilised similar underlying cognitive mechanisms of holistic processing during face and non-face object recognition. Furthermore, we found that face recognition abilities (FRAs) were associated with holistic face processing similarly in both cultures across different measures. Specifically, both cultures' FRAs were positively correlated with FIE and PWE, but not CFE. Nonetheless, we found that the GPE was associated with FRAs only in WCs, but not EAs. This suggests that delayed global processing of non-face objects might contribute to poor face recognition in WCs, but not EAs. One possible explanation for this is that WCs who are better at face recognition are also better at general global processing. In contrast, EAs have a general bias in global processing independent of their face recognition ability.

Notably, we found that the CFE was not correlated with face identification (i.e., CFMT) across both cultures, as well as when analysing both groups together, replicating previous findings (Konar et al., 2010; Verhallen et al., 2017). Furthermore, we also found that the CFE did not load onto the same component as FRA, suggesting that the CFE measures an aspect of holistic processing that does not reflect individual differences in face recognition. For instance, the CFE may tap into other cognitive mechanisms that involve general perceptual abilities (e.g., working memory; Fitousi, 2015), as opposed to those in the part-whole and inversion effect, or even with the *complete* version of the composite task (Boutet et al., 2021; Richler & Gauthier, 2014). In fact, the standard CFE that we used has been shown to measure distinct underlying constructs than those in the complete version (Richler & Gauthier, 2014). Nonetheless, Verhallen et al. (2017) found that holistic processing, as indexed with the complete version of the composite task, was not associated with FRA. Although additional analyses by Verhallen et al. using *d*-prime and/or the raw accuracy scores indicate a strong association between complete CFE and CFMT, arguing that the complete CFE does indeed tap into a common mechanism measured by CFMT, this association is dependent on how the CFE is calculated. In general, we argue that the standard CFE may reflect other aspects of holistic processing that are not strongly associated with individual differences in face processing *per se*.

In line with our predictions, the overall scores on the CFMT, FIE, and PWE loaded onto the first major component, revealing a specific factor underlying FRAs in these three tasks. Similar to Boutet et al. (2021), both the CFE and PWE did not load onto the same component, suggesting that they are measuring distinct underlying cognitive mechanisms of holistic processing in face recognition. As mentioned, Verhallen et al. (2017), using principal component analysis found that holistic processing, as measured by the CFE, did not load onto *f*. In consideration of both our current and Boutet et al.'s findings, it is possible that *f* explains the variance from only parts of face processing that are not reflected by the CFE. For instance, all the face perceptual and/or recognition tasks in Verhallen et al.'s study have a common requirement to integrate facial features across space, while the CFE reflects the inability to suppress the integration process (i.e., interference). As shown by Boutet et al., the FIE, PWE, and CFE tap into distinct cognitive mechanisms, arguing that there are multiple sub-components in holistic processing.

The notion that the inversion, the part-whole and the composite tasks are tapping into distinct cognitive mechanisms is not surprising, given that there are notable differences between these tasks (Boutet et al., 2021; Li et al., 2017, 2019; Rezlescu et al., 2017). For instance, the CFE is based on the magnitude of holistic interference, reflected by the failure to selectively attend to the top half of the face (Richler & Gauthier, 2014). While the PWE is generally demonstrated by the magnitude of facilitation in encoding and/or integration of featural information into a whole (Rezlescu et al., 2017). Conversely, FIE was thought to be an index for the sensitivity towards facial configuration (Rossion, 2008; Carbon & Leder, 2005). For example, configural manipulations impaired the recognition of upright faces more strongly than inverted faces (Carbon & Leder, 2005). Furthermore, inverting faces also significantly affects the magnitude of both the part-whole and composite effects (McKone et al., 2013). This argues that the FIE is tapping into an overlapping mechanism that encompasses all three mechanisms (Boutet et al., 2021; Gerlach & Mogensen, 2023). While the FIE, PWE, and CFE are related to holistic processing in face recognition, they measure different aspects of this phenomenon and contribute to FRA in distinct ways.

More recently, principal component analysis by Bobak et al. (2023) found two main components, reflecting response strategies of “confirmation” and “elimination”, from different measures of face recognition and perception ability. They found that in these tasks, accuracy from trials in which a target face matched a face they learnt (i.e., from memory) or viewed simultaneously loaded strongly on the confirmation component. Accuracy from trials in which a target face did not match what they learnt or viewed simultaneously loaded heavily on the elimination component. They proposed that both components are tapping into different cognitive sub-processes of face recognition. In brief, the confirmation component represents ‘match’ trials (i.e., discriminating between similar faces), whereas the elimination component represents ‘mismatch’ trials (i.e., discriminating between dissimilar faces). Importantly, Bobak et al. (2023) found that the CFMT+ (Russell et al., 2009), which is akin to our CFMT task, loaded strongly onto the first component. Accordingly, our component *HF* may instead reflect strategies and/or biases of “confirmation”, because target faces are always present in every trial (that also matches the learnt face) of these three tasks (e.g., CFMT, part-whole, and inversion tasks) that we used. Here, participants were always required to ‘confirm’ which is the target face among an array of faces. In contrast, the standard composite task used in our study, which consists of non-match faces and target-absent trials, may also load onto the elimination component (Bobak et al., 2023). In the standard composite task, the irrelevant (bottom) face parts are always different, and the target (top) halves were either same or different. This means that half the trials in the composite tasks may load onto the confirmation component, and another half of the trials may load onto the elimination component. We are unable to examine this directly in the current study as all the trials in the CFMT, FIE, and PWE are target-present, while all the trials in the CFE consist of both target-present and absent elements. It is thus not possible to examine the trials within each task separately. In short, based on these findings by Bobak et al. (2023), it is possible that *HF* reflects the confirmation component.

In addition, the overall loading pattern from our factor analysis was replicated for WCs but not EAs. Specifically, the PWE did not load into *HF* for EAs. In line with previous literature involving face processing (Miyamoto et al., 2011; Tardif et al., 2017), our results suggest cultural differences in holistic face processing. These findings argue that the underlying cognitive mechanisms of holistic processing during face recognition are not *universal* – wherein the underlying mechanisms are influenced by cultural factors. These observed cultural differences might be the consequence of how distinct cultures spread their attention during face recognition (see review by Blais et al., 2021). In consideration of neural findings that showed a cultural bias in holistic and featural processing between EAs and WCs (Wang et al., 2020), our findings suggest that there are multiple ways that holistic representation can be formed. For instance, the initial extraction of holistic information by EAs allows them to form a stable face template, which facilitates later featural embedding processes (i.e., featural processing). On the contrary, WCs' initial extraction of featural information allows subsequent integration of these individual features into a unitary whole (i.e., holistic processing). First, this theory is in line with the notion that there are different cognitive mechanisms underlying holistic processing. Most importantly, this concept would also explain why there are cultural differences in eye-gaze behaviour (Blais et al., 2008; Kelly et al., 2010) and spatial frequency processing (Tardif et al., 2017) of faces, at the same time, not undermining the importance of holistic processing in face recognition (Richler et al., 2012; Rossion, 2013) and own-race advantage (Zhao & Bentin, 2008, 2011). Nevertheless, more cross-cultural research involving these three holistic measures is required to test such assumptions.

While our factor analyses revealed culture-specific holistic mechanisms underlying FRA, the strength of correlations between FRA and the three holistic measures was comparable between EAs and WCs. Thus, how can WCs and EAs rely on similar holistic mechanisms while using different strategies of visual sampling (Blais et al., 2008; Kelly et al., 2010)? A past study found that WCs and EAs could switch their sampling strategies when their fixations are constrained by an aperture (Caldara et al., 2010). Caldara et al. (2010) showed that when EA observers' fixations are constrained with a gaze-contingent aperture, they were able to switch their default fixation strategy (e.g., central processing of the nose) to those of WCs (e.g., more fixations near the eyes and mouth). Consequently, we suggest that different cultures can also use multiple distinct holistic processing strategies, as reflected by different holistic indexes, and can flexibly switch among these strategies. For instance, when learning and recognising a face, observers may utilise a "default" holistic strategy, possibly due to the consequence of cultural influences. However, when their default strategy is hindered, they can flexibly switch to other holistic sampling strategies based on the task constraints (e.g., integrating features into a whole and/or embedding features onto a face template). Overall, our factor analyses were able to provide novel implications on the relationship between face recognition ability and cognitive mechanisms underlying holistic processing.

Alternatively, despite some evidence showing that different information sampling can lead to the extraction of different information, not many studies have related them to the "availability" of such information. In the framework presented by Blais et al. (2021), the *available* facial information between different ethnicities may differ, leading to different sampling and/or representations by participants. Although it has often been assumed that both EA and WC faces are similar in overall configuration, they argued that it is possible that there are different levels of heterogeneity of local features. For instance, faces from one society may have more varieties of eye-colour, while faces from the other society have more varieties of nose shapes (Blais et al., 2021). Consequently, if WCs' faces have more varieties of eye colour than EAs, extracting facial information from the eyes in WCs would be more diagnostic for identification. As mentioned above, higher exposure to own-race faces influences the development of face processing strategies (Bate et al., 2019a, DeGutis et al., 2013a). Hence, such differences in facial features might affect the tuning of spatial frequencies seen in previous studies (Estéphan et al., 2018; Tardif et al., 2017). More specifically, EAs are tuned to processing lower spatial frequency information because EA faces have more available lower spatial frequency content. As far as we know, it is still unclear to what extent the race of faces and the type of available information affects face processing strategies.

Nonetheless, the current study is not without limitations. Specifically, our factor analysis revealed that *HF* did not account for a large portion of the variance (~17% to 20%), even when the data was separated by cultures. This was expected, given that our measures have low test reliabilities (Rezlescu et al., 2017). Further, we only included one principal measure of face recognition (i.e., CFMT). For instance, even when previous studies included a number of principal measures of face processing: multiple face recognition and face perception tasks (Verhallen et al., 2017), familiar and unfamiliar face recognition tasks (McCaffery et al., 2018), or multiple measures of holistic face processing (Boutet et al., 2021), the common factor found could best account for only approximately 23%, 25% and 20% of the variance, respectively (but see Bobak et al., 2023). If holistic processing is a product of multiple underlying mechanisms, it would make sense to have only a small portion explained by a common structure between holistic processing and FRA. Additionally, we also did not include a measure of other high-level processes, e.g., featural processing, in the current factor analysis. Although holistic processing has been argued to be the “backbone” of FRA, recent studies found that featural processing is also important (Belanova et al., 2021; DeGutis et al., 2013b; Dunn et al., 2022; Tsantani et al., 2020). This would explain why the common factor(s) underlying face processing found across studies have consistently accounted for only a small portion of the variance.

Lastly, although the Caucasian and Asian faces used in our face recognition tasks were obtained from similar databases and manipulated in a similar manner, the set of faces could differ in terms of within-database variability. For instance, it is possible that the set of faces from one race has less variability, which makes distinguishing between faces more difficult. While we acknowledge that this as a limitation in cross-cultural studies, we found comparable performances in face recognition (CFMT) and holistic face processing (face inversion, part-whole, composite face tasks) across Eastern and Western cultures.

3.8 Future Directions: Multiple Holistic Mechanisms of Face Processing

The current study posited that the three traditional measures of holistic processing (e.g., the inversion, part-whole and composite tasks) are measuring different underlying mechanisms, providing possible explanations on why there have been inconsistent findings concerning individual differences in face recognition ability and holistic processing. We suggest that this rationale may also extend to mixed findings observed at the extreme ends of the FRA spectrum – individuals with developmental and acquired prosopagnosia (DP and AP respectively). For instance, some studies found individuals with DP (Avidan et al., 2011; DeGutis et al., 2012; Liu

& Behrmann, 2014; Susilo & Duchaine, 2013) or AP (Busigny et al., 2010, 2014; Busigny & Rossion, 2011; Rezlescu et al., 2012) to have impaired holistic processing, while other studies did not (DP: Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017; AP: Finzi et al., 2016; Rezlescu et al., 2012). In short, it is possible that the mixed findings regarding holistic deficits in prosopagnosia are due to the assumption that there is a single common cognitive mechanism underlying holistic processing. To our knowledge, studies have yet to examine prosopagnosics with all three traditional holistic measures, particularly at an individual level. Thus, using a similar methodology, the subsequent chapter aims to investigate whether holistic processing is impaired for individuals with face recognition deficits.

In conclusion, our findings suggest that holistic processing facilitates face recognition ability similarly across different cultures. We also provide further criticism for the composite effect as a measure of holistic face processing. Moreover, we propose that there is a general construct underlying face recognition ability, specifically involving multiple mechanisms of holistic processing. However, this general construct seems to be influenced by culture, wherein the cognitive mechanisms underlying individual differences in face recognition and holistic processing are *not* universal. Finally, we speculate that different cultures may have distinct preferences for processing faces holistically, in which they can flexibly switch from one to another based on task constraints.

CHAPTER 4: The Heterogeneity of Holistic Processing Profiles in Prosopagnosia

4.1 Holistic Processing and Developmental Prosopagnosia

Despite face processing being ordinary during human interactions, there are individuals who suffer a lifelong neurodevelopmental condition with severe deficits in face recognition – Developmental Prosopagnosia (DP; Duchaine & Nakayama, 2006). Developmental Prosopagnosics (DPs) fail to develop face recognition skills despite having normal intelligence, vision, and memory, along with no obvious brain damage (Cook & Biotti, 2016; Susilo & Duchaine, 2013). Many studies have proposed that face processing impairments in DPs extend from personally familiar faces, such as family members and close friends, to their own faces (Bowles et al., 2009; Kennerknecht et al., 2006, 2008). Nonetheless, there has been development of treatments that specifically emphasize on compensatory strategies and cognitive training in DPs (Bate & Bennetts, 2014; Bate et al., 2015, 2022; Corrow et al., 2019; DeGutis et al., 2014a, 2014b). In addition, people with DP are more likely to suffer social and psychological dysfunctions, including increased levels of anxiety in social situations, depression, lack of interest in social activities, and difficulties creating and maintaining personal relationships (Yardley et al., 2008).

It has often been proposed that holistic processing is necessary for face recognition, which has been classically captured with three traditional measures: the face inversion effect (FIE), the part-whole effect (PWE), and the composite face effect (CFE) (see Chapter 2 for detailed description). If holistic processing is critical and sufficient for face recognition, one would expect to see holistic processing impairments in DPs (e.g., Avidan et al., 2011; DeGutis et al., 2012; Esins et al., 2016; Liu & Behrmann, 2014; Palermo et al., 2011; Susilo & Duchaine, 2013; Towler et al., 2018). Consistent with this interpretation, a single-case study by Avidan et al. (2011) showed no inversion and composite effects in a DP patient, suggesting impairments in holistic processing. Similarly, a different study using the part-whole task showed holistic processing impairments in DPs (DeGutis et al., 2012). However, impaired holistic processing, as measured with the PWE, was only evident when DPs processed the eyes but not for mouth regions. This suggests that holistic processing is impaired but not completely absent in DPs (DeGutis et al., 2012). Other research has shown that the holistic processing deficits in DPs also extend to non-face objects (Bentin et al., 2007; Gerlach et al., 2017; Gerlach & Starrfelt, 2018a, 2021; but see Bennetts et al., 2022; Duchaine et al., 2007b), such as recognition of Navon compound stimuli (e.g., a global H formed with local S, see Navon, 1977). For instance, Gerlach et al. (2017) found that DPs were not only slower in the processing of global letters, but also showed a diminished global precedence effect (GPE) (i.e., more reliance on featural processing). Their findings suggest that holistic deficits seen in DPs may be extended to several object categories (i.e., not face-specific) (for evidence regarding individual differences in face and object recognition, see Gerlach & Starrfelt, 2018a).

However, other studies have reported normal holistic processing in DPs (Bennetts et al., 2022; Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017). For example, Susilo and colleagues (2010) presented the case of a DP, who despite being severely impaired in face recognition, presented normal composite and inversion effects. Similarly, Le Grand et al. (2006) found that seven out of eight of their DPs showed typical CFE, suggesting some individual differences in holistic processing among DPs. More recently, Biotti et al. (2017) also found normal holistic processing in a large group of DPs compared to NTs, as measured with the composite task. Consequently, their results suggest that the recognition deficit in DPs might lie elsewhere on the face processing stream that is not tapped by the CFE (Biotti et al., 2017). In addition, some studies also showed that DPs performed worse than controls in the misaligned condition of the CFE (Liu & Behrmann, 2014) and inverted conditions of the FIE (Bennetts et al., 2022), suggesting that DPs' deficit in face recognition are the consequence of impaired featural processing, rather than holistic processing. In general, the findings regarding holistic processing and face recognition ability have been rather mixed, especially involving individuals with face recognition deficits.

4.2 Underlying Mechanism(s) of Holistic Processing Measures

Given these mixed findings, whether DP can be explained by a deficit in holistic processing is still an open question. One major weakness of studies that have attempted to address this question in the past is the assumption that the three traditional measures of holistic processing (i.e., inversion, part-whole and composite effects) reflect the same underlying cognitive mechanism(s). This assumption is based on two indirect findings: (1) these effects start to develop in early infancy and reach their peak around the same age (e.g., three to five years; McKone et al., 2012a), and (2) these effects are consistently more prominent for faces than other non-face objects (McKone & Robbins, 2011). However, the assumption that these three effects are measuring the same cognitive process has rarely been tested directly (McKone et al., 2007; Piepers & Robbins, 2012).

In fact, recent evidence points out that these measures might reflect different cognitive mechanisms. For example, in a recent study, Rezlescu et al. (2017) found that the FIE and the PWE were only weakly correlated with each other, and the CFE did not correlate with either of those two (see also Lee et al., 2022a; Wang et al., 2012). These findings suggest that there may not be a common mechanism explaining the three putative effects of holistic processing (see review by Boutet et al., 2021). Furthermore, they also found that each of the three measures had a varying relationship with face identification, as measured with the Cambridge Face Perception Test (CFPT; Duchaine et al., 2007a). Specifically, while the inversion and the part-whole effects were moderately correlated with face identification, the composite effect was not. This suggests that the different measures of holistic processing might contribute differently to the wide range of individual differences seen in face identification. This notion is further evident in Chapter 3, where the findings showed that the three holistic measures had varying association with CFMT and there is no single factor explaining all three effects. Consequently, impaired holistic processing indexed with these traditional holistic measures may also be dissociable between different DPs (Biotti et al., 2017). Even though these three holistic effects share a common characteristic in which they rely on a difference in performance between a condition in which a complete, intact, and upright face is present and a condition in which the holistic representation of faces is inhibited (Maurer et al., 2002; McKone & Yovel, 2009; Richler et al., 2011a). However, as argued by Boutet et al. (2021), commonality among these measures (if any) may not always be driven by holistic processing *per se*, but instead by other cognitive processes depending on task demands. For instance, the PWE and CFE may share a common reliance towards the processing of individual features.

The fact that the inversion, the part-whole and the composite tasks reflect different cognitive mechanisms is perhaps unsurprising, as there are notable differences between these tasks (Boutet et al., 2021; Li et al., 2017, 2019; Rezlescu et al., 2017). For example, in the part-whole task, holistic processing is generally demonstrated by the magnitude of facilitation in encoding and/or integration of featural information into a whole (Rezlescu et al., 2017). However, in the composite task, holistic advantage is based on the magnitude of holistic interference, reflected by the failure to selectively attend to the top half of the face (Richler & Gauthier, 2014). Neural studies have also shown differences in the activation patterns of the face fusiform area (FFA) between the two tasks. For instance, Li et al. (2017) found that the FFA is activated for PWE and suppressed for the CFE. On the contrary, holistic processing measured by the inversion task was thought to be an index for the sensitivity towards facial configuration (Rossion, 2008; Carbon & Leder, 2005). For example, configural manipulations impaired the recognition of upright faces more strongly than inverted faces (Carbon & Leder, 2005). Additionally, McKone et al. (2013) demonstrated that inverting faces also significantly affects the magnitude of both the part-whole and composite effects. This argues that the FIE is tapping into an overlapping mechanism that encompasses all three effects (Boutet et al., 2021; Gerlach & Mogensen, 2023). In other words, holistic processing measured with FIE is thought to involve in the interplay of part-whole integration, composite interference, and sensitivity to facial configuration.

Additionally, the performance in these three tasks also stresses on different cognitive abilities, such as reliance on working memory and selective attention (Fitousi, 2015, 2020; Rezlescu et al., 2017; Tanaka & Simonyi, 2016). For instance, target faces are repeatedly presented in the part-whole task. However, target faces are always different in the composite task, wherein the faces always consist of different distractor bottom halves. In contrast, while the target faces are also repeatedly presented in the inversion task, the target faces in any trial of the inversion task are also repeated as distractors in other trials. Moreover, participants may also depend on distinct decision strategies for each holistic task (Bobak et al., 2023; Rezlescu et al., 2017). For example, participants must make a single same/different judgement on whether the two faces presented consecutively had the same top halves in the composite task, while the part-whole task requires participants to distinguish the target face from one distractor face. In the inversion task, the target face is always presented among two other distractor faces. Consequently, target faces are always present in the part-whole and inversion tasks but may be absent in the composite task (for further discussion, see Bobak et al., 2023). Overall, these studies suggest that there may not be a common holistic mechanism explaining the three putative effects of holistic processing (Boutet et al., 2021; Rezlescu et al., 2017).

4.3 Experiment 1: Developmental Prosopagnosia

The findings reported above lead to three possibilities. First, not all holistic face tasks are measuring the same aspect of holistic processing (i.e., underlying cognitive mechanism) and, therefore, all DPs may be impaired in some but not other aspects of holistic processing (e.g., all DPs may show relatively reduced susceptibility towards the PWE but not the composite or inversion effects). We call this account the *universal holistic processing deficit hypothesis*. Second, different DPs may present qualitatively different holistic processing impairments (e.g., case A might show reduced susceptibility to the PWE, while case B may present reduced susceptibility to the CFE). We call this the *heterogeneous holistic processing deficit hypothesis*. Third, DPs deficits in face identification might not be explained by holistic processing impairments. To explore the first and third possibilities, this study employed the three gold-standard measures of holistic face processing on the same group of DPs and compared their performance with those of the NTs control group. In addition, to examine potential holistic processing deficits for non-face stimuli, our participants also performed a Navon task. To explore the second possibility, besides classical group-level comparisons between DPs and a group of NTs, we compared each DP's performance individually to their corresponding age-matched NT group. This was done so because the heterogeneity (if any) amongst DPs might be masked by group comparisons (Bennetts et al., 2022). Consequently, this approach could provide further insight into whether the holistic deficits are universal or heterogeneous across DPs (Corrow et al., 2016; Le Grand et al., 2006; Susilo & Duchaine, 2013).

4.4 Methods

4.4.1 Participants

All participants were recruited through online social media platforms (i.e., prosopagnosia social support groups) and word of mouth. The initial recruitment of DPs was based on self-reports of their severe difficulties in recognizing faces (Burns et al., 2022) and confirmed by objective measures of face and object identification (hereon referred to as "suspected DPs"). All suspected DPs indicated no previous brain damage and other known neurological or psychiatric disorders. Initially, we recruited 27 Caucasian suspected DPs, but only data from 17 DPs were included in the analysis. Seven of the suspected DPs were excluded as their face recognition abilities score was in the normal range (less than two SD from the mean) in the Cambridge Face Memory Test (CFMT; Duchaine & Nakayama, 2006). In addition, all these suspected DPs performed similarly or better with the recognition of faces than cars (i.e., scores in Cambridge Car Memory Test; CCMT; Dennett et al., 2012), which suggests that their face identification difficulties can be explained by a more general object recognition deficit. Another three suspected DPs did not complete all the tasks in the experiment. Similarly, although we recruited

55 Caucasian NTs based on self-reports, data from 10 NTs were removed from further analysis as their CFMT scores were below the normal range (i.e., less than 42). Thus, our final sample comprised 17 Caucasian DPs (DPs; 4 males) and 45 Caucasian neurotypical control participants (NTs; 21 males). The age of our DPs ranged from 19 to 69 (*M*= 46.88 years, *SD*= 17 years), while NTs were from 20 to 70 (*M*= 46.36 years, *SD*= 17 years).

Participants were included in a lucky draw that gifted every 1 in 10 participants an Amazon eGift card valued at £30, as compensation for their time. A digital informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ250920).

4.4.2 Apparatus

This study was conducted fully online using the experimental platform Testable (www.testable.org; Rezlescu et al., 2020), and all tasks were completed on participants' own computers (laptops or desktops). To minimise possible differences in the visible size of stimuli across different computer screens, participants were required to adjust the length of a yellow line that appeared on their screens to match the width of a debit/credit card they had in possession This allowed Testable to calculate how many screen pixels (px) mapped on to 1 centimetre (cm) and scale all stimuli based on this conversion. Adobe Photoshop CS6 was used to edit stimuli where necessary (refer to Stimuli and Procedure).

4.4.3 Stimuli and Procedure

Each participant was first briefed about the experiment and was informed that they had to complete two different stages: the "evaluation" stage and the "experimental" stage, over two different days (i.e., one stage per day). The “evaluation” stage, which was always completed first, included the CFMT, the CFPT and the CCMT. This was followed by the “experimental” stage, which included the part-whole task, the composite task, the face inversion task and the Navon’s task. The order of the face holistic measures was counterbalanced across all participants. However, the Navon’s task was always completed last as some research has shown that this task could bias subsequent face processing tasks (e.g., Estudillo et al., 2022; Gao et al., 2011; Macrae & Lewis, 2002; Lewis et al., 2009). Accuracy and reaction time (Navon’s task only) were measured and recorded.

4.4.4 Evaluation Stage

This stage is comprised of the basic evaluation tasks for screening DPs: the CFMT, CFPT and CCMT. The CFMT was used as a measure of face recognition abilities, the CFPT was used to examine whether DPs’ impairment is also characterised by a deficit in the mere perception of faces, while the CCMT was to control for potential object recognition deficits in DPs.

Cambridge Face Memory Test (CFMT)

We used the original version of the CFMT (Duchaine & Nakayama, 2006). Stimuli and procedural descriptions of this test are described in Chapter 2 (p. 59 – 61).

Cambridge Face Perception Test (CFPT)

The CFPT (Duchaine et al., 2007a) is a computerized sorting task in which participants arrange six morphed images (i.e., test faces) based on their similarity to a target face, taken from Rezlescu et al. (2017). A total of eight male faces were used. The target faces were presented in ¾ profile views. On the other hand, “test” faces were morphs of the target faces (i.e., target faces morphed with a different identity), whereby any single target face in its frontal view was morphed with one of the other targets, also in their frontal view. The morphed images contained 88%, 76%, 64%, 52%, 40%, and 28% of the target face. In all faces, the individual wore a black seamed cap to cover up external features such as hair and ears. The faces were cropped similarly (e.g., from above the eyebrows) and embedded on a 190 x 190 px grey (e.g., morphed faces) and white (e.g., target faces) background.

Eight different *sort* trials were created, and each sort was presented once in upright and once in inverted orientation (N = 16 trials). Participants reordered the test faces (e.g., select a test face and then click on the column they want it to be repositioned) in terms of resemblance to a target face (e.g., most similar at the very left to least similar at the very right). Participants had one minute to complete each sorting trial. Scores for each item were computed by summing the deviations (i.e., errors) from the correct position for each face. For example, if a face was one position away from its correct position, that was counted as an error of one. If it were two positions away, that would be an error of two. Thus, a higher score in the CFPT represents poorer performance. Scores for the eight upright items and the eight inverted items were averaged. Performance at chance in the CFPT is 93.3 errors (Duchaine et al., 2007a).

Cambridge Car Memory Test (CCMT)

We used the original Cambridge Car Memory Test (Dennett et al., 2012). Stimuli and procedural descriptions of this test are described in Chapter 3 (refer to p. 99).

4.4.5 Experimental Stage

Face Inversion Task (adapted from Rezlescu et al., 2012)

A total of 30 male face identities in three different viewpoints (taken from Rezlescu et al., 2012), were used for this task. The face stimuli were all male faces, with their hair completely covered by a standard black cap. This was done to ensure that recognition judgements were based on internal facial features alone. The faces were also in grey-scale and were embedded in a 300 × 300 px (6 × 6 cm) white background.

On any given experimental trial, participants were asked to match one of three test faces (i.e., mid-profile view) with a target face (i.e., frontal view) in terms of identity. The orientation of the target and test faces are always consistent in each trial. Target identities in one trial were also used as test faces (i.e., distractor faces) in other trials that had a different target identity. Participants first saw the target face flashed for 400 ms, followed by three simultaneous test images for 2000 ms, and lastly a blank screen that was presented until the participant responded. Participants were required to press the key “1” if the test face on the left matched the target, “2” for the face in the middle and “3” for the face on the right. The test had a total of 60 trials (30 upright and 30 inverted), presented in a randomised order. Participants were instructed not to tilt their heads when they see inverted faces. Across all trials, each target identity was presented twice – once upright and once inverted.

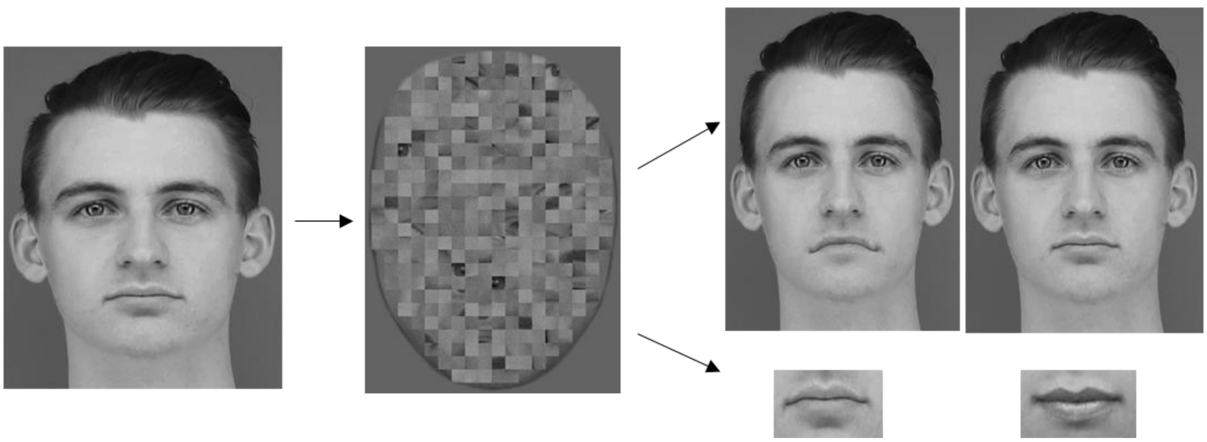
Part-whole task

Face images for this task were taken from Wong et al. (2021; see also Estudillo et al., 2022) and procedures were similar to those used in Rezlescu et al. (2017) and Estudillo et al. (2022). These images were modified to create new faces with unique combinations of internal features using Photoshop (see Chapter 3 for detailed stimuli description).

In each trial, one target image of a whole face was presented for 1000 ms, immediately followed by a mask (i.e., a scrambled face created by randomizing the position of the features of a new face) for 500 ms (see Figure 4.1). Two test images were presented side-by-side until participants responded. The test images were either two whole faces (whole conditions) or two isolated features (e.g., two eyes), one from each face (part conditions). Participants had to indicate which of the test stimuli matched the target, by pressing one of two allocated keys. There were 144 trials: 2 conditions (whole and part) × 3 features (eyes, mouth and nose) × 24 trials per feature. The trials had an equal number of male and female targets presented in a randomised order.

Figure 4.1.

An example of the stimuli used in the part-whole task.



Note. A target face is shown on the left-hand side and 4 test stimuli are shown on the right-hand side: the whole condition (top row) and the part condition (bottom row).

Face Composite Task (adapted from Retter & Rossion, 2015)

Stimuli were obtained from Retter and Rossion (2015) and were made from 15 faces (seven females). All faces were in grayscale with neutral expressions. Composite faces have their top and bottom halves separated horizontally by a white gap of three pixels. The separation between halves is achieved by splitting the face at the bridge of the nose (5% of the length of the face above the nostrils). Initially, five composites were created, where one of them had a combination of the same identity for the top and bottom halves. The other four were a combination of the top half of one identity with the bottom half of one of the other remaining identities, chosen to match for gender and face width as closely as possible. These composites were duplicated to create “misaligned composites” where the bottom half of the composite was translated to the right by 25% of its width. These aligned and misaligned composites were used as “target” stimuli. Composites used as targets (227 × 325 px; 4.54 × 6.5 cm) were enlarged by 5% of their original size to create the “test” stimuli (238 × 350 px; 4.76 × 7 cm) to minimise matching based on low-level features alone (Rossion, 2013).

The bottom halves were always different between the test and target composites, while the top halves were the “same” in half of the trials and “different” in the remaining trials. Participants were asked to ignore the bottom halves and decide whether the top halves of the two composites are the same or different. The participants were required to press the key “Q” for same and “P” for different. The test had 120 randomized trials (40 same-aligned, 40 same-misaligned, 20 different-aligned, 20 different-misaligned). Each trial consisted of two composite faces that were presented sequentially (e.g., the first composite for 400 ms and the second composite for 400 ms) and separated by a grey blank screen for 500 ms. In each trial, both composite faces presented sequentially were either aligned or misaligned. The measurement of the composite effect relies solely on “same” trials as holistic processing makes a clear prediction that “same” responses should be more difficult for aligned than misaligned trials, while the direction for “different” trials is ambiguous (for detailed discussion, see Robbins & McKone, 2007). This is the standard version of the composite task (e.g., Rossion, 2013).

Navon’s task (adapted from Gerlach & Starrfelt, 2018a)

Participants were presented with large letters, either ‘H’ or ‘S’, that were made of either smaller ‘H’s or ‘S’s. The stimuli of this test are similar to the Navon’s task provided in Chapter 3 (refer to p. 103 – 104). Similarly, each participant was presented with four experimental blocks. In two blocks (“A”), the participants were required to report the identity of the global letter (e.g., press the key ‘H’ if the global letter ‘H’ is presented). In the other two blocks (“B”), they were to report the identity of the local letters. The blocks were always presented in an ‘A-B-A-B’ order. However, in this study, we decreased the number of trials to accommodate our DPs. Participants performed a total of 48 trials, where 24 trials consisted of congruent stimuli (e.g., the same identity of local and global letters) and 24 trials consisted of incongruent stimuli. An equal number of stimulus types (global and/or local identity) were presented within each block. Congruent and incongruent trials were randomized within each block. Each trial began with a fixation cross presented in the middle of the screen for 1000 ms, followed by the test stimulus shown for 180 ms and a blank screen which remained until a response was recorded.

4.5 Data Analysis

To test for internal consistency and/or reliability of our tasks, we calculated Guttman’s λ_2 and Cronbach’s α with the raw scores for each task, separated by group (i.e., DP and NT) and conditions. The test reliabilities of these tasks are better described in Chapter 3 which consists of a larger Caucasian sample (N = 102) compared to the current study (N = 45). We separated the data by groups because DPs impairment in face recognition would affect the observed reliability of these tasks. Previous studies that used the three evaluation tasks here (e.g., CFMT, CFPT, CCMT) have consistently shown that they have high reliabilities (Bowles et al., 2009; Dennett et al., 2012; Murray & Bate, 2020; Rezlescu et al., 2017). The reliability of the Navon task (Dale & Arnell, 2013; Hedge et al., 2018) and the global precedence index (Gerlach et al., 2017) has also been examined in detail. However, as described by Ramon (2021), reliability should be routinely examined. For this reason, we assessed the reliabilities of our four holistic tasks (face inversion, part-whole, composite face, and Navon's tasks). The analyses were done using the R package *psych* (Revelle, 2023). Additionally, using Guttman's λ_2, we also calculated the reliability of our tasks in computing holistic advantage using the subtraction (for Navon's task) and regression (for face inversion, part-whole, composite face task) approach (Malgady & Colon-Malgady, 1991), following the method of calculation in DeGutis et al. (2013b). We used Guttman's λ_2 due to its robustness in measuring reliability when dealing with measures that includes multiple factors (Callender & Osburn, 1979).

We ran three types of analyses. First, we wanted to confirm that our different measures of holistic processing performed similarly as in other studies. For this, we compared NTs' performance in each *condition of interest* (i.e., upright, whole and same-aligned trials in the inversion, part-whole and composite tasks, respectively) to their respective *control conditions* (i.e., inverted, part, same-misaligned trials). Second, to examine group differences in holistic processing for each holistic task, we used the control-based regression approach (DeGutis et al., 2013b) in which the variances of the *control conditions* are regressed from the *condition of interest* of the NT group. We only included the data of NTs to ensure that the regression lines were based on normative performances (DeGutis et al., 2012). Then, we applied the *line of best fit* equation to calculate the residuals for each of the DPs, as seen in Equation (1) (Berger et al., 2022). The calculated residual scores of all participants are illustrated in Figure 4.2.

$$\text{residuals} \;=\; \text{condition of interest} - m(\text{control condition}) - c \tag{1}$$

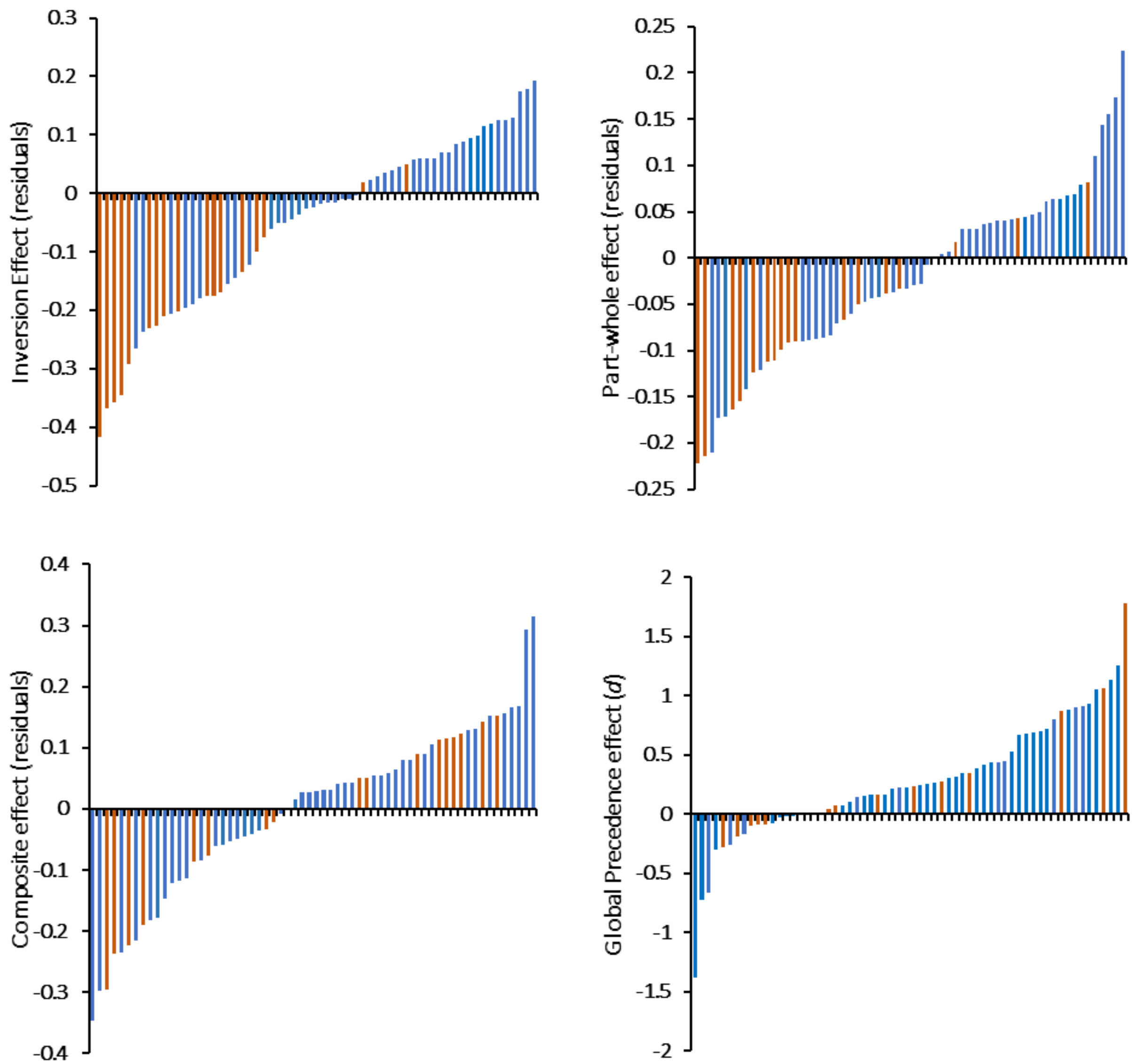
We then compared residual scores across both groups using independent *t*-tests. A higher residual score represents stronger holistic processing.

For the Navon's task, we calculated the global precedence index for correct trials as the standardized mean difference (Cohen's *d*) between RTs of Local congruent and Global congruent trials. Compared to other Navon indexes, this index offers a purer precedence index as it is not confounded with interference effects (for discussion, see Gerlach & Krumborg, 2014; Gerlach & Starrfelt, 2018b). These standardized differences were then compared between DPs and NTs (Gerlach & Krumborg, 2014). A higher standardized difference represents a stronger holistic advantage.

Moreover, we also examined whether holistic processing deficits in DPs (if any) are universal or *heterogeneous* across different DPs (e.g., case A is only impaired in the inversion task, but case B is impaired only in the part-whole task) for our third analysis. To explore this, we first separated DPs and NTs into three different age groups: 18 to 35 years old, 36 to 59 years old, and 60 years and above. The mean age of NTs for each group was 25.1 (*SD* = 5 years), 48.6 (*SD* = 6 years) and 65.4 years (*SD* = 3 years), respectively. The selection of these groups was based on previous research suggesting that face recognition ability and/or holistic processing peaks at the age of 35, remains stable and/or declines from 36 years onwards, and falls below the initial threshold after 60 years old (Boutet & Meinhardt-Injac, 2021; Germine et al., 2011; Jaworska et al., 2020; Meinhardt et al., 2016; Staudinger et al., 2011). Then, we calculated the holistic face advantage using the regression approach for all participants in each of the three age groups, separately. As for the Navon's task, the effect size was calculated similarly as previously specified. Lastly, we ran modified *t*-tests designed for single-case analyses (Crawford & Garthwaite, 2002) with the residual scores (e.g., inversion, part-whole and composite effects) and effect size (Navon's task) between each DP's performance and their age-matched NT group (N = 15), respectively.

Figure 4.2.

Distribution of DPs' (orange) and NTs' (blue) residual scores (for the inversion, part-whole and composite task) and effect size (for the Navon's task) based on the normative regression line.



4.6 Results

A summary of our DPs' performance in the evaluation stage is shown in Table 4. Our sample of suspected DPs (N= 17) and NT controls (N= 45) performed in accordance with our predictions in the evaluation tests (i.e., CFPT and CCMT, see Table 4). At a group-level, DPs had significantly poorer performance than NTs in face perception as measured by the CFPT. This difference was largely driven by DPs' inability to perceive upright faces rather than inverted faces. The single-case analyses of the CFPT showed that seven of the DPs had significantly higher errors than their age-matched control group (e.g., NC: t = 1.946, p = .036; MT: t = 3.179, p = .003; BC: t = 1.918, p = .038; LM: t = 3.523, p = .002; DM: t = 2.720, p = .008; DG: t = 1.839, p = .044; RP: t = 2.849, p = .006; see Figure 4.3). However, at a group-level, DPs and NTs were comparable in the CCMT. The single-case analyses also revealed that none of the DPs had significantly poorer performance than their age-matched control group in the CCMT.

Table 4.

DPs demographics, followed by scores on the CFMT, CFPT and CCMT.

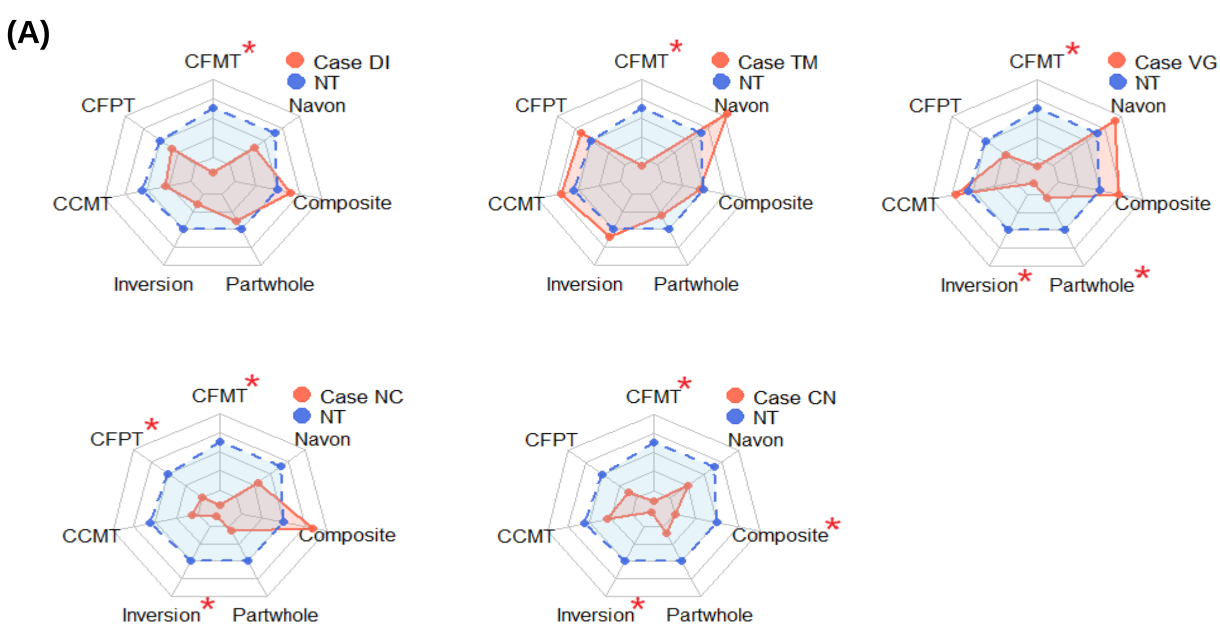
DPs	Age	Age Group	Sex	CFMT (sum)	CFPT (mean)	CFPT upright	CFPT inverted	CCMT
DI	19	18-35	F	36	53	42	64	41
TM	20	18-35	F	39	38	30	46	59
VG	21	18-35	F	39	59	50	68	49
NC	22	18-35	F	33	69	74	64	36
CN	34	18-35	F	38	63	72	54	44
MT	41	36-59	F	36	76	74	78	50
CL	47	36-59	F	37	44	56	32	46
BC	48	36-59	F	25	65	72	58	35
LM	49	36-59	F	29	79	82	76	44
DM	54	36-59	M	40	72	62	82	57
EM	57	36-59	F	32	50	48	52	62

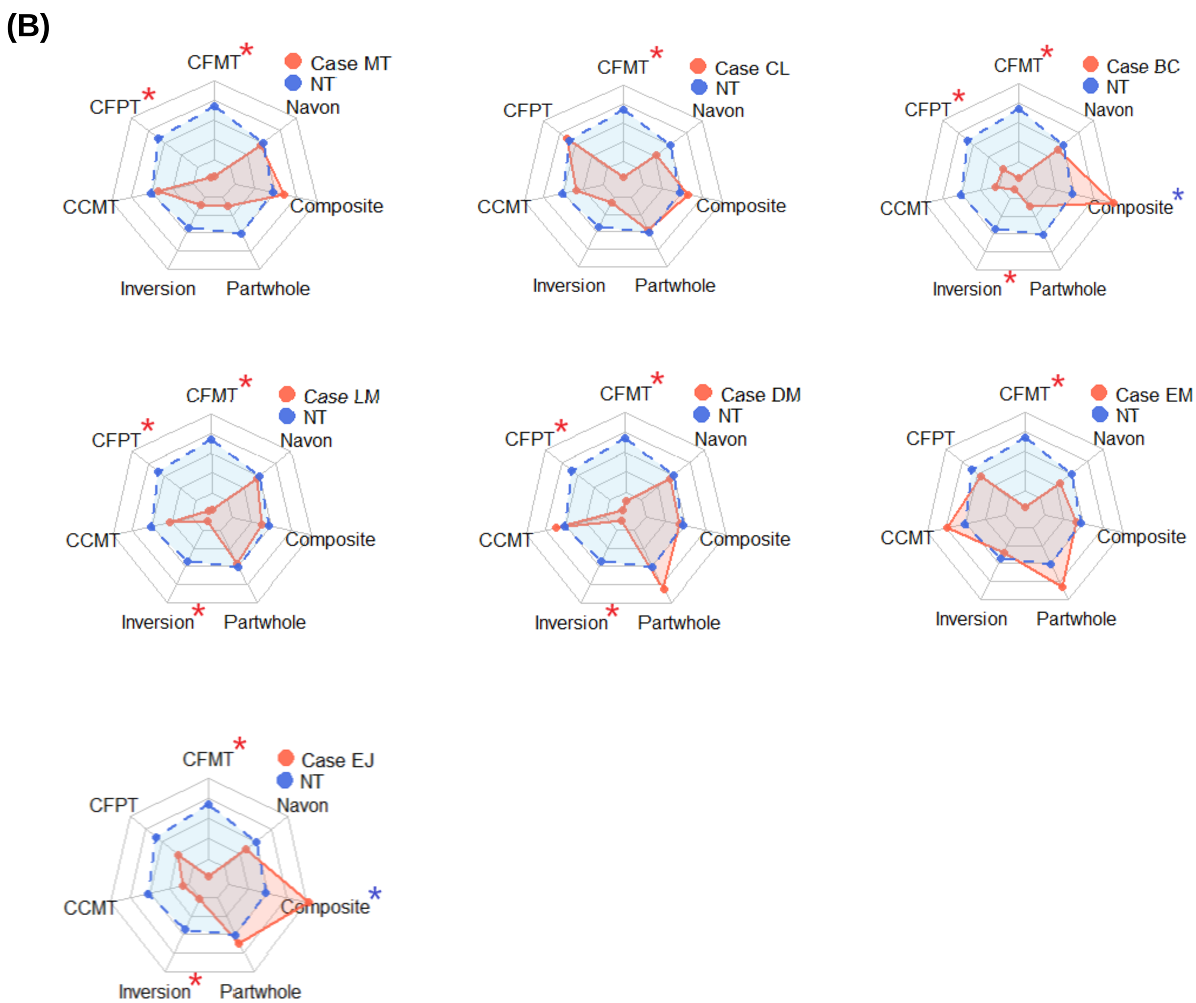
EJ	59	36-59	F	33	57	62	52	36
DG	62	>60	F	33	78	86	70	55
DJ	63	>60	M	36	53	66	40	55
KC	65	>60	F	25	65	62	68	58
RP	67	>60	M	37	87	88	86	43
JC	69	>60	M	34	73	76	70	58
DP Mean				34.24	63.59	64.82	62.35	47.70
DP *SD*				4.51	13.35	15.84	14.90	8.97
NT Mean				59.13	51.62	48.40	54.84	49.91
NT *SD*				9.02	12.02	13.79	15.79	9.33
t				-10.84	3.39	4.02	1.73	-0.46
p				<.001***	.001**	<.001***	.089	.648
Cohen's *d*				-3.09	.97	1.14	.49	-.13

Note. The *t*-statistics, *p*-values and Cohen's *d* effect sizes reported are based on independent samples t-tests comparing developmental prosopagnosics (DPs) and neurotypical (NTs): **p* <. 05, ***p* <.01, ****p* < .001.

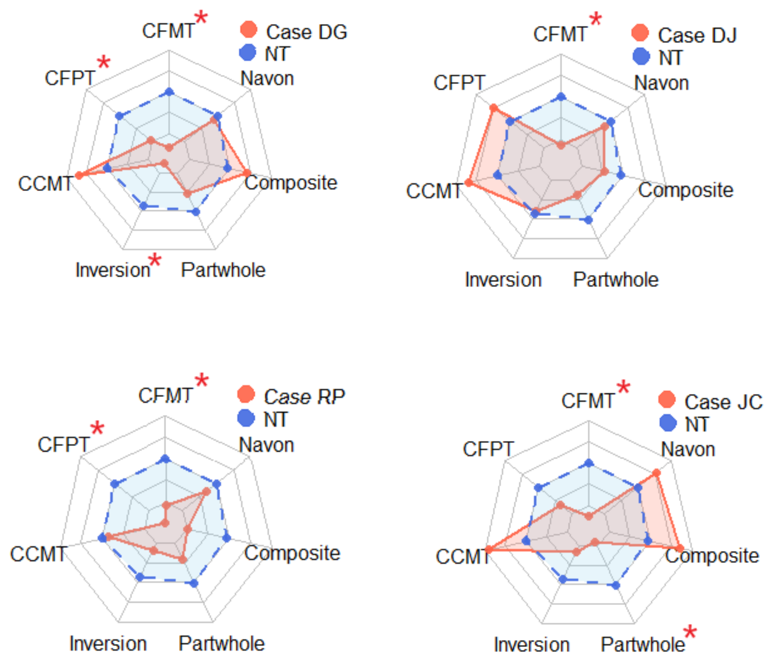
Figure 4.3.

Developmental Prosopagnosics' individual performances in A) Group 1 (18-35 years old), B) Group 2 (36-59 years old), and C) Group 3 (>60 years old).




(B)
CFMT
CFPT
Navon
Composite
CCMT
Inversion
Partwhole
Case MT
NT
Case CL
Case BC
Case LM
Case DM
Case EM
Case EJ

(C)



Note. The maximum (outermost grid) and minimum (innermost grid) threshold of each subscale are ± 2 standard deviations from the mean scores (centre grid) of their age-matched NTs (*N* = 15). Each scale contains 4 segments, in which each segment represents ± 1 SD from the mean. For the CFPT, the error scores were reversed so that a higher score shown here reflects a better performance. A red asterisk (*) signifies that the differences in performance were significant between DPs and NTs (one-tailed).

Table 5.

Accuracy (inversion, part-whole and composite task), reaction time (Navon's task) and reliability scores (Guttman's λ_2 and Cronbach's α) between DPs and NTs.

Tests	DP			NT		
	M	*SD*	λ_2 (α)	*M*	*SD*	λ_2 (α)
Inversion						
Upright	.569	.170	.88 (.86)	.799	.128	.79 (.76)
Inverted	.497	.135	.75 (.56)	.570	.140	.78 (.71)

Part-whole						
Whole	.647	.117	.89 (.79)	.779	.104	.82 (.80)
Eyes	.716	.143	.72 (.63)	.846	.131	.76 (.73)
Nose	.537	.138	.61 (.49)	.706	.132	.60 (.54)
Mouth	.689	.143	.68 (.59)	.784	.143	.72 (.69)
Part	.622	.102	.87 (.70)	.694	.073	.72 (.47)
Eyes	.689	.116	.51 (.35)	.760	.099	.38 (.27)
Nose	.571	.094	.11 (-.18)	.650	.095	.12 (-.04)
Mouth	.605	.176	.76 (.71)	.673	.115	.43 (.35)
Composite						
Aligned	.687	.207	.91 (.90)	.738	.164	.86 (.86)
Misaligned	.746	.225	.93 (.93)	.828	.187	.93 (.93)
Navon's (ms)						
Global	1763.4	1076.2	.83 (.74)	822.8	685.3	.87 (.86)
Local	1806.1	1051.9	.82 (.72)	872.3	678.2	.88 (.87)

Face Inversion Task

The internal consistencies of the inversion effect using the regression approach in NTs (λ_2 = .692) and DPs (λ_2 = .189) were moderate and weak, respectively. Our ANOVA revealed a significant main effect of condition, where all participants, in general, were more accurate with upright compared to inverted trials, $F(1,60) = 62.897$, $p < .001$, $\eta_p^2 = .512$. This pattern replicates the classical inversion effect reported by previous studies (e.g., Yin, 1969; Rossion, 2008). Furthermore, there was a significant main effect of group, $F(1,60) = 18.798$, $p < .001$, $\eta_p^2 = .239$, showing that DPs performed significantly poorer than NTs in the inversion task. In addition, there was a significant interaction between condition and group, $F(1,60) = 17.081$, $p < .001$, $\eta_p^2 =$

.222. Holm Bonferroni-corrected paired samples *t*-tests revealed that DPs were significantly poorer than NTs in the upright ($t(60) = -5.783$, $p < .001$), but not the inverted ($t(60) = -1.836$, $p = .139$) conditions. Further, there was a significant difference between upright and inverted conditions in NTs ($t(44) = 11.519$, $p < .001$), but not in DPs ($t(16) = 2.229$, $p = .089$), suggesting that DPs may have an impaired inversion effect.

This was further supported by the analysis of residuals that revealed a smaller inversion effect in DPs ($M = -0.201$, $SD = 0.131$) compared to NTs ($M = 2.289e^{-5}$, $SD = 0.116$), $t(60) = -5.890$, $p < .001$, $d = -1.677$ (see Figure 4.4). However, despite these group differences, our single-case analyses of the residual scores showed that only nine out of 17 DPs had a significantly smaller inversion effect than their age-matched control groups (refer to Table 6).

Part-whole task

The internal consistencies of the part-whole effect using the regression approach in NTs ($\lambda_2 = .699$) and DPs ($\lambda_2 = .635$) were modest. We found a significant main effect of condition, where all participants, in general, were more accurate with whole compared to part trials, $F(1,60) = 17.228$, $p < .001$, $\eta_p^2 = .223$, replicating previous results using this task (DeGutis et al., 2013b; Estudillo et al., 2022). Furthermore, there was a significant main effect of group, $F(1,60) = 18.515$, $p < .001$, $\eta_p^2 = .236$, showing that DPs performed significantly poorer than NTs in the part-whole task. In addition, there was a significant interaction effect between condition and group, $F(1,60) = 4.982$, $p = .029$, $\eta_p^2 = .077$. Holm Bonferroni-corrected paired samples *t*-tests showed that DPs were significantly poorer than NTs in both whole ($t(60) = -4.854$, $p < .001$) and part ($t(60) = -2.676$, $p = .026$) conditions. Further, there was a significant difference between whole and part conditions in NTs ($t(44) = 11.519$, $p < .001$), but not in DPs ($t(16) = 1.126$, $p = .265$), suggesting that DPs may have impaired part-whole effect.

This was further supported by the analysis of residuals that revealed a smaller part-whole effect in DPs (M = -0.084, SD = 0.083) compared to NTs (M = -3.796e^{-5}, SD = 0.093), $t(60)$ = -3.279, p = .002, d = -.933 (see Figure 4.4). Our single-case analyses showed that only two DPs had a significantly smaller part-whole effect than their age-matched control groups (refer to Table 6).

To examine if DPs have impaired holistic processing only for specific features, we also compared the residuals between DP and NTs for each feature (see DeGutis et al., 2012). Our analyses revealed smaller part-whole effects in DPs (eyes: M = -.081, SD = .117, nose: M = -.141, SD = .131, mouth: M = -.076, SD = .117) compared to NTs (eyes: M = 2.685e^{-5}, SD = .112, nose: M = -3.944e^{-5}, SD = .128, mouth: M = 3.852e^{-5}, SD = .139) for the eyes ($t(60)$ = -2.506, p = .015, d = -.713), and nose ($t(60)$ = -3.841, p < .001, d = -1.093), but not for the mouth ($t(60)$ = -1.995, p = .051, d = -.568). These findings replicate previous differences found between DPs and NTs using the part-whole task (DeGutis et al., 2012). Accordingly, our single-case analyses showed that only two DPs had a significantly smaller part-whole effect than their age-matched control groups for both eyes and nose, and one DP for the eye and mouth regions. Further, we also found that the age-matched control groups were significantly better than one DP for the eyes only, three DPs for the nose only, and one DP for the mouth only (see Table 7).

Face Composite Task

The internal consistencies of the composite face effect using the regression approach in NTs (λ_2 = .774) and DPs (λ_2 = .730) were moderate. Our ANOVA revealed a significant main effect of condition, where all participants, in general, were more accurate with same-misaligned compared to same-aligned trials, $F(1,60)$ = 9.787, p = .003, η_p^2 = .140, replicating previous results (Hole, 1994; Rossion, 2013). However, there was no significant main effect of group,

$F(1,60) = 1.945$, $p = .168$, $\eta_p^2 = .031$, showing that the performance in the composite task across groups were comparable. In addition, there was also no significant interaction between condition and group, $F(1,60) = .429$, $p = .515$, $\eta_p^2 = .007$, suggesting normal composite effect in DPs.

This was further supported by the analysis of residuals that revealed comparable composite effects between DPs ($M = -0.012$, $SD = 0.149$) and NTs ($M = - 4.056e^{-5}$, $SD = 0.138$), $t(60) = -0.301$, $p = .765$, $d = -.086$ (see Figure 4.4). The single-case analyses showed that one of the DPs had a significantly smaller composite effect than their age-matched control group (refer to Table 6).

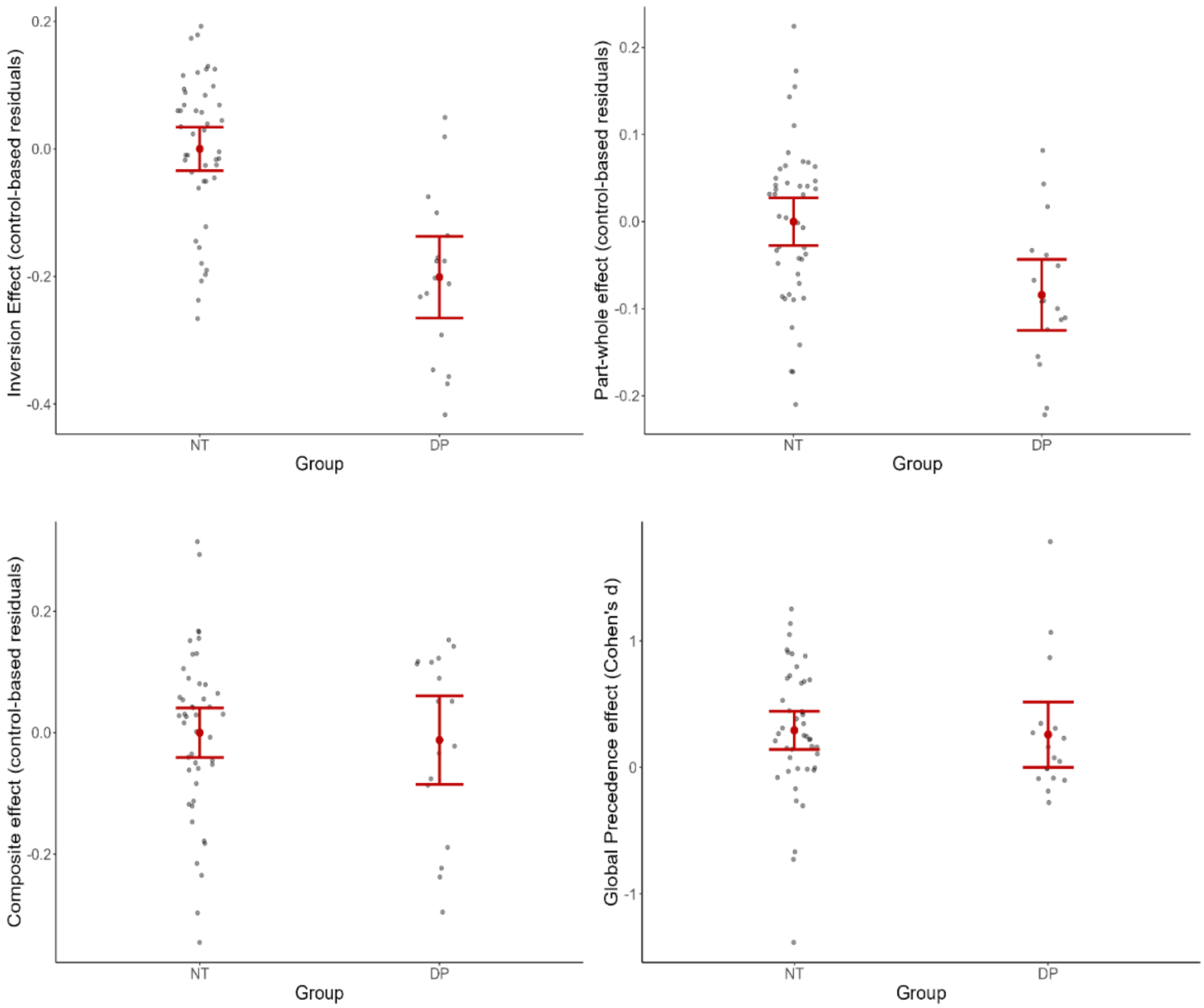
Navon's task

The reliability analysis revealed weak and moderate internal consistency of the global precedence effect in NTs ($\lambda_2 = .274$) and DPs ($\lambda_2 = .769$), respectively. We found a significant main effect of condition, participants were faster with global-congruent compared to local-congruent trials, $F(1,60) = 4.556$, $p = .037$, $\eta_p^2 = .071$, replicating previous results (Navon, 1977). Furthermore, there was a significant main effect of group, $F(1,60) = 18.994$, $p < .001$, $\eta_p^2 = 0.240$, showing that DPs performed significantly slower than NTs in the Navon's task, irrespective of conditions. However, there was no significant interaction effect between condition and group, $F(1,60) = .719$, $p = .400$, $\eta_p^2 = .012$, suggesting normal global precedence effect in DPs.

The standardized difference (i.e., Cohen's *d*) of the global precedence effect in DPs ($M = 0.259$, $SD = 0.528$) was comparable to that of the NTs ($M = 0.293$, $SD = 0.508$), $t(60) = -0.231$, $p = .818$, $d = -.066$ (see Figure 4.4). Our single-case analyses revealed that none of the DPs showed a significantly smaller global precedence effect than their age-matched control groups. (Table 6).

Figure 4.4.

The magnitude of holistic advantage (residuals and Cohen's d) between DPs and NTs in the four holistic measures.



Note. Error bar represents the standard error of the mean and grey dots represent individual residuals and/or effect size.

Table 6.

Single-case analyses of each DPs and their age-matched control group in the four holistic measures.

DP	Inversion effect		Part-whole effect		Composite effect		Global Precedence Effect	
	Residuals	*t*	Residuals	*t*	Residuals	*t*	Cohen's *d*	*t*
DI	-.106	-1.392	-.045	-.472	.070	.566	-.010	-.557
TM	.033	.429	-.072	-.072	-.024	-.024	1.785	3.074
VG	-.240	-3.150**	-.170	-1.783*	.105	.106	1.068	5.532
NC	-.192	-2.520*	-.166	-1.741	.166	1.340	-.102	-.754
CN	-.446	-5.853***	-.151	-1.584	-.234	-1.893*	-.188	-.929
MM	-.168	-1.498	-.133	-1.463	.064	.413	.273	-.178
CL	-.192	-1.673	-.012	-.091	.052	.310	-.089	-.871
BC	-.588	-4.563***	-.138	-1.519	.389	3.107	.161	-.393
LM	-.401	-3.198**	-.020	-0.181	-.043	-.474	.273	-.179
DM	-.299	-2.454*	.102	1.206	-.021	-.292	.231	-.259
EM	-.046	-.608	.108	1.271	-.033	-.391	-.010	-.720
EJ	-.219	-1.870*	.039	.492	.286	2.253	.602	.449
DG	-.297	-2.361*	-.086	-1.031	.110	.650	.095	-.252
DJ	-.014	-.111	-.110	-1.318	-.091	-.541	.047	-.335
KC	-.314	-2.496*	.023	0.276	-.257	-1.527	-.278	-.892
RP	-.181	-1.439	-.105	-1.258	-.222	-1.319	-.084	-.559
JC	-.189	-1.502	-.195	-2.337*	.182	1.082	.868	1.075

Note. Residual scores are based on the normative regression lines of each age group, wherein a significantly different score between DPs and their age-matched control group is highlighted in grey; modified independent *t*-test: *p <. 05, **p <.01, ***p< .001 (one-tailed).

Table 7.

Single-case analyses of DPs and their age-matched NTs for each features in the part-whole task.

DP	Eyes		Nose		Mouth	
	Residuals	*t*	Residuals	*t*	Residuals	*t*
DI	-.030	-.326	-.125	-1.053	.030	.217
TM	-.057	-.619	-.150	-1.264	-.054	-.393
VG	-.072	-.782	-.328**	-2.764	-.116	-.844
NC	-.240*	-2.280	-.244*	-2.056	-.053	-.386
CN	-.169*	-1.834	-.242*	-2.039	-.054	-.393
MM	-.183**	-2.905	-.010	-.071	-.096	-.794
CL	.028	.437	-.255*	-1.817	-.141	-1.167
BC	-.375***	-5.952	-.111	-.791	-.229*	-1.895
LM	-.002	-.032	-.146	-1.040	-.104	-.861
DM	.085	1.348	-.031	-.221	.075	.623
EM	.026	.421	.135	.965	.075	.623
EJ	-.043	-.683	-.005	-.036	.099	.819
DG	-.104	-.661	.012	.092	-.311*	-1.771
DJ	-.061	-.381	.000	.000	.004	.020
KC	-.078	-.496	-.178	-1.360	-.071	-.404
RP	.034	.216	-.375**	-2.866	-.046	-.262
JC	-.201	-1.277	-.208	-1.590	-.159	-.906

Note. Residual scores are based on the normative regression lines of each age group, wherein a significantly different score between developmental prosopagnosics (DPs) and their age-matched control groups are highlighted in grey; modified independent *t*-test: **p* <. 05, ***p* <.01, ****p*< .001 (one-tailed).

4.7 Discussion

The aim of this study was to determine whether the impairment to recognize faces in individuals with Developmental Prosopagnosia can be explained by deficits in holistic processing. Additionally, we wanted to examine whether these potential holistic processing impairments are universal or *heterogeneous* across DPs. In the inversion, part-whole, composite and Navon's tasks, our analyses revealed that control participants replicated previous effects with these tasks (Hole, 1994; Rossion, 2008, 2013; Tanaka & Farah, 1993; Tanaka & Simonyi, 2016; Yin, 1969; Navon, 1977). Interestingly, at a group level, DPs were less susceptible to the inversion and part-whole effects compared to NTs but were comparable in the composite and Navon tasks. In other words, across the three traditional measures of holistic processing of faces, NTs showed stronger holistic face processing compared to DPs only in the inversion and part-whole effects (Avidan et al., 2011; Behrmann et al., 2005; DeGutis et al., 2012; Duchaine et al., 2007b; Klargaard et al., 2018). In line with DeGutis et al. (2012), although DPs showed impaired part-whole effects, particularly the eye and nose regions, they presented normal holistic processing for the mouth region. Our current findings are also consistent with earlier literature that found normal holistic face processing in DPs, as indexed with the composite task (Bennetts et al., 2022; Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017). In contrast to Gerlach and Starrfelt (2018a), holistic deficits seen in DPs were specific to faces.

Interestingly, results from our single-case analyses revealed that holistic processing deficits in DPs, rather than being universal, are *heterogeneous*. This is such that only one DP (Case CN) was impaired for both the inversion and composite tasks, another DP (Case VG) was impaired in both the inversion and part-whole tasks (Case VG), and eight DPs were impaired only in the inversion or part-whole tasks (see Table 6). Interestingly, none of the DPs was impaired in all the holistic processing tasks, which suggests that holistic processing, although impaired, is not totally absent in DPs (DeGutis et al., 2012). In addition, only seven DPs were impaired on the CFPT from our single-case analyses when compared to their respective age-matched controls. Contrary to previous studies (Macaskill, 2021), this argues that face perception is dissociable from face recognition (i.e., face memory), and is not always impaired in DPs (Klargaard et al., 2018; Pertzov et al., 2020; Ulrich et al., 2017).

Our findings suggest that holistic processing impairments in DPs, rather than being consistent, present both quantitative and qualitative differences across distinct individuals (Corrow et al., 2016; Le Grand et al., 2006; Tardif et al., 2019). In short, DPs could have an impairment specific to distinct cognitive mechanism(s) measured by each of the three holistic paradigms. This also further supports that holistic processing is not a unitary process and there is no common mechanism that explains these three distinct effects of holistic processing (Boutet et al., 2021; Rezlescu et al., 2017). Additionally, single-case analyses of the CCMT and Navon's task further support our hypothesis that DPs' impairment in identification and holistic processing is specific to faces, and not generalized across all domains (Duchaine et al., 2007b; Fry et al., 2020; Wang et al., 2012). From a more general perspective, our results also highlight the importance of single-case analyses in neuropsychological and neurodevelopmental disorders (Cubelli & Della Sala, 2017).

To our surprise, the CFE was not impaired in DPs in our group analyses, and only one DP was significantly impaired in the composite task of our single-case analyses. Consequently, this null effect cannot be attributed to the poor reliability of our composite face task, particularly, given that the CFE had the highest reliability among the three holistic face measures across groups. Multiple studies have argued that the CFE might not be measuring holistic face processing at all. Instead, it could be tapping into other cognitive mechanisms related to general perceptual abilities, which serve different roles in facilitating face recognition, as opposed to those in the part-whole and inversion effect (Rezlescu et al., 2017), or even with the *complete* version of the composite task (Boutet et al., 2021; Richler & Gauthier, 2014). Consequently, we did not include the complete CFE in this study for this reason. Specifically, it has been argued that the complete version does not capture the face-specific holistic mechanisms that we are currently investigating (McKone et al., 2013; Rezlescu et al., 2017). For example, the complete version of the composite task was shown to have comparable effects with upright faces and other non-face visual stimuli, such as cars (Bukach et al., 2010) and words (Wong et al., 2011). This suggests that the complete CFE might reflect a general attentional mechanism, rather than a pure measure of holistic face processing. In brief, the CFE may reflect other aspects of holistic processing that are not exclusively associated with face processing, such as selective attention and working memory (Fitousi, 2015, 2020).

Accordingly, our findings might also be explained by response strategies of “confirmation” and “elimination” (Bobak et al., 2023). Using principal component analysis, Bobak et al. (2023) found that accuracy from trials in which a target face matched a face they learnt (i.e., from memory) or viewed simultaneously loaded strongly on the *confirmation* component (‘match’ trials). Accuracy from trials in which a target face did not match what they learnt or viewed simultaneously loaded heavily on the *elimination* component (‘mismatch’ trials). Bobak et al. proposed that both components are tapping into different cognitive sub-processes of face recognition (see Chapter 3 for detailed explanation). In the context of our study, the CFMT, part-whole, and inversion tasks always present target faces in every trial, that also matches the learnt face. Therefore, these three tasks are likely to tap into the confirmation component. In contrast, the standard composite task, which also consists of non-match faces and target-absent trials, may load onto the elimination component instead. In this sense, our DPs impairment might be explained by a deficit in cognitive sub-processes pertaining the confirmation component, and not holistic processing per se.

Nevertheless, the current study is not without limitations. Some studies have shown that prosopagnosia often co-occurs with other neurodevelopmental disorders, such as autism spectrum disorder (ASD) or dyslexia (co-occurrence hypothesis; Cook et al., 2015; Cook & Biotti, 2016; Minio-Paluello et al., 2020). Cook et al. (2015) suggested that despite being independent of each other, individuals with prosopagnosia reported higher autistic traits than controls, while individuals with ASD reported higher prosopagnosic traits (e.g., face recognition difficulties) than controls. Consequently, domain-general holistic processing deficits (i.e., weak central coherence; Happé, 1996; Nakahachi et al., 2008) seen in ASD are more likely to also present themselves in DPs, which would then explain why some DPs also present impaired holistic processing across all visual perceptual domains (Gerlach et al., 2017; Gerlach & Starrfelt, 2018a), ultimately causing poorer visual recognition (e.g., CFMT & CCMT; Gerlach et al., 2016; see review by Geskin & Behrmann, 2018). More direct evidence was reported in Morgan and Hills' (2019) study, in which they found a positive association between autistic traits and the magnitude of holistic processing, as measured with the FIE, but not for PWE and CFE. Even though none of our DPs reported suffering from autism or any other neurodevelopmental disorder, as we did not include any measure of autistic traits (Baron-Cohen et al., 2001), we cannot rule out the possibility that face recognition difficulties in some DPs can be explained by high autistic traits.

Furthermore, our current study is also limited by the inclusion of only one objective test for assessing face recognition abilities. In contrast, the majority of previous studies typically confirm DP using at least two objective memory tests (e.g., CFMT and famous face memory tests), as recommended by DeGutis et al. (2023). This approach is important because relying on a single measure may not always provide a reliable basis for making a diagnosis (Sachdev et al., 2014). While we acknowledge that our study did incorporate a subjective questionnaire (Burns et al., 2022*)* and other objective measures of non-face objects (e.g., CCMT), as means to show that our suspected DPs recognition deficits are specific to faces, we recognise that the screening protocol employed remains limited (Dalrymple & Palermo, 2016). Additionally, the current study also examined the heterogeneity in DPs using a relatively small sample size (N = 17), which may be subjected to criticism. Nonetheless, due to the nature of our study in which we examine participants case-by-case, we believe that recruiting more DPs would not impact the observed heterogeneity. For instance, even with our limited sample of 17 DPs, none of them exhibited impairments in all three holistic face measures. This suggests that the probability to observe a universal holistic impairment in DPs is well below chance.

Our findings also revealed that the reliability of the FIE in DPs was notably weak. This is not surprising given that DPs' performance in the inverted conditions were close to chance, therefore restricting observable variance in their scores. Recent studies have challenged the notion that the FIE solely captures holistic processing of upright faces, but also applies to inverted faces as well (Gerlach & Mogensen, 2023; Murphy & Cook, 2017). For instance, disrupting holistic processing by limiting participants to view faces through an aperture was shown to affect recognition performance of both upright and inverted faces alike (Murphy & Cook, 2017). Given the possibility of preserved holistic processing for inverted faces (Meltzer et al., 2017) and the assumption that DPs have deficits in holistic face processing, we would expect impaired recognition of inverted faces in DPs, albeit to a lesser extent. Accordingly, this would explain the findings in our group comparisons, wherein FIE was impaired in DPs, at the same time having poor performance in the inverted conditions. Since upright faces retain most, if not all, of the holistic information contained in a face, holistic processing deficits would therefore be more prominent here. In contrast, inverted faces only retain some holistic information, therefore DPs' deficits are less obvious. Overall, findings involving holistic processing, measured with FIE, should be interpreted with caution.

In conclusion, our results suggest that DPs have specific diminished susceptibility for holistic processing (as reflected by the inversion and part-whole, but not the composite effect), rather than abolished holistic processing. First, none of the DPs was impaired in all three holistic face measures. Second, our group comparisons showed that the part-whole effect was comparable between DPs and NTs for the mouth region, but not the eyes and nose. Third, holistic processing deficits within this task were also heterogeneous. Interestingly, the observed holistic deficits seem to be specific to faces, as reflected by the comparable global precedence effect across groups. Furthermore, we found that not all DPs may have an impairment in holistic processing (on an individual level) and these impairments could be for only specific mechanism(s), further implying the importance of single-case analyses for studies involving individuals with neurodevelopmental disorders. Our findings also raise the possibility that some DPs may have a general deficit in strategic perceptual face encoding, particularly involving both holistic and featural processing.

4.8 Experiment 2: Acquired Prosopagnosia

The human face recognition system is often associated with the (mostly right) occipito-temporal cortex (Haxby et al., 2000; Barton, 2008a). In fact, lesions in these regions cause acquired prosopagnosia (AP), a neuropsychological condition characterized by a severe deficit in the recognition of faces but with normal object recognition (Barton, 2008b; Barton et al., 2019; Busigny et al., 2010; Rezlescu et al., 2012). The impairments in acquired prosopagnosics (APs) are characterized by the inability to recognize previously known faces or form new memories of novel faces after brain injury, despite the absence of low-level visual defects or intellectual disorders (see review by Benton, 1990). Early accounts of AP (Levine & Calvanio, 1989; Riddoch & Humprey, 1987) reported that APs have a general deficit at integrating individual features into a whole, regardless of whether the stimuli were faces or nonface objects (i.e., Navon letters; Navon, 1977). Further evidence was shown in Barton et al.'s (2004) study, in which multiple APs had difficulties in recognizing overlapping figures or reconstructing letters.

Despite that, other studies argue that holistic processing deficits in APs are specific to faces (Busigny et al., 2010, 2014; Busigny & Rossion, 2011; Rezlescu et al., 2012). Contrary to early accounts, in which the majority of the APs also showed significantly impaired object recognition (i.e., general visual agnosia; see Barton, 2018), these studies showed a "pure" case of AP (i.e., Patient PS) with normal object recognition (Rossion et al., 2003; Rossion, 2014). Patient PS was found to be comparable to age-matched neurotypicals (NTs) in the Navon's task but was severely impaired in processing faces holistically, as reflected in all the three traditional measures of holistic processing: part-whole, composite and inversion task (Busigny et al., 2014; Busigny & Rossion, 2010; Ramon et al., 2010). In addition, other cases of APs also showed abolished or atypical inversion (de Gelder & Rouw, 2000), part-whole (de Gelder et al., 2003) and composite effect (Busigny et al., 2010; Monti et al., 2019), but normal holistic processing for non-face objects (e.g., overlapping non-face figures and reconstructed letters; Barton et al., 2004). Together, these studies suggest that APs have a specific impairment in the holistic processing of faces.

In contrast, more recent studies argue that holistic face processing is not always impaired in APs (Finzi et al., 2016; Rezlescu et al., 2012). For instance, Finzi et al. (2016) found that five out of seven of their APs showed normal CFE for upright faces, while four out of seven APs showed normal CFE for inverted faces. They argued that holistic processing can remain intact in some APs because holistic information from faces is represented in multiple "regions" of the face processing network. Thus, some APs may have intact regions that are sufficient to relay degraded visual input holistically (see also Duchaine & Yovel, 2015). Similar to those found in developmental prosopagnosics (DPs), the findings regarding holistic deficits in APs have been rather mixed. These mixed findings may be the result of using different holistic paradigms, in which the three traditional holistic measures are reflecting different underlying cognitive mechanisms (Boutet et al., 2021; Rezlescu et al., 2017). Thus, it is possible that holistic processing impairments in APs are similar to those found in DPs, in which both quantitative and qualitative differences are present across distinct individuals (i.e., heterogeneous; Corrow et al., 2016). Consequently, individual APs may have an impairment specific to distinct cognitive mechanism(s) as measured by each of the three holistic paradigms.

Accordingly, we ran a second experiment to compare individual APs and their matched-NTs performance across all three measures of holistic processing (face inversion task, part-whole task, and composite task). Here, we present the cases of RM and DS, two acquired prosopagnosics with face recognition difficulties following trauma and stroke, respectively. We also included the CFPT and CCMT to examine if AP have deficits in face recognition that extends to the perception of faces and whether their difficulties are specific to faces. Finally, to examine whether holistic processing deficits of APs are also specific to faces, we compared the performance of our participants in a Navon's task that measures holistic processing for non-face stimuli (i.e., alphabetical characters). Overall, we expect APs to perform significantly poorer than their respective matched-NTs in the CFMT, CFPT and all three holistic face indexes, but not for the CCMT and Navon's task.

4.9 Methods

4.9.1 Participants

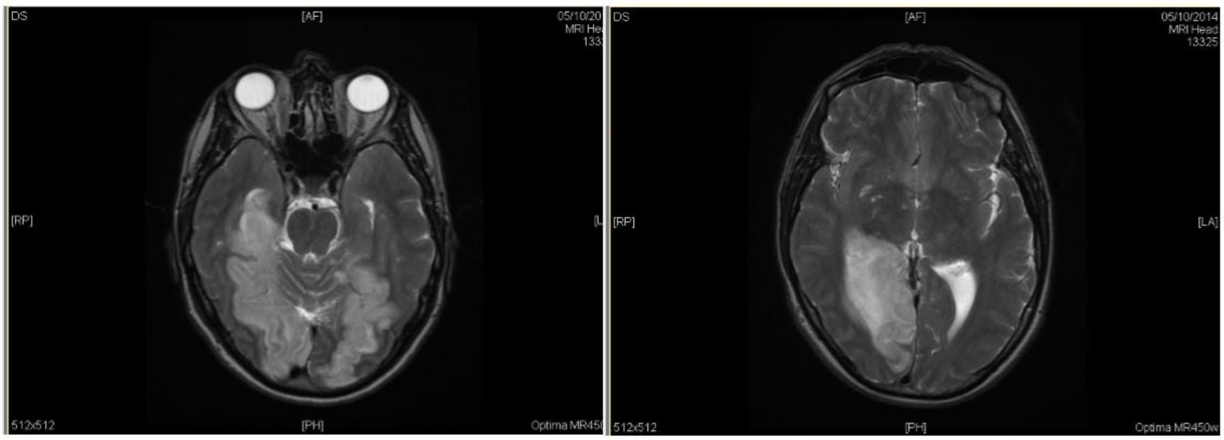
We tested four cases of AP, but only data from two APs were used as they were willing to share more detailed information about their brain damage. The two cases of AP were referred to as RM and DS (refer below for description). Five Mexican Hispanic (*M* = 52 years) and 15 Caucasian (*M* = 48.6 years, *SD* = 6 years) neurotypical adults, that were demographically-matched (to Case RM and DS, respectively) were also tested as controls.

Case RM is a 51-year-old Mexican Hispanic male, who suffered bilateral damage in the temporo-parietal areas following a traumatic brain injury in his early 40s. Patient history revealed initial interviews that showed RM has problems recognizing familiar faces and naming objects. A formal evaluation confirmed these patterns and some minor problems to recognize daily life objects. Subsequent assessments showed normal object recognition and naming, but severe familiar face recognition (i.e., famous face memory test).

Case DS is a 55-year-old British Caucasian male, who suffered diffused brain damage in the (mostly right) medial temporal lobes following an ischemic stroke in his late 40s (see Figure 4.5). Following the brain damage, DS was diagnosed with AP, acquired topographical agnosia (i.e., difficulties recognizing environmental stimuli; Barton, 2014) and aphantasia (i.e., inability to voluntarily create mental images; Zeman et al., 2015, 2020), despite normal object recognition.

Figure 4.5.

Structural MRI showing the diffuse bilateral brain damage suffered in the occipital temporal lobes of Case DS following an ischemic stroke.



All participants were recruited through online social media platforms and word of mouth. Participants were included in a lucky draw that gifted one out of every five participants an Amazon eGift card valued at £30, as compensation for their time. A digital informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ250920).

4.9.2 Apparatus, Stimuli and Procedures

Apparatus, stimuli and procedural descriptions, as well as data analyses of this study, are similar to the preceding experiment (refer to p. 133 – 142). All tasks were also translated into Spanish for Hispanic participants.

4.10 Results

A summary of Case RM and DS performances is summarized in Table 8. Similar to the preceding experiment, we ran modified t-tests designed for single-case analyses (Crawford & Garthwaite, 2002) with the residual scores (e.g., inversion, part-whole and composite effects) and standardized differences (Navon's task) between each AP and their age-matched NT group, respectively (see Table 9).

Table 8.

The accuracy (inversion, part-whole and composite tasks) and reaction time (Navon's task) performances between APs and their respective matched-NTs.

Tasks/Conditions	Case RM	Hispanics NTs	Case DS	Caucasian NTs
	M	*M(SD)*	*M*	*M(SD)*
Inversion				
Upright	.575	.595 (.125)	.556	.843 (.126)
Inverted	.575	.670 (.078)	.500	.588 (.095)
Part-whole				
Whole	.708	.728 (.099)	.625	.796 (.096)
Part	.722	.697 (.074)	.625	.728 (.048)
Composite				
Aligned	.925	.760 (.135)	.250	.778 (.153)
Misaligned	.850	.885 (.118)	.375	.883 (.125)
Navon's (ms)				
Global	702.5	717.1 (229.8)	2922.5	887.5 (711.6)
Local	689.0	798.9 (234.6)	2837.0	949.8 (711.7)

Table 9.

Single-case analyses of both APs and their age-matched control group.

Tasks		Case RM	Case DS
CFMT	Sum	42	32
	t	-1.873	-3.016**
CFPT	Mean	57	98
	t	-1.029	5.701***
CCMT	Sum	55	49
	t	-1.826	-.416
FIE	Residuals	-.160	-.472
	t	-2.880*	-3.716**
PWE	Residuals	-.040	-.096
	t	-.456	-1.055
CFE	Residuals	.180	-.017
	t	1.317	-.257
GPE	Cohen's *d*	-.103	-.274
	t	-.815	-1.224

Note. Residual scores are based on the normative regression lines of each age group, wherein a significantly different score between APs and their age-matched control groups are highlighted in grey; modified independent *t*-test: *p <. 05, **p <.01, ***p < .001 (one-tailed).

4.11 Discussion

The aim of this second experiment was to determine whether the impairment to recognize faces in individuals with Acquired Prosopagnosia (AP) extends to deficits in holistic processing. Additionally, we wanted to examine whether these potential holistic processing impairments in APs are face-specific or generalized across all visual domains. First, compared to their control groups, both cases of AP were impaired in face recognition but had normal non-face object recognition (i.e., “pure” Acquired Prosopagnosics; Barton, 2018). Our single-case analyses revealed that Case RM and DS were comparable to their age-matched controls in the part-whole, composite and Navon's task, but not for the inversion task (see Table 9), partially replicating previous studies (Busigny et al., 2010, 2014; Busigny & Rossion, 2011; Finzi et al., 2016; Rezlescu et al., 2012). In other words, across the four measures of holistic processing of faces, NTs only showed stronger holistic face processing compared to the respective APs only in the face inversion effect (FIE).

In contrast, we found that holistic processing is not always impaired amidst face recognition difficulties seen in APs (Busigny et al., 2010, 2014; Ramon et al., 2010). This also argues that holistic processing is impaired but not completely abolished in APs, whereby neither of our APs was impaired in all three holistic face indexes. Furthermore, we also provide further evidence that these holistic deficits are face-specific in APs, as reflected by their performance in the Navon's task (Busigny & Rossion, 2011). Thus, our findings provide further support that holistic representations of faces are constituted by multiple underlying mechanisms of the face processing network, in which APs may have intact "regions" that are sufficient to relay degraded holistic visual input (Finzi et al., 2016). Thus, it is possible that the three traditional holistic paradigms are indeed measuring different underlying cognitive mechanisms, in which some APs with (milder) brain damage to face-specific regions have spared holistic face perception. For instance, the composite and part-whole effects may be tapping into multiple cognitive mechanisms, possibly involving other general perceptual abilities, that are resilient towards brain injuries in face-specific regions.

The FIE has been regarded as the most reliable and best predictor of FRA (Boutet et al., 2021; Rezlescu et al., 2017) and reflects a more naturalistic disruption of holistic processing (Alzueta et al., 2021), as compared to the part-whole and composite effects. Although some studies have suggested that the FIE may be reflecting qualitative differences in face processing, where holistic processing is eliminated by the inverting of faces and forced observers to utilize featural processing (Reed et al., 2003), other studies have argued that identification of both upright and inverted faces rely on similar processes (e.g., Willenbockel et al., 2010). The recognition of inverted faces has been argued to impair other “information gathering” processes, in which both holistic and featural processing of facial information may be disrupted (Hayward et al., 2016; McKone & Yovel, 2009; Murphy & Cook, 2017). For instance, the FIE generally impairs the extraction of facial information (e.g., Lee et al., 2022a), in which both the encoding and subsequent integration of individual features into a unitary whole are disrupted. Thus, findings pertaining to the FIE should be inferred with caution.

Furthermore, our current study is not without limitations. For instance, supplementary analyses of the Hispanic control sample also did not reveal any classical effect from the part-whole task (e.g., performance in the ‘whole’ and ‘part’ condition of the part-whole task were not significantly different). Importantly, the single-case analyses also did not reveal any significant differences between Case RM and the Hispanic matched-NTs in face recognition nor face perception ability (i.e., CFMT & CFPT respectively), albeit there was a trend towards significance. This argues that Case RM and the Hispanic matched-NTs were comparable in face processing. Notably, studies have shown that APs can achieve “normal” accuracy performances when reaction time is not considered (Fysh & Ramon, 2022). For instance, APs may rely on time-consuming strategies, e.g., featural processing, that may aid in accurate but inefficient face recognition (Ramon et al., 2016). In view of this, when comparing Case RM accuracy in the CFMT to age-matched Hispanic NTs, although close, does not meet the requirements for prosopagnosia diagnosis. For this reason, we further examined the RTs in the task to see if there is a speed-accuracy trade-off. In fact, the single-case analysis revealed that Case RM took a significantly longer duration (19 seconds) than Hispanic matched-NTs (6 seconds) in the CFMT (i.e., $t = 14.210$, $p < .001$, $Zcc = 15.567$). This suggest that Case RM indeed had a speed-accuracy trade-off during face recognition (i.e., CFMT).

Additionally, the current study is also limited as we did not account for the other-race effect (Kho et al., 2023; McKone et al., 2012b) when examining the FRAs of our Hispanic participants. Previous studies have shown that this effect extends to even subtle differences (i.e., ethnicity of faces), which may also obscure prosopagnosics' deficit as they may use distinct (atypical) strategies (McKone et al., 2011, 2012b). For instance, McKone et al. (2011) found that some Australian DPs (i.e., Northern European) that are characterized by face recognition difficulties in the CFMT-Australia appeared normal on the original CFMT, which consisted of Caucasian faces from other ethnicities (i.e., Southern European). Nonetheless, there is currently no Hispanic version of the CFMT. Consequently, face recognition difficulties in our Latin-American AP (i.e., Case RM) may be obscured by the atypical processing of other-race faces in the original CFMT.

In conclusion, our results from this experiment suggest that APs have specific diminished susceptibility for holistic processing (as reflected by the inversion, but not the part-whole and composite effects) that is specific to faces (as reflected by the GPE), rather than abolished holistic processing (e.g., neither APs were impaired in all three measure of holistic face processing). Furthermore, we suggest that holistic representations of faces are represented in multiple "regions" of the face processing network, in which holistic processing can be spared in some milder forms of Acquired Prosopagnosia. Lastly, our current findings suggest that holistic processing deficits are homogeneous across distinct APs (e.g., both cases have impaired performance only in the FIE).

4.12 Future Directions: Functional Role of Featural Processing

The findings above, specifically in Experiment 1, also lend support to an alternative possibility – face recognition impairments in prosopagnosics extend to both holistic and featural processing (Bennetts et al., 2022; Verfaillie et al., 2014; Yovel & Duchaine, 2006). For instance, despite being poorer in the *conditions of interest* (e.g., whole conditions), our DPs were also poorer in the *control conditions* (e.g., part conditions), which often reflects the featural processing of faces (see Table 5). Recently, Bennetts et al. (2022) found that some DPs showed typical FIEs, while some DPs had reduced or abolished FIEs. However, they found that these DPs with typical FIEs were also significantly poorer at perceiving and/or recognising inverted faces, arguing that some DPs' face recognition difficulties are the result of impaired featural processing. Consequently, a study by Tsantani et al. (2020) also found that DPs and NTs showed a similar level of impairment when faces were viewed through a dynamic aperture (i.e., whole-face processing is disrupted; see Murphy & Cook, 2017). Tsantani et al. argued that the perceptual difficulties seen in DPs arise from imprecise recognition of facial features, not aberrant holistic processing. If DPs are impaired or underdeveloped in strategic face perceptual encoding (Dalrymple & Palermo, 2016; Towler et al., 2018; Tsantani & Cook, 2020), facial information encoded may be less accurate and/or less differentiated at recognition (Shah et al., 2015a; Stumps et al., 2020). Consequently, impaired face encoding might introduce both poorer holistic and featural perceptual representations in DPs (McKone & Yovel, 2009). Overall, this suggests that individual differences in face recognition abilities may also reflect variations in the ability to process the featural aspects of faces, and not only holistic processing expertise. Specifically, the heterogeneities of DPs might even extend to different “information-gathering” processes. Accordingly, the upcoming chapter will extensively explore the importance of processing individual features during face learning and recognition on an individual level.

In conclusion, our findings suggest that holistic processing is impaired in both DPs and APs, but the pattern of impairments across prosopagnosics are not consistent. Particularly, prosopagnosics may be impaired in some but not all of the three gold-standard measures of holistic face processing. Importantly, these impairments are distinct across individual DPs, but consistent among APs. This indicates that holistic processing impairments in DPs are heterogenous, but holistic deficits in APs are homogeneous. While our findings showed that APs’ holistic processing deficits were homogeneous, the sample size is too small to make any generalization claims. Overall, this suggests that the concept of holistic processing is not unitary and there is no common mechanism explaining the three putative effects of holistic processing.

CHAPTER 5: The Role of Holistic and Featural Processing in the Individual Differences of Face Recognition Abilities during Face Learning and Face Recognition

5.1 Holistic and Featural Processing

Recognising the identity of an individual by perceiving their face is a fundamental social skill. Most human faces adhere to a standard template and configuration of facial features such as the eyes, nose, and mouth. While the isolated processing of different facial features is known as "featural processing", the combination of these facial features and their configuration into a whole is referred to as "holistic processing" (Piepers & Robbins, 2012). Although both processes are believed to contribute to face recognition, the popular view is that holistic processing is relatively more crucial (Jacques & Rossion, 2010; Rossion, 2008, 2013). However, the contribution of holistic and featural processing to different stages of the face recognition process (i.e., learning vs. recognition) and their relationship with individual differences in face recognition are largely unknown.

In typical adults, the *face inversion*, *face composite* and *part-whole* tasks are conventionally used to demonstrate the dominance of holistic processing in face recognition (see Chapter 2 for full description; Rezlescu et al., 2017). Although holistic processing is widely recognized as critical for face recognition, its reliability in predicting face recognition abilities (FRA) is still inconsistent. Some studies have reported positive correlations between these tasks and face identification (Belanova et al., 2021; DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012), pointing to holistic processing as the underlying mechanism explaining individual differences in face recognition. However, others failed to report such association (Konar et al., 2010; Verhallen et al., 2017). For instance, DeGutis et al. (2013b) found that holistic processing, as indexed with the part-whole and composite tasks, was positively correlated with FRA, as measured with the Cambridge Face Memory test (CFMT; Duchaine & Nakayama, 2006). In contrast, Konar et al. (2010) and Verhallen et al. (2017) did not find any association between the composite face effect and FRA. Additionally, these inconsistencies extend to individuals with clear face recognition deficits, for example in Developmental Prosopagnosics (DPs). While some have reported impaired holistic processing in DPs (Avidan et al., 2011; DeGutis et al., 2012; Susilo & Duchaine, 2013), others have reported normal holistic processing (Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010). Together, these studies suggest that holistic processing, as indexed with these three traditional measures, may not be a reliable predictor of face recognition ability (but see chapters 3 and 4).

However, there is also emerging evidence suggesting that featural processing is important for face identification too. For instance, Cabeza and Kato (2000) found that participants were equally prone to falsely recognise novel faces (what they called “prototype faces”) that only had either holistic information or featural information preserved from previously learnt faces. This reflects that both holistic and featural information were encoded and stored, and that they may be equally important in face recognition. More recently, DeGutis et al. (2013b) used the part-whole and composite tasks to demonstrate that both holistic and featural processing contributes independently and significantly to FRA. First, they obtained an independent measure of recognition based on featural processing by calculating the accuracy for the control conditions (e.g., part condition in the part-whole task) where holistic information is disrupted. Second, they regressed the variance of the control conditions from the experimental conditions (e.g., whole condition in the part-whole task) to obtain an independent score of holistic processing. They found significant positive correlations between these independent estimates of holistic as well as featural processing and their measures of FRA (scores in the Cambridge Face Memory Test; CFMT; Duchaine & Nakayama, 2006). Furthermore, it has also been suggested that featural processing is more important for the recognition of unfamiliar faces than familiar faces (Johnston & Edmonds, 2009). For example, Lobmaier and Mast (2007) found that matching two sequentially presented faces is relatively more impaired when the two faces are blurred (i.e., disrupting featural processing) than when they are scrambled (i.e., disrupting holistic processing), but this disadvantage for blurred faces was more pronounced for novel faces than for previously learnt faces.

Moreover, the functional significance of featural processing is highlighted by its role in cognitive training methods aimed at enhancing face recognition ability. For instance, Towler et al. (2020) suggested that expertise in featural processing requires deliberate effort, as opposed to holistic processing which develops naturally (see also Hills & Lewis, 2018). As a result, Towler et al. argued that only featural processing can be trained, as most individuals are already proficient in holistic processing. This notion is supported by prior research (Young & Burton, 2018; Nakabayashi & Liu, 2014) and provides an alternate explanation for why individuals with developmental prosopagnosia (DPs) may perform better in featural processing than holistic processing (e.g., no holistic advantage or reduced susceptibility). DPs may have underdeveloped holistic processing, and consequently, compensate for their face recognition deficits by relying on alternative strategies, such as featural processing (i.e., a compensatory strategy; Adams et al., 2020; Boutsen & Humphreys, 2002). Nonetheless, these studies suggest that expertise in featural processing can enhance FRA, even in individuals with face recognition deficits.

5.2 Indexing Holistic and Featural Processing

With conventional measures of holistic processing (i.e., composite, part-whole and inversion effects), the assumption is that their experimental manipulations (e.g., misaligning faces in the composite task) are meant to disrupt holistic processing. However, these measures are not free of criticism as there are secondary factors that could drive the same effects too (for discussion, see McKone et al., 2013). For example, in the part-whole task, faces are always encoded in their whole, arguing that the part-whole effect could be driven by encoding specificity (Leder & Carbon, 2005). Further, the experimental condition generally contains more facial information than the control condition. Here, the so-called holistic advantage measured by the part-whole effect could reflect differences in the amount of featural information contained between the two conditions. Besides that, recent studies have also criticised the functional significance of the composite face task (Rezlescu et al., 2017; Fitousi, 2015). For instance, Fitousi (2015) showed that aligned composite faces (that are often used to demonstrate interference from holistic processing) were not affected by the Garner interference paradigm. In other words, participants were perfectly capable of selectively attending to target facial features even when other irrelevant features were manipulated, casting doubt on the fact that holistic processing may be interfering with perception in aligned composites. To control for secondary cognitive factors, studies have often adopted these two holistic measures with the inversion effect. Following this argument, the pure contribution of holistic processing would be observed when the part-whole and composite effects are only present with upright faces and disappear for inverted faces (McKone et al., 2013).

With regard to the inversion task, the most common interpretation is that we are better at recognising upright as opposed to inverted faces (i.e., the “face inversion effect”; FIE) because the former facilitates holistic processing (Yin, 1969; Rossion, 2008). If that is the case, when we force observers to view both upright and inverted faces in a featural manner, the FIE should reduce, or disappear. To test this assumption, studies have compared people's ability to recognise upright and inverted faces using a gaze-contingent aperture paradigm. Here, facial features visible to the viewer are determined by where the viewer is fixating at any given time point, while features outside of the fixation would be occluded, forcing the observers to serially process facial features (Van Belle et al., 2010, 2011; Verfaillie et al., 2014). In short, the gaze-contingent aperture paradigm disrupts holistic processing without affecting the available featural information used by participants. These studies observed a holistic advantage for upright faces (i.e., superior recognition for upright compared to inverted faces) only when the faces were viewed fully, but not when viewed through the aperture. This also further strengthens the argument that the FIE occurs because upright faces facilitate, while inverted faces disrupt, holistic processing.

5.3 Fixed-Trajectory Aperture Paradigm

However, as Murphy and Cook (2017) point out, in gaze-contingent paradigms, the order and duration of fixating on facial features are contingent on the participants and the experimenter has no control over it. Hence, how information is sampled by observers is not consistent. This leads to a further question of whether face recognition depends on an individual's visual input (i.e., possible qualitative differences), which can potentially confound the findings with participants' fixation strategy. For instance, each individual has different visual input based on their fixation strategies. This highlights the need to have an alternate paradigm that controls which (and in which order) different facial features are sampled.

The fixed-trajectory aperture paradigm (FTAP) offers a solution to this limitation. In the FTAP, observers are prevented from holistically processing the face, while ensuring that all observers sample the same regions or features of the face in the same order and for the same duration (Murphy & Cook, 2017; Murphy et al., 2020). This paradigm typically has two experimental conditions: (1) the "whole" condition in which the entire face is visible to the observer, and (2) the "aperture" condition in which a transparent, rectangular window smoothly moves from the top of the face to the bottom, revealing parts of the face in a sequential order. Murphy and Cook (2017) found that faces are recognised better in the whole condition compared to the aperture condition (i.e., "the aperture effect"), suggesting that the dynamic aperture successfully disrupts holistic processing. This is in line with holistic accounts, showing that holistic processing is important for face recognition (Rossion, 2013; Richler et al., 2012). Interestingly, the magnitude of the aperture effect was comparable in both the upright and inverted conditions. This is in stark contrast with the holistic accounts of the face inversion effect, which predicts that an inversion effect should only be observed when the entire face is fully visible. These findings further support the view that the inversion effect does not fully disrupt holistic processing (Gerlach & Mogensen, 2023; Murphy et al., 2020; Richler et al., 2011b), at the same time providing a paradigm that systematically disrupts or facilitates holistic processing.

Interestingly, the FTAP is also a good paradigm to measure individual differences in holistic and featural processing. For example, using the FTAP, Tsantani et al. (2020) showed that DPs were less accurate in recognising upright faces in both the whole as well as the aperture conditions, compared to typical adults without face recognition deficits. Poor recognition with the aperture was interpreted as a difficulty in DPs to extract and accumulate featural information from faces. However, the magnitude of the holistic advantage (i.e., higher accuracy in the whole compared to the aperture condition) was similar between DPs and typical adults, showing that DPs also rely on holistic processing, perhaps to a similar extent. This suggests that DPs have impaired featural processing but not necessarily impaired holistic processing. Although these findings challenge the common view that face recognition deficits are caused by impairments in holistic processing (Avidan et al., 2011; DeGutis et al., 2012; Susilo & Duchaine, 2013), Tsantani et al. (2020) show that the FTAP could differentiate between holistic and featural processing capabilities in individuals with face recognition deficits.

5.4 Unfamiliar Face Learning and Recognition

Recognising the identify of an unfamiliar face is a product of at least two exposures to the same face. In its simplest order, the first exposure results in the observer learning the identity of the face and during the second exposure, the observer recognises a face they have learnt before. Neuroimaging evidence has shown that: 1) distinct brain regions are involved during the learning and recognition of faces (Haxby et al., 1996), and 2) distinct brain mechanisms are affected by manipulations of holistic and featural information in faces (Júnior et al., 2014; Mercure et al., 2008). Interestingly, most studies attempting to examine the contribution of holistic and featural processing to face identification do not specifically address the role of these processes in the learning and recognition of faces.

To the best of our knowledge, only one study has attempted to directly examine holistic and featural processing across these two stages. For instance, Tanaka et al. (2019) employed the part-whole task, in which the target identities were learnt (in upright or inverted orientation) and tested (i.e., recognition of target faces as a whole or parts), either immediately, one, or two weeks after learning. When target faces were learnt in an upright orientation, participants showed significant PWE when recognizing upright but not inverted faces, regardless of the retention period. However, when target faces were learnt in their inverted orientation (i.e., disrupted holistic processing), no PWE was found when recognizing either upright or inverted faces, and their accuracy was declining with increasing retention period. If it is assumed that upright faces are processed more holistically than inverted faces, the findings above indicate that holistic processing facilitates both face learning and recognition, wherein facial information can be efficiently encoded and/or retrieved from long-term memory. However, given that inverted faces may not be a good representation of featural processing (Gerlach & Mogensen, 2023; Murphy & Cook, 2017), the role of processing individual features at different stages of face recognition remains unclear.

Additionally, other studies have used oculomotor behaviour to index the processes involved during visual sampling (Holmqvist & Andersson, 2017). Measuring fixations, Henderson et al. (2005) found that face recognition is better if observers were allowed to freely fixate on the face during learning, rather than being forced to learn faces with just a single fixation. Further, eye movement patterns during recognition were comparable between conditions in which participants learnt faces by freely fixating them and by means of a single fixation. These findings suggest that, although recognition ability depends on how observers sampled facial information during learning, the information sampling strategy employed by observers during recognition is independent of how faces were learnt. Henderson et al. also reported that when observers freely fixated on faces during learning and recognition, they were largely directed at internal facial features. Although these fixations were attributed to processing holistic information (i.e., configural distance between features), we could also assume that they served a simpler purpose of separately encoding individual features at high resolution, in other words, featural processing (Hills, 2018; Lee et al., 2022b). Lastly, Henderson et al. (2005) also reported that fixations during recognition were much more restricted than those during learning (when free viewing was allowed). This could suggest greater reliance on featural processing during learning, or greater reliance on holistic processing during recognition. While both interpretations are possible, there is no way to be certain of the purpose of fixations, as they can be used, at best, as indirect measures of these processes (Lee et al., 2022b).

A recent study by Dunn et al. (2022), using a gaze-contingent paradigm, further examined the contributions of both holistic and featural processing in the individual differences of face recognition, at the learning and recognition stages. Faces were viewed either in full-view or through circular apertures varying in sizes. When observers were allowed to sample faces freely during face learning and face recognition, super-recognizers (SRs) had a broader gaze distribution and more exploratory fixations than control participants. Most importantly, SRs were consistently better than control participants regardless of the aperture size. This indicates that the underlying perceptual processes contributing to superior face recognition can be explained by featural processing. Interestingly, these differences were more evident during face learning than during face recognition, in which Dunn et al. coined SRs to be “super-learners”. In line with Henderson et al. (2005), these findings suggest that broader exploration of the face during face learning facilitates face recognition and could quantitatively explain individual differences in face recognition.

Despite that, even though the aperture sizes were increased in subsequent experiments by Dunn et al. (2022) as means to promote holistic processing, it was observed that SRs engaged in more explorations. This implies that even in the presence of holistic information, SRs continue to depend on featural information, suggesting that holistic processing cannot be solely explained by individual differences in FRA. Nonetheless, it remains unclear whether increasing the size of the aperture effectively allows holistic information to become more available, particularly when the gaze-contingent paradigm is used. For instance, the visual input of participants is dependent on their sampling strategies (for discussion, see Murphy & Cook, 2017). Although increasing aperture sizes may allow extracting more configural information, whole-face processing was still disrupted. Consequently, the increase of exploratory fixations during face learning seen in SRs could be the result of accumulating featural information for integration into a whole representation (Gold et al., 2012). Here, it is unclear if SRs gaze patterns facilitate this accumulation for holistic integration or the result of better featural processing. Thus, using the FTAP in the learning and recognition stages separately allows us to better assess the contribution of holistic and featural processing at each stage.

We aimed to quantify to what extent individual differences in FRA are quantitatively related to holistic and featural processing in typical adults, particularly during face learning and face recognition stage. To this end, we used an old/new recognition memory task (RMT) incorporating the FTAP to measure holistic and featural processing abilities in our participants. In addition, to measure individual differences in face recognition, observers performed the Cambridge Face Memory Test – Chinese (CFMT-Chi; McKone et al., 2012b), a highly reliable and valid measure of individual differences in face recognition skills (Duchaine & Nakayama, 2006; Hendel et al., 2019; Russell et al., 2009). Recognition performance in the aperture condition of the FTAP informs us how good our participants are with featural processing. Correlating this with the CFMT-Chi scores would tell us to what extent featural processing contributes to FRA. The improvement in performance in the whole condition compared to the aperture condition of the FTAP informs the magnitude of the holistic advantage experienced by participants, i.e., how good they were with holistic processing. Correlating this holistic advantage with the CFMT scores would tell us to what extent holistic processing contributes to FRA.

5.6 Experiment 1: Face Learning

Experiment 1 examined if face recognition ability was related to differences in people's ability to process faces through an aperture or as a whole during face *learning*. Based on previous findings that showed identification is impaired due to disruption towards holistic processing by an aperture (Murphy et al., 2020; Murphy & Cook, 2017; Tsantani et al., 2020), we expect participants' recognition performances to be significantly impaired when faces are shown through an aperture. Further, given that holistic (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012) and featural processing (Dunn et al., 2022; Tsantani et al., 2020) have been shown to play an important role for face recognition, we expect participants' FRA, as measured by the CFMT-Chi, will positively correlate with the increased ability to accurately recognise faces in the aperture and whole conditions.

5.7 Methods

5.7.1 Participants

An *a-priori* power analysis using G*Power (Faul et al., 2007) estimated that a sample size of 82 is required to obtain a moderate effect size of 0.3 with a statistical power of 80% (α = .05), for a Pearson's test of correlation between FRA and the conditions of the RMT. We recruited 87 Malaysian Chinese (44 females) participants with no known clinical diagnosis of a mental health disorder, with ages ranging from 18-54 years (*M*= 25.00 years, *SD*= 5.29). Participants were paid 5 Malaysian Ringgits as compensation for their time. All participants reported normal or corrected-to-normal vision. A digital informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ210421).

5.7.2 Apparatus

This study was conducted using the online experimental platform Testable (www.testable.org; Rezlescu et al., 2020). The study comprised two tasks: the CFMT-Chi (McKone et al., 2012b) and an old/new recognition memory task (RMT) with two viewing conditions (whole or aperture viewing). Participants used their own computers (laptops or desktops) to complete the two tasks online in a web browser. To minimise differences in the visible size of stimuli across different computer screens, participants were required to adjust the length of a horizontal yellow line that appeared on the screen to match the size of a debit/credit card they possessed. Based on this, the testing platform calculates how many pixels correspond to one centimetre, and all stimuli within the study were rescaled using this mapping to the required dimensions in centimetres. All face stimuli were edited and cropped using Abobe Photoshop CS6, while the dynamic aperture was created in Matlab R2019b (Mathworks, Version 9.7.0.1247435).

5.7.3 Stimuli and Procedure

Cambridge Face Memory Test – Chi (CFMT-Chi)

We used the validated Chinese version of the Cambridge Face Memory Test (i.e., CFMT-Chi). All faces and procedures were those used in the original paper (McKone et al., 2012b). For detailed stimuli and procedural description, refer to Chapter 1 (p. 59 – 61).

Old/New Recognition Memory Task (RMT)

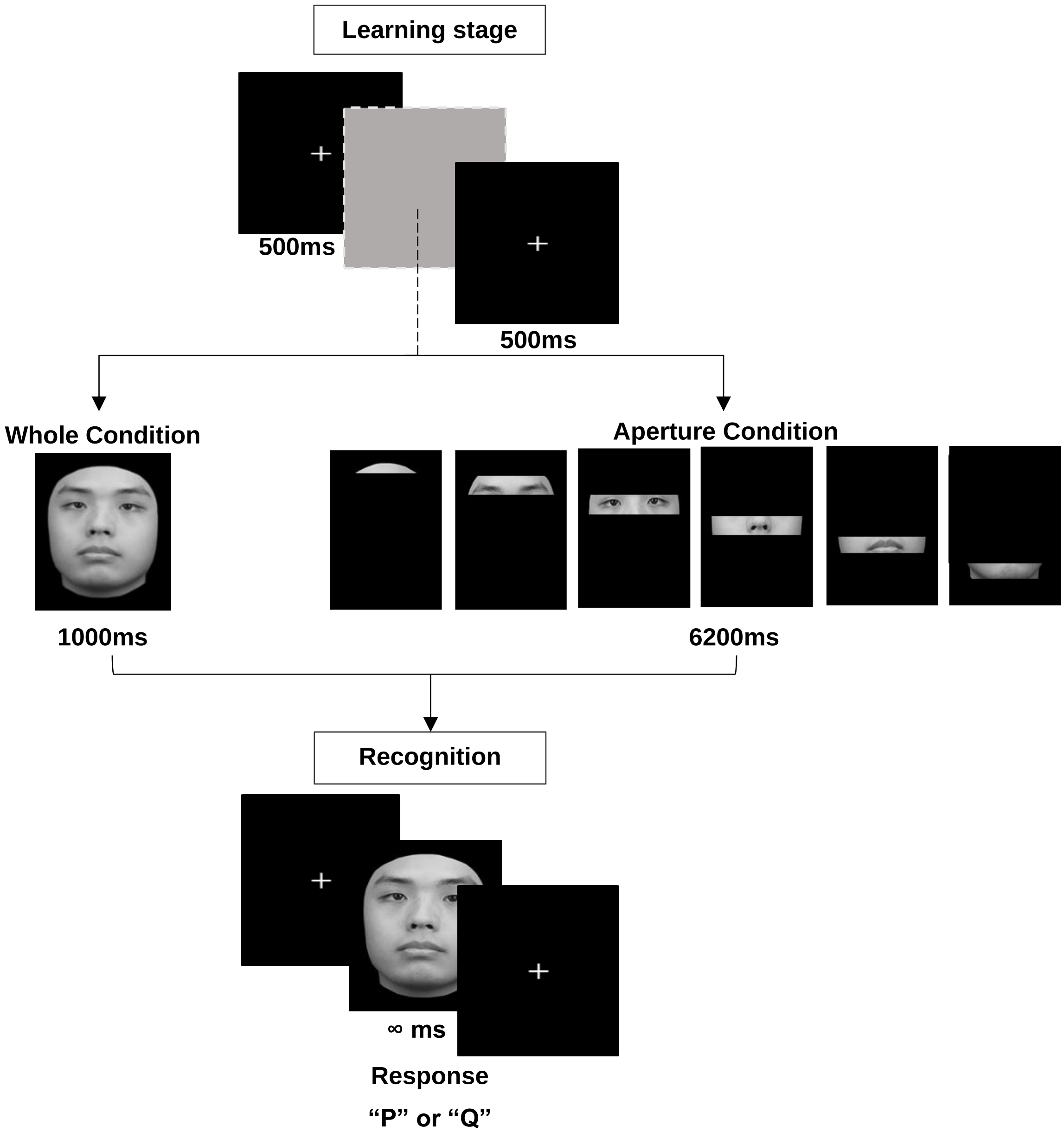
Face images were those of Malaysian Chinese males in their early or mid-20s in neutral expressions. All individuals were photographed in the same range of poses and lighting conditions in the Face Laboratory at the University of Nottingham Malaysia. For each identity, only frontal view face images were used. All external features in the faces were removed. The faces were then resized to approximately 160 px in width and exactly 195 px in height (subtending approximately 3.2° × 4° at a viewing distance of 57 cm), converted into grey-scale and embedded in the centre of a uniformly black background of 200 × 250 px (4 × 5 cm).

The RMT consisted of four blocks (two whole and two aperture conditions). The four blocks were randomized across participants. Each block started with an initial “learning” stage, followed by a filler task and finally a “recognition” stage. In any given block, the learning stage showed faces of six unique identities to participants. The recognition stage sequentially presented the same six identities (“old”) randomly intermixed with 6 new and unique identities that the participants had not seen before (“new”), leading to a total of 12 test faces. This led to a total of 48 unique faces (e.g., 24 old and 24 new unique identities) that were used throughout the entire experiment. In the learning stage of the “whole” condition, each trial started with a white central fixation cross (22 × 22 px; 0.4 × 0.4 cm) shown for 500 ms, followed by a fully visible unique face stimulus presented in the centre of the screen for 1000 ms (Figure 5.1). Old faces presented in the “whole” condition during the recognition stage are exactly the same as those in the learning stage. In contrast, in the learning stage of the “aperture” condition, the face image was shown through a dynamic window that moved smoothly from the top of the face to the bottom, revealing features of the face in a sequential order (Figure 5.1). The dynamic window started and ended with a fully black display. The height of the aperture that moved from top to bottom was 12% (i.e., 30 px) of the overall height of the face and took approximately 6200 ms to move across the entire face (i.e., black-to-black display). The sequential display and frame rate generated a smooth aperture motion (~11 frames per second). All sequences were constructed from a series of bitmap images and saved as .GIF files. For both conditions, six of such trials were presented in the learning stage, and participants were asked to learn and memorize all six faces for a subsequent recognition stage. This led to a total of 24 unique faces (e.g., six faces from two conditions with two blocks each) that needed to be learnt throughout the entire experiment.

Following the learning stage, in both conditions, participants were given a short filler task that involved mathematical calculations (e.g., “5 – 6 / 2 + 10 = ?”), which took less than a minute to complete. This was followed by the recognition stage. During this stage, the 12 test faces were sequentially presented over 12 trials. Each trial began with a 500 ms presentation of a white central fixation cross. This was followed by the presentation of a fully visible face that remained on the centre of the screen until a response was recorded. The participants were required to indicate whether they had previously seen this face in the learning stage, by pressing the key “Q” on the keyboard if they have seen it and the key “P” if they have not seen it before. Participants were instructed to respond as quickly and accurately as possible. In both stages, the presentation timing was adopted from previous studies using the FTAP (Murphy & Cook, 2017; Murphy et al., 2020; Tsantani et al., 2020). In the whole condition, old faces presented during recognition and learning were both fully visible. However, in the aperture condition, old faces shown during learning were viewed through an aperture and when the same identities were shown during recognition, they were fully visible.

Figure 5.1

Chronological procedure (in Experiment 1) and examples of stimuli in a single trial of the old/new recognition memory task.



Note. In the aperture condition (centre right), a dynamic window moves smoothly across the face image from top to bottom (images from left to right). In Experiment 2, the aperture condition was moved to the recognition stage instead.

5.8 Results

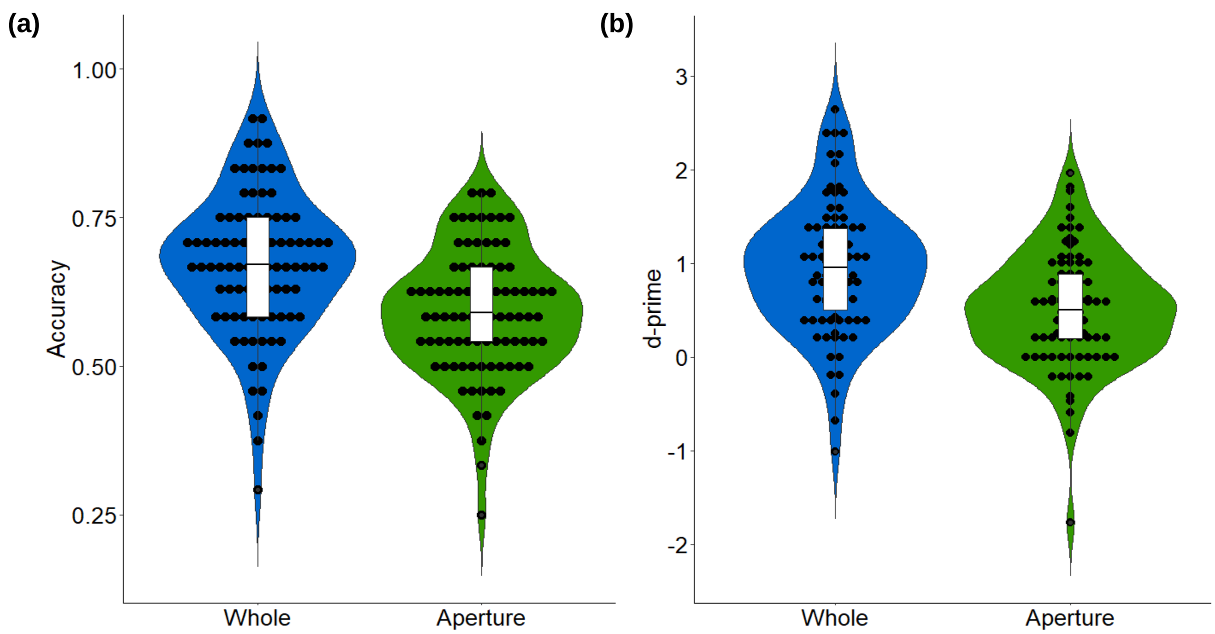
Our main measure of face recognition ability was the CFMT-Chi score, which denoted the sum of correct responses. The maximum achievable score for the CFMT-Chi is 72, in which our current sample had a mean score of 57.98 (*SD* = 8.93). This shows that our participant samples are largely similar to those of previous studies (Estudillo, 2021; Estudillo et al., 2020; Estudillo et al., 2021; McKone et al., 2012b, 2017).

Mean accuracy scores of the RMT were calculated separately for each of the two viewing conditions: "whole" and "aperture" (see Figure 5.2a). Two-tailed paired samples *t*-tests were conducted to compare accuracy scores between the two conditions of the RMT. We found a significant difference in the mean scores between the conditions, $t(86) = 5.67$, $p < .001$, $\eta_p^2 = .607$, in which mean accuracy in the whole condition ($M = 0.672$, $SD = 0.117$) was significantly higher than that of the aperture condition ($M = 0.590$, $SD = 0.104$). A one-sample t-test revealed that the accuracy in the aperture conditions was significantly better than chance (accuracy more than 0.5) at the group level: $t(86) = 7.978$, $p < .001$.

We also recorded the mean hit rates and false alarm rates in the RMT, separated based on the viewing conditions, to calculate *d*-prime scores (i.e., a measure of sensitivity; see Tajika, 2001) using the R package *psycho* (Makowski, 2018). This was done to obtain a purer measure of recognition performance that is not affected by response bias (Stanislaw & Todorov, 1999). Likewise, two-tailed paired samples *t*-tests were conducted to compare sensitivity scores between the two conditions of the RMT (see Figure 5.2b). We found a significant difference in the mean scores between the conditions, $t(86) = 5.34$, $p < .001$, $\eta_p^2 = .572$, in which mean *d*-prime in the whole condition ($M = 0.950$, $SD = 0.686$) was significantly higher than that of the aperture condition (M = 0.503, SD = 0.607). Above chance performance was also replicated with *d*-prime scores (more than zero), $t(86) = 7.726$, $p < .001$.

Figure 5.2

Mean accuracies and sensitivity scores for the whole (blue) and aperture (green) conditions in the RMT.



Note. The violin plot represents the density distribution of accuracy and *d*-prime in each condition. Black-filled circles represent the accuracy scores of individual participants. The horizontal line within the boxplot represents the mean scores, whilst the top and bottom hinge of the boxplot represent the first and third quartiles. The vertical black line outside of each boxplot represents the 95% confidence interval.

We can assume that the accuracy in the aperture condition is largely driven by featural processing. However, in order to calculate how much holistic processing helps in accurate recognition, we need to find out to what extent a condition that facilitates holistic processing (whole condition) improves recognition performance compared to a condition that disrupted holistic processing (aperture condition), i.e., the holistic advantage. We followed two methods to calculate the holistic advantage. One was the conventionally used subtraction method, which has been used by several studies in the past to calculate a holistic advantage (e.g., Konar et al., 2010; Richler et al., 2011a; Wang et al., 2012). In the case of the FTAP, the subtraction method would involve subtracting the mean accuracy/sensitivity in the aperture condition from the mean accuracy/sensitivity in the whole condition. We termed this the "aperture effect" and a positive value here indicates a holistic advantage. However, subtraction methods can be difficult to interpret (DeGutis et al., 2013b; Wilmer, 2017), as a lower value for the aperture effect can indicate close-to-ceiling performance in the aperture condition, close-to-floor performance in the whole condition, or both. To account for this, we also used the "regression" approach (DeGutis et al., 2013b; Rezlescu et al., 2017) to calculate the holistic advantage experienced by participants in the whole condition, after accounting for the variation in performance that the whole condition shares with the aperture condition. Using the equation of the line of best fit of the overall scores, each participant's expected score on the whole condition (i.e., residual scores) was calculated based on their performance in the aperture condition. Here, accuracy/sensitivity in the aperture condition is regressed from the whole condition to compute residuals, which we termed "residuals of aperture effect" (RAE). A higher RAE score indicates stronger holistic processing.[1]

Next, we ran a number of Pearson's product-moment correlation tests for the data obtained. First, to explore if both tasks are measuring similar constructs, we correlated the accuracies of the whole condition in the RMT with the CFMT-Chi scores. The test showed a

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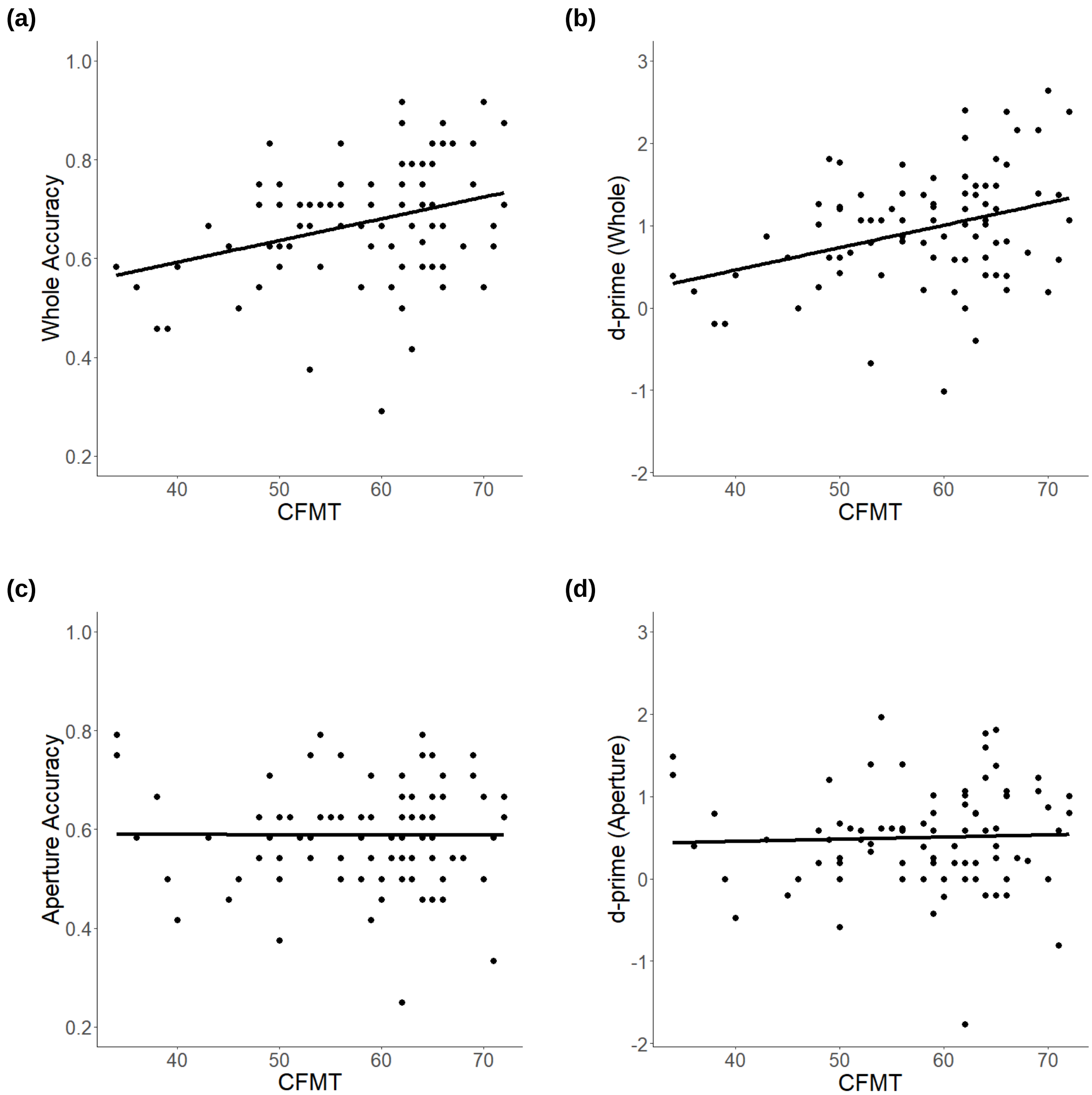
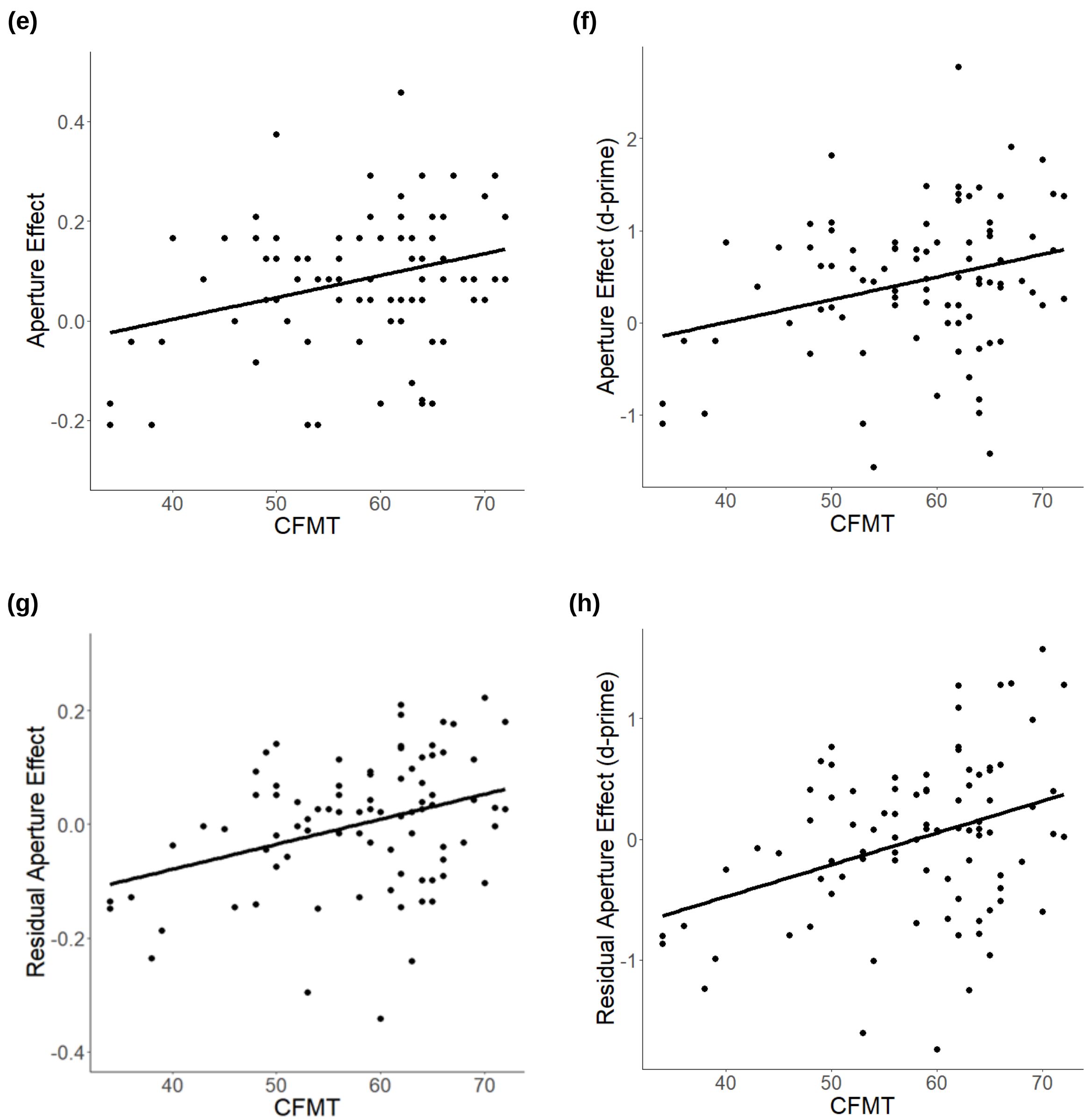
[1] The regression approach assumes that the relationship between the two variables, whole and aperture accuracies, are linear. To test this assumption, we correlated the accuracy scores of both conditions. In fact, we found a significant correlation between both conditions, $r(85) = .264$, $p = .013$. Likewise, we replicated this with d-prime scores, $r(85) = .274$, $p = .010$.

significant positive correlation between the two tasks, $r(85) = .334$, $p = .002$ (refer to Figure 5.3a). This positive association between the whole condition and CFMT was replicated with *d*-prime scores, $r(85) = .355$, $p < .001$ (refer to Figure 5.3b). Second, to explore the relationship between featural processing ability and FRA, we correlated the accuracies of the aperture condition with the CFMT-Chi scores, and the test showed no significant correlation between the two, $r(85) = -.002$, $p = .986$ (refer to Figure 5.3c). Similarly, we found that the association between *d*-prime scores in the aperture condition and CFMT did not reach significance, $r(85) = .039$, $p = .722$ (refer to Figure 5.3d). Third, to explore the relationship between holistic processing ability and FRA, we correlated measures of holistic advantage with CFMT-Chi scores. There was a significant positive correlation between aperture effect scores and CFMT-Chi scores, $r(85) = .292$, $p = .006$ (refer to Figure 5.3e). We also found a significant positive correlation between aperture effect scores (based on *d*-prime) and CFMT-Chi scores, $r(85) = .282$, $p = .008$ (refer to Figure 5.3f). Further, there was a significant positive correlation between the RAE scores and CFMT-Chi scores, $r(85) = .347$, $p < .001$ (refer to Figure 5.3g). Similarly, we found a significant positive correlation between RAE scores (based on *d*-prime) and CFMT-Chi scores, $r(85) = .358$, $p < .001$ (refer to Figure 5.3f). These correlations showed that with increasing holistic advantage, there is an increase in FRA.

Figure 5.3

Correlation analyses between face recognition abilities with featural and holistic processing.





Note. Black-filled circles represent scores from individual participants. Black solid lines are least-squares regression fits to individual data.

5.9 Discussion

The current experiment aims to investigate the role of holistic and featural processing in face recognition ability (FRA), specifically, during face learning. The findings showed that forcing observers to rely on featural processing with a small aperture during face learning reduced recognition accuracy and sensitivity significantly. We found that accuracy and sensitivity for recognising faces learnt through featural processing were uniform, *albeit* poor, across the whole spectrum of FRA. In contrast to previous studies (Dunn et al., 2022), our findings suggest that featural processing during face learning does not contribute to face recognition ability.

Moreover, our correlation analyses revealed a significant relationship between holistic processing and FRA. Based on the aperture effect scores using the subtraction method (i.e., whole - aperture), we found that people better in FRA are also better at holistically processing faces during face learning. Similarly, the RAE scores using the regression method (i.e., whole ~ aperture) also showed that people's ability to process faces holistically during face learning could be a strong determinant of their FRA. The relationships found with both analyses further support that higher face recognition abilities are associated with stronger holistic processing (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012).

Overall, the current experiment showed that disrupting holistic processing by forcing participants to learn faces through an aperture significantly impaired face recognition. The findings also revealed that enhanced holistic (but not featural) processing during face learning contributes to individual differences in FRA.

5.10 Experiment 2: Face Recognition

To quantify to what extent individual differences in FRA are quantitatively related to holistic and featural processing in typical adults at the face recognition stage, we ran a second experiment. Similar to the prior experiment, we used an old/new RMT incorporating the FTAP to measure holistic and featural processing abilities in our participants, and the CFMT-Chi (McKone et al., 2012b) to measure individual differences in face recognition. However, to explore these relationships separately at the stages of learning and recognising faces, the following changes were made. In Experiment 1, during learning, some faces were viewed through an aperture (“aperture condition”), and some were viewed in their entirety (“whole condition”), whereas during recognition all faces were viewed in their entirety. This manipulation was reversed in the current experiment (i.e., Experiment 2). In the current experiment, all faces were viewed in their entirety during learning. However, during recognition, some faces were viewed through an aperture while others were viewed in their entirety. This allowed us to isolate the contribution of holistic and featural processing during face recognition to FRA.

5.11 Methods

5.11.1 Participants

We recruited 86 healthy typical Malaysian Chinese participants (70 females), with age ranging from 18 to 47 years (M= 22.34 years, SD= 5.10). Participants were paid five Malaysian Ringgits as compensation for their time. All participants reported normal or corrected-to-normal vision. A digital informed consent was obtained prior to participation. All experimental procedures were approved by the Science and Engineering Research Ethics Committee of the University of Nottingham Malaysia (approval code: BLQZ210421).

5.11.2 Apparatus, Stimuli and Procedure

The apparatus, stimuli and procedure of the current experiment are identical to the preceding experiment, except for the following changes in the old/new RMT. Irrespective of the experimental condition (whole or aperture), participants were always shown a white central fixation cross, followed by fully visible faces for 1000 ms in the learning stage. A total of six target faces were shown in each block. During the "recognition stage", they were shown with the 12 test faces that were either in full-view (for the "whole" condition) or viewed through an aperture (for the "aperture" condition). Faces to be recognised stayed on screen for the same duration of 6200 ms in both conditions, and this was followed by a black screen that remained until a response was recorded.[2] Responses could also be provided while the faces were shown or after the faces were removed from the screen, either of which terminated the trial. Similar to Experiment 1, participants pressed the key "Q" or "P" to indicate whether they have seen each test face in the learning stage or not, respectively.

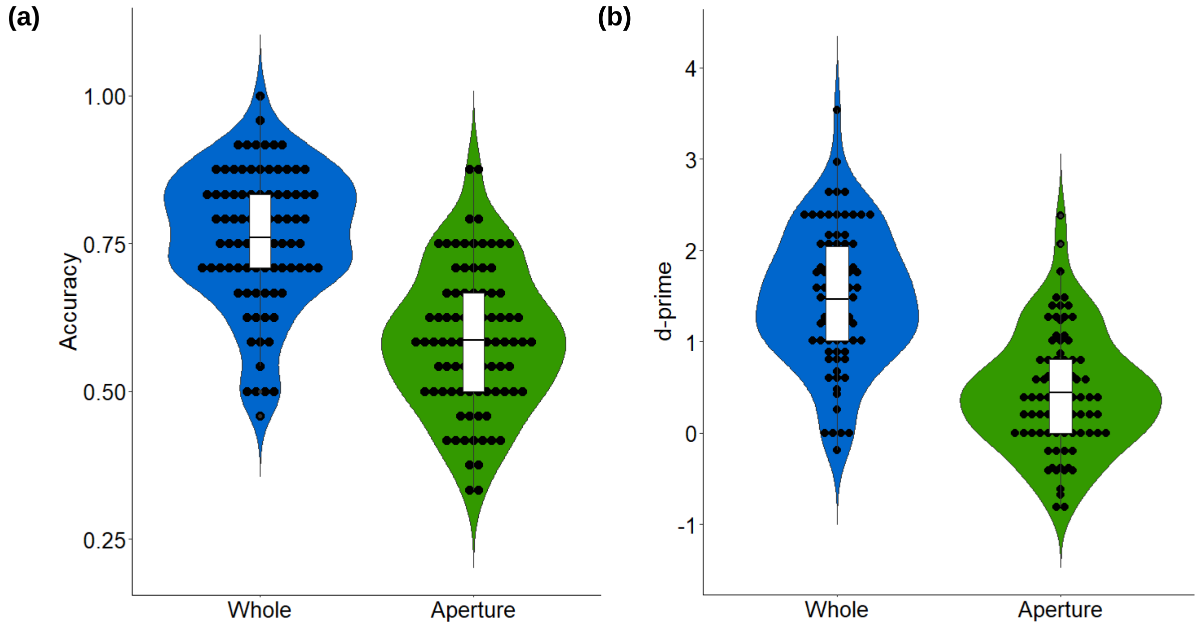
5.12 Results

The current sample had a mean score of 58.28 (*SD* = 8.53) in the CFMT-Chi. Mean accuracy and *d*-prime scores of the RMT were calculated separately for each of the two viewing conditions: "whole" and "aperture" (see Figure 5.4).

[2] In Experiment 1, the test faces remained on screen indefinitely irrespective of the experimental condition. To achieve the same consistency between experimental conditions in Experiment 2, we made the presentation duration of test faces identical (6200 ms) for both whole faces and faces viewed through an aperture.

Figure 5.4

Mean accuracies and sensitivity scores for the whole (blue) and aperture (green) conditions of the RMT.



Note. The violin plot represents the density distribution of accuracy and *d*-prime in each condition. Black-filled circles represent the accuracy scores of individual participants. The horizontal line within the boxplot represents the mean scores, whilst the top and bottom hinge of the boxplot represent the first and third quartiles. The vertical black line outside of each boxplot represents the 95% confidence interval.

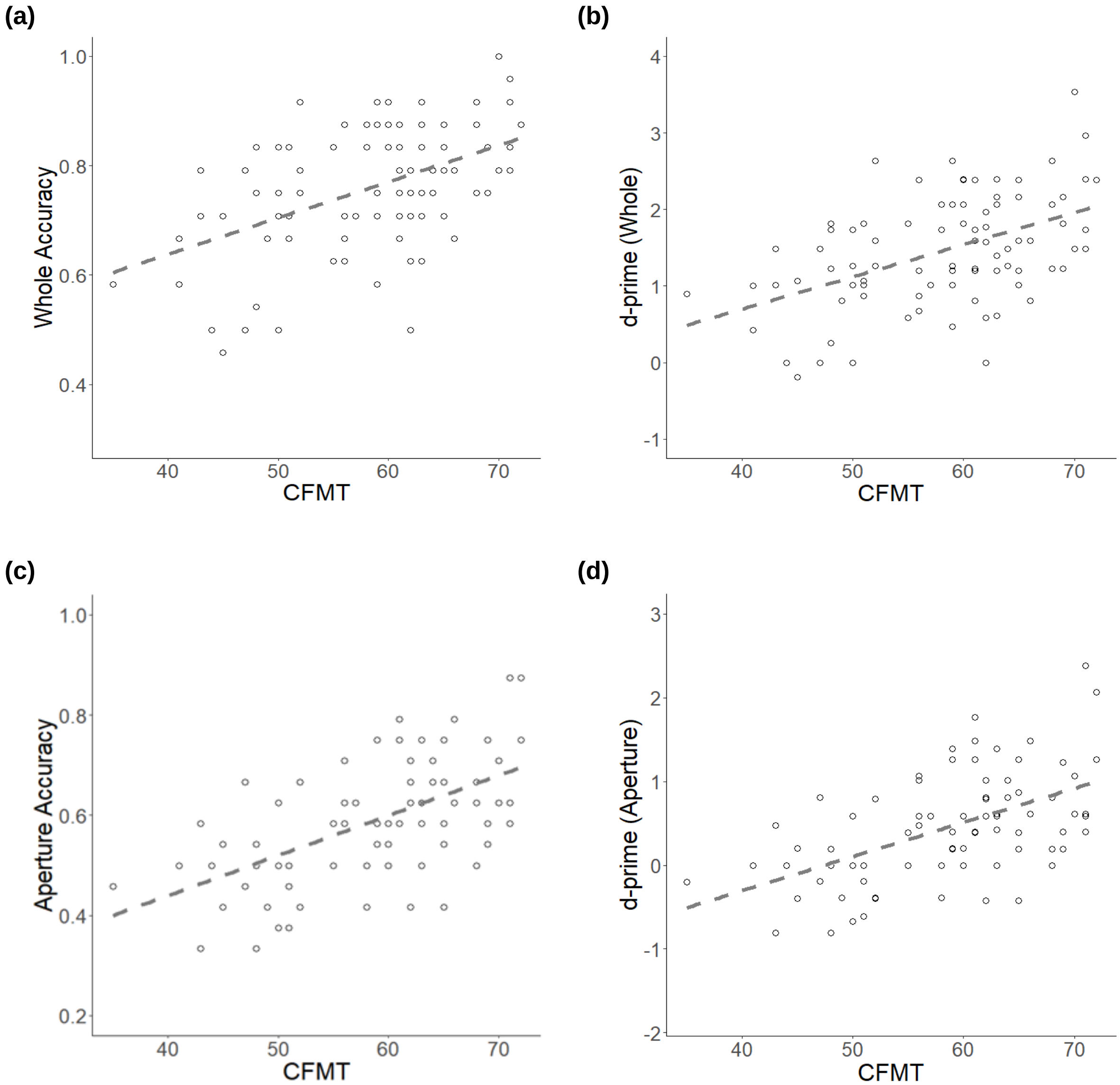
Two-tailed paired samples *t*-tests were conducted to compare accuracy scores between the two conditions of the RMT. We found that there was a significant difference in accuracy between the two conditions, $t(85) = 11.21$, $p < .001$, $\eta_p^2 = 1.209$, in which mean accuracy for the whole condition ($M = 0.759$, $SD = 0.116$) was higher than that of the aperture condition ($M = 0.586$, $SD = 0.120$). One-sample t-tests revealed that the accuracy in the aperture conditions was significantly better than chance (accuracy more than 0.5) at the group level, $t(85) = 6.638$, $p < .001$.

We also conducted two-tailed paired samples *t*-tests to compare *d*-prime scores between the two conditions of the RMT. We found a significant difference in the mean scores between the conditions, $t(85) = 11.750$, $p < .001$, $\eta_p^2 = 1.267$, in which mean *d*-prime in the whole condition ($M = 1.468$, $SD = 0.733$) was significantly higher than that of the aperture condition ($M = 0.440$, $SD = 0.636$). Similarly, above chance performance was also replicated with *d*-prime scores (more than zero), $t(85) = 6.417$, $p < .001$.

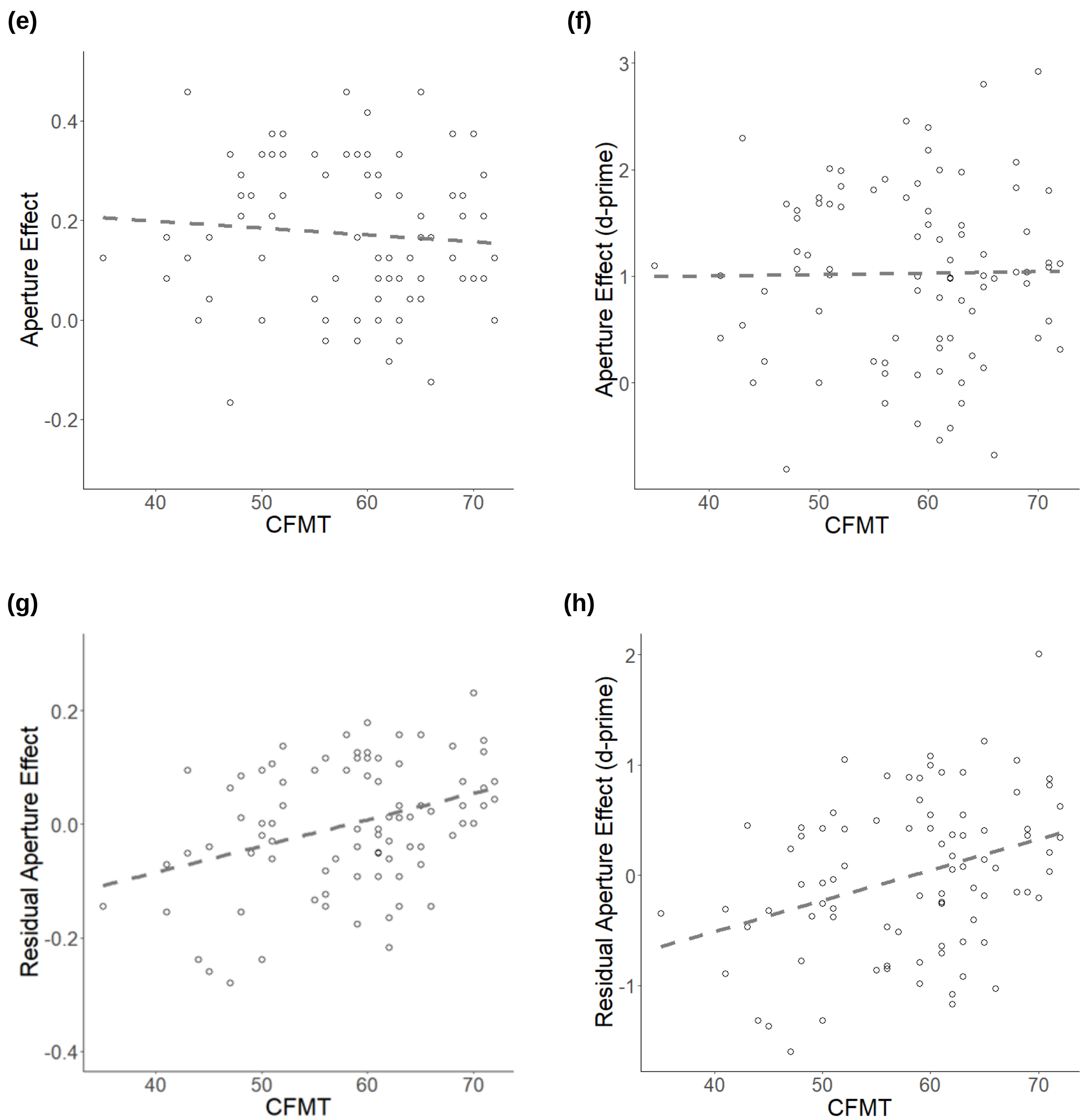
Likewise the previous experiments, the holistic advantage was calculated using subtraction and regression methods and ran a number of Pearson's product-moment correlation tests. We found a positive correlation between the accuracy in the whole condition and their respective scores on the CFMT-Chi, ($r(84) = .489$, $p < .001$, refer to Figure 5.5a). This positive association between the whole condition and CFMT was replicated with *d*-prime scores, $r(84) = .490$, $p < .001$ (refer to Figure 5.5b). Additionally, there was also a strong positive correlation between the accuracy in the aperture condition and their respective scores on the CFMT-Chi ($r(84) = .570$, $p < .001$, refer to Figure 5.5c). Similarly, we found a positive association between *d*-prime scores in the aperture condition and CFMT, $r(84) = .546$, $p < .001$ (refer to Figure 5.5d). Specifically, the higher the participants' FRA, the more accurate they were in the "aperture" condition. Further, there was no correlation between the aperture effect and CFMT-Chi scores ($r(84) = -.082$, $p = .455$, refer to Figure 5.5e). We also found a significant positive correlation between aperture effect scores (based on *d*-prime) and CFMT-Chi scores, $r(84) = .014$, $p = .898$ (refer to Figure 5.5f). In contrast, there was a significant positive correlation between the RAE and CFMT-Chi scores, $r(84) = .354$, $p < .001$ (refer to Figure 5.5g). Similarly, we found a significant positive correlation between RAE scores (based on *d*-prime) and CFMT-Chi scores, $r(84) = .340$, $p = .001$ (refer to Figure 5.5h). This suggests participants with higher FRA have a higher magnitude of holistic advantage, but only when the variability of featural processing was removed.[3]

Figure 5.5

Correlation analyses between face recognition abilities with featural and holistic processing.



[3] To test for the assumption of linearity, we correlated the accuracy scores of the whole and aperture conditions in the RMT. We found a significant correlation between both conditions, $r(84) = .258$, $p = .017$. Similarly, we duplicated this pattern using *d*-prime scores, $r(84) = .305$, $p = .004$.



Note. Grey annuluses represent scores from individual participants. Grey dashed lines are least-squares regression fits to individual data.

Furthermore, to compare the strengths of correlations with CFMT-Chi between conditions of the RMT, we transformed the Pearson's correlation coefficient values into *z* scores (Hinkle et al., 1988). The correlation coefficients between aperture accuracy with CFMT-Chi, and RAE with CFMT-Chi, were significantly different ($z = 1.788$, $p = .032$). Subsequently, the coefficients between aperture *d*-prime with CFMT-Chi, and RAE (based on *d*-prime) with CFMT-Chi, were significantly different (z = 1.666, p = .048). Specifically, the correlation with CFMT-Chi was stronger for aperture accuracy (i.e., featural processing) than RAE scores (i.e., holistic processing).

Comparisons across experiments

We also ran multiple analyses to compare performances across experiments. As revealed by a two-tailed independent-samples *t*-test, the mean CFMT-Chi scores for both experiments were not significantly different from each other, $t(171) = -0.23$, $p = .820$, $\eta_p^2 = -.035$. This shows that our participant samples are largely similar between the two experiments as well as to those of previous studies (Estudillo, 2021; Estudillo et al., 2020; Estudillo et al., 2021; McKone et al., 2012b, 2017). A further independent-samples *t*-test confirmed that these mean aperture accuracies in the RMT are comparable between experiments, $t(172) = .222$, $p = .824$. In addition, we also compared the strengths of correlations between the two experiments, using their *z*-scores (Hinkle et al., 1988). We found a significant difference in coefficients between Experiment 1 and 2 for the correlations between aperture accuracy and CFMT-Chi (z = -4.197, p < .001), but not for the correlations between RAE and CFMT-Chi (z = -.050, p = .960). Subsequently, the analyses also found a significant difference in coefficients between Experiment 1 and 2 for the correlations between aperture *d*-prime and CFMT-Chi (z = -3.710, p < .001), but not for the correlations between RAE (based on *d*-prime) and CFMT-Chi (z = .137, p = .891). Specifically, both analyses revealed that the correlation coefficient between aperture recognition performance and CFMT-Chi was larger in Experiment 2 than in Experiment 1. Lastly, for the correlations between whole condition's accuracy and CFMT-Chi scores, the coefficients were comparable between Experiments 1 and 2 (z = -1.211, p = .113). This association was also replicated using *d*-prime scores (z = -1.066, p = .143).

Although the overall aperture condition accuracies were above chance at the group level, the associations (or the lack of it) between aperture accuracies/RAE scores and CFMT-Chi could be driven by *near or below chance* performances in some participants (i.e., floor effects). To address this concern, we identified individuals who did not perform above chance levels and removed them from the correlation tests. For this purpose, we used the binomial distribution and calculated the accuracy required to reject the null hypothesis that accuracy was simply based on guessing. Given that we had 24 trials per condition, with a chance-level performance set at 0.5, we estimated that above chance performance is characterised 17 or more correct trials per condition. The cumulative binomial probability that this accuracy (or higher) occurs if the null hypothesis is true is 0.032, which is less than the significance criterion of α = 0.05. Accordingly, for the correlations between aperture accuracy and CFMT-Chi, we only included participants with 17 or more correct trials (16 and 18 participants for Experiment 1 and 2, respectively), and the same for the correlation between whole accuracy and RAE scores with CFMT-Chi (41 and 60 participants for Experiment 1 and 2, respectively).

For Experiment 1, there was a significant positive correlation between the whole accuracy and CFMT-Chi, $r(39)$ = .380, p = .014, but not between aperture accuracy and CFMT-Chi, $r(14)$ = -.363, p = .167. There was also a significant positive correlation between the RAE scores and CFMT-Chi scores, $r(39)$ = .325, p = .038. For Experiment 2, we found significant positive correlations between the accuracy in the whole condition and participants' respective scores on the CFMT-Chi, $r(58)$ = .327, p = .011, accuracy in the aperture condition and their respective scores on the CFMT-Chi, $r(16)$ = .534, p = .022, as well as between the RAE scores and CFMT-Chi scores, $r(58) = .289$, $p = .025$. While the pattern of results remains similar to what were reported in the main analyses, the significance levels of the correlations reported here are relatively lower. This most likely reflects the exclusion of a significant number of participants from the main analysis. Overall, these findings further confirm our interpretations that the difference in associations between featural processing and face recognition ability during different stages of face recognition is not due to floor effects.

5.13 Discussion

The current experiment aims to examine the role of holistic and featural processing in face recognition ability (FRA), particularly during the face recognition stage. First, we found that forcing observers to rely on featural processing with a small aperture reduced recognition accuracy and sensitivity significantly. Importantly, we found that accuracy and sensitivity for recognising faces through featural processing varied as a function across the whole spectrum of FRA. This suggests that featural processing during face recognition contributes to identifying learnt faces, and it is in support of past findings showing that good recognisers make good use of featural processing when attempting to recognise a learnt face.

Consequently, we assessed the relationship between holistic processing and FRA. Based on the aperture effect scores using the subtraction method, we found that people better in FRA were not better in holistically processing faces during face recognition. In contrast, our RAE scores showed that people's ability to process faces holistically during face recognition could be a strong determinant of their FRA. The current findings indicate that higher face recognition abilities are associated with stronger holistic processing (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012), however, this significant association is dependent on how holistic advantage is calculated.

In short, the second experiment showed that disrupting holistic processing during the face recognition stage impairs the ability to identify learnt faces. Additionally, we found that poor FRA arises from the lesser reliance on holistic and featural information during face recognition. Overall, the findings across both experiments suggest that the role of holistic and featural processing in FRA is distinct at different stages of face recognition.

5.14 General Discussion

The purpose of the present study was to examine the role of holistic and featural processing in face recognition ability (FRA). Both experiments showed that forcing observers to rely on featural processing with a small aperture reduced recognition performances (both accuracy and *d*-prime) significantly. This impairment was observed irrespective of whether the aperture was applied during face learning or recognition. One unique characteristic of our study is that we measured to what extent featural and holistic processing can explain FRA at different stages of face recognition, separately. In Experiment 1, we found that accuracy and sensitivity for recognising faces learnt through featural processing were uniform, *albeit* poor, across the whole spectrum of FRA. To our knowledge, no past study had systematically restricted participants along the FRA spectrum to both featural and holistic processing during face learning. Accordingly, our findings are novel in isolating the contribution of featural processing during face learning to face recognition ability. Based on our findings, featural processing during face learning does not account for individual differences in face recognition abilities.

In Experiment 2, we found that individuals with better FRA were also better at using featural processing during recognition than individuals with poor FRA. This suggests that featural processing during face recognition contributes to identifying learnt faces, and it is in support of past findings showing that good recognisers make good use of featural processing when attempting to recognise a learnt face. These past studies have used various tasks to assess the contribution of featural processing (e.g., part-whole task, familiar face recognition test) in recognising famous faces as well as recently learnt unfamiliar faces (DeGutis et al., 2012, Tardif et al., 2019; Tsantani et al., 2020). Nonetheless, there are also some exceptions (Dunn et al., 2022; Abudarham et al., 2021). One could argue that the lack of correlation between featural processing ability and FRA in Experiment 1 is a result of floor effects. However, accuracies were above chance and comparable across both experiments. In addition, individual differences in the aperture condition were related to FRA in Experiment 2, but not in Experiment 1. Therefore, floor effects are unlikely to explain a lack of correlation in Experiment 1.

In line with Dunn et al. (2022), we found that featural processing is positively correlated with FRA. However, we only found this association during face recognition and not face learning (i.e., Experiment 1). These disparities could be the result of our viewing manipulations. Dunn et al. allowed observers to actively explore the faces, whereas the FTAP constrained all observers to learn faces in a similar fashion, which could interfere with unique perceptual encoding strategies used by good recognizers. For instance, Dunn et al. found that super recognisers (SRs) had broader gaze distributions and more fixations than typical observers, but these differences were more apparent during face learning. In contrast, Abudarham et al. (2021) showed that Developmental Prosopagnosics (DPs) and SRs are similarly good at featural processing. However, DPs tend to be heterogenous in deficits, with some cases having featural processing deficits and some not (Bennetts et al., 2022; Corrow et al., 2016), and deficits can be qualitatively different from neurotypicals with poor FRA (e.g., atypical sampling of faces; Barton, 2018; Barton & Corrow, 2016; Bobak et al., 2017; Tian et al., 2020).

Next, we assessed the relationship between holistic processing and FRA. Based on the aperture effect scores using the subtraction method (i.e., whole - aperture), we found that people better in FRA are also better in holistically processing faces during face learning (Experiment 1), but not during face recognition (Experiment 2). However, the aperture effect may not be a very informative measure of holistic advantage (DeGutis et al., 2013b; Rezlescu et al., 2017). This is because, although the whole condition facilitates holistic processing, it does not block featural processing. An informative measure must account for the variability in performance due to featural processing in the whole condition and provide an estimate of the increase in performance due to facilitated holistic processing. This is exactly what the RAE scores calculated from the regression method represent. Based on RAE scores, we found that higher FRA is associated with holistic processing in both experiments. Here, we see a clear disparity in the results, depending on the method of calculating holistic advantage. Therefore, we stress on the importance of considering the statistical variability of the control conditions in future experiments when measuring the contribution of holistic processing. If we fail to account for this, we might miss detecting good recognisers' enhanced ability to process faces holistically, due to their increased ability to process faces featurally too (DeGutis et al., 2013b; Sunday et al., 2017). Accordingly, our RAE scores showed that people's ability to process faces holistically (but not featurally) during face learning could be a strong determinant of their FRA. The relationship found in Experiment 2 further supports previous findings showing that higher face recognition abilities are associated with stronger holistic processing (DeGutis et al., 2013b; Richler et al., 2011a; Wang et al., 2012).

Nonetheless, as we find, why would good recognisers rely more on processing holistic but not featural representations of a face during face learning? We encounter a large number of faces in everyday life. Obviously, the more faces we can store in our memory, the better our social interactions would be. However, storing individual features of every single face we encounter would be very taxing for human memory. Holistic representations provide a way of reducing this memory load, by allowing us to store more identities in the form of a simplified gist (Curby & Gauthier, 2007; Pertzov et al., 2020). Moreover, holistic information of faces is more stable in memory than featural information (Rossion, 2013; Richler et al., 2012; Tanaka et al., 2019). For example, Peters and Kemner (2017) showed that long-term memory for faces is better when face identities were learnt from their low spatial frequencies conveying holistic information, than from their high spatial frequencies conveying fine details of features. Given that holistic representations allow us to efficiently utilise memory and form stable traces over time, it would be expected that good recognisers make better use of holistic processing than featural processing during face learning.

Furthermore, some studies have demonstrated that when we attempt to recognise a face, we follow a coarse-to-fine strategy (Gerlach & Starrfelt, 2018b; McKone et al., 2007; Peters et al., 2018). Here, a holistic representation of the to-be-recognised face is initially matched to face representations in our memory to narrow down the most likely candidate representations (Gerlach & Starrfelt, 2018b). Next, in an empirical sense, features of the to-be-recognised face are compared with those selected representations in memory, whereby identity-specific, distinct features could help to distinguish a learnt identity from other similar-resembling faces.

Extending this explanation to our case, it appears important that we compare a to-be-recognised face to memory representations both at the holistic and featural levels, and good recognisers might be adept at doing both.

We would also like to emphasise on an interesting finding of our study. In the aperture condition of Experiment 1, when participants' face learning was restricted to featural processing, even good recognisers failed to use this information. However, in Experiment 2, when we allowed participants to learn faces freely (i.e., not restricting the processing), good recognisers were able to recognise these faces better even when holistic processing was largely interrupted during recognition due to the aperture. As the FRA of participants decreased, this advantage with featural information diminished. Based on this, we can claim that forming a holistic representation when learning a face is also important for good recognisers to effectively use featural information during recognition. If that's the case, a weak holistic representation formed by poor recognisers during learning may have led to poor use of both holistic and featural information during recognition (as shown in Experiment 2; Fig. 5.5).

Notably, we are at odds with Tsantani et al.'s (2020) findings. They manipulated holistic and featural processing at the recognition stage using the same aperture paradigm we employed. Yet, they showed that DPs, who have a deficit in face recognition, have impaired featural processing but not holistic processing. However, as we highlighted above, DPs' deficits are heterogenous and could be qualitatively different from that of neurotypicals, which makes comparisons difficult. From a separate point of view, given that the aperture does not fully block holistic processing, one possibility is that people still engage in some form of holistic processing in the aperture condition (e.g., processing configural information between features). Although speculative, the aperture could also facilitate the integration of sequentially viewed features into a perceptual whole in memory (for discussion, see Gold et al., 2012). In that case, in the aperture condition, these DPs (in Tsantani et al.'s study) could be poor at those possibilities, or good recognisers in our study could have been better at them. One or a combination of these possibilities can contribute to the disparities between our findings and that of Tsantani et al.

However, our study is not without limitations. First, we did not account for the congruency effects between face learning and face recognition. Previous research has shown the importance of congruency in face identification (Estudillo & Wong, 2022; Manley et al., 2019; Toseeb et al., 2014). For example, faces learned with a ski mask are better recognized when they are also presented with a ski mask compared to full-view faces (Manley et al., 2019). In our study, there is an incongruence between face learning and recognition, as the aperture was only applied during learning (Experiment 1) or recognition (Experiment 2) stages. However, as all our participants were given the same tasks, it is unlikely that incongruence between learning and recognition explains any observed relationships between face recognition skills and the different conditions of the FTAP.

Second, it could be argued that the FTAP also disrupts featural processing. For example, the FTAP might impair the encoding of featural information at the learning stage, which would explain why aperture accuracy was not associated with FRA in Experiment 1. However, this also seems unlikely. Research has shown that holistic processing is mostly engaged by the presence of a whole and intact face (Farah et al., 1998; McKone & Yovel, 2009; Tanaka & Farah, 1993). Importantly, this whole and intact face processing is indeed avoided by the aperture. To ensure the serial processing of each facial feature, the aperture used in this study was created to be large enough to reveal the entire eye and mouth regions, and approximately 75% of the nose. Therefore, although the serial presentation of the features through the aperture might also impair some featural processing, it seems unplausible that this disruption is comparable to that of holistic processing. In fact, if such disruptions were comparable, as observers would not be able to use either featural or holistic processing, performance in the aperture conditions should be at chance levels (e.g., Schwaninger et al., 2002). However, as our results showed, participants' performance in the aperture condition was above chance levels in both experiments.

Third, we applied the regression method to compute the holistic advantage of participants. While this approach does control for variance in the aperture condition (DeGutis et al., 2013b), one important limitation of the regression method is its assumption of a linear relationship between the whole and aperture conditions. In fact, as shown by the weak correlations, it is possible that a non-linear model could better explain the relationship between the whole and aperture conditions. To address potential concerns with the regression approach, we applied other transformations (*d*-prime) to assess the robustness of our results. Consequently, we were able to replicate similar pattern of findings, as evidenced by the sensitivity analyses.

5.15 Future Directions: Prospects of the Aperture Paradigm

Methodological differences in the type of task that was employed could also explain the contrasting implications (e.g., poor FRA is a result of imprecise featural encoding, rather than aberrant holistic processing) between our findings and those from Tsantani et al. (2020). We adopted the aperture paradigm with an unfamiliar old/new recognition memory task (i.e., face identification) rather than a categorization task or familiar/famous recognition task. Using an unfamiliar old/new face-identification task may require holistic processing for better encoding of novel faces; as compared to categorization (e.g., categorising celebrity by nationality) or face matching tasks, where featural processing is found to be more important (Estudillo et al., 2021;

Harel & Bentin, 2009; Mohr et al., 2018; Wenger & Townsend, 2000). This argues that there was a higher “requirement” to rely on holistic processing in our RMT than those of categorization tasks (Tsantani et al., 2020). Moreover, the widely used famous face recognition task was also described as challenging due to its over-reliance on memory, in which the task requires an extremely accurate perceptual representation over a long period (Bate et al., 2019b; Kok et al., 2017), even more so for DPs (McKone et al., 2011; Pertzov et al., 2020; Towler et al., 2018; Robotham & Starrfelt, 2018). Additionally, familiar or famous face recognition also relies on contextual cues and prior knowledge (e.g., how often participants watch blockbuster films), which may influence the reliance on holistic processing (Canas-Bajo & Whitney, 2020; Estudillo, 2012). Together, these findings suggest that reliance on different “information-gathering” strategies is based on familiarity and task constraints (e.g., Berger et al., 2022). Consequently, future studies could adopt the FTAP onto different face recognition tasks (e.g., familiar and unfamiliar) to investigate the role of familiarity and holistic processing in face identification.

As discussed above, groups differences in the aperture effect do not always inform us that one group utilizes holistic processing more than the other during face learning, specifically, the latter group may integrate individual facial features into a whole (as compared to embedding individual parts onto a stable template) during face encoding. In other words, the sequential presentation of featural information would impair the formation of a holistic “face template” (Richler et al, 2012; Rossion, 2013), however, it may spare the integration process of individual features into a whole (Murphy & Cook, 2017). To address this, we can incorporate the FTAP in conjunction with the part-whole task, as studies have proposed that the PWE measures the holistic integration of facial features (Boutet et al., 2021). Together, these adopted tests could explore if encoding through an aperture would also result in diminished PWE during recognition. Two interpretations can be acquired by adopting the FTAP in the part-whole task: (1) if PWE is reduced when faces are learnt through an aperture, compared to when faces are learnt in full, it shows that holistic processing facilitates face encoding and represents a whole-face template percept; (2) if not, this argues that face encoding relies on the integration of individual features into a whole, wherein a whole face percept is nothing more than the sum of the features and its configurations (Gold et al., 2012).

Lastly, the FTAP could also be used to investigate the relationship between spatial frequency (SF) and holistic processing, as the findings in recent years have been mixed between these two perceptual processes. Previous studies often suggest that low SF information in faces conveys holistic and configural cues, whereas featural details are extracted from high SF information (Goffaux et al., 2005; Goffaux & Rossion, 2006). In contrast, Cheung et al. (2008) found that low and high SF-filtered faces were processed equally holistically, as measured with the complete composite face task. Thus, using the FTAP, we can clarify the relationship between low and higher-level processes. Faces encoded either via full-faces or through an aperture may affect the type of spatial information used during recognition or *vice versa*. For instance, if holistic information is only conveyed by low SF content, unfamiliar faces learnt through an aperture should impair recognition of low, but not high SF-filtered faces, while learning whole faces should facilitate the recognition of low SF-filtered faces more than high SF-filtered faces. In short, the current FTAP is a relatively new methodology but presents itself as a reliable and flexible paradigm, which could be adopted into other face identification tasks to further explore the contribution of holistic and featural processing in face recognition.

In conclusion, we show that poor FRA arises from the poor encoding of holistic and featural information during face recognition. We also show that enhanced holistic (but not featural) processing during face learning contributes to better FRA. In addition, our findings raise the intriguing possibility that good recognisers' ability to effectively utilise featural information during recognition may depend on the extent to which faces are processed holistically during learning. We demonstrate these using the FTAP that deals with several limitations of other paradigms (i.e., inversion, composite and part-whole tasks). Moreover, the FRA of our sample is broad, to the extent of capturing individuals with FRAs (according to CFMT scores) similar to DPs and SRs identified in past studies, as well as those in between. Therefore, we provide reliable insight into the contribution of holistic and featural processing during face learning and face recognition.

CHAPTER 6: Summary, Conclusions and Future Research

6.1 Summary and Conclusions

While face recognition may appear effortless in daily life, the ability to recognize faces varies significantly among individuals (Duchaine & Nakayama, 2006; Russell et al., 2009). Over the years, researchers have developed objective measures of face recognition abilities (FRAs) that reliably distinguish individuals with face recognition deficits, such as Developmental Prosopagnosia (DP), and those with exceptional face recognition skills, known as Super-recognizers (SRs), within the general population. However, the extent of the diverse range of face recognition and perception abilities within the typical population remains less clear. Specifically, it is unclear whether face recognition can be quantified across this spectrum and/or if it is determined by specific capacities or mechanisms at an individual level. In other words, the factors contributing to the interobserver variability in face recognition remain unclear. To shed light on this issue, the current thesis investigated the role of low- and higher-level processes underlying individual differences in FRAs.

In the first empirical chapter (Chapter 2), we examined the role of low-level visual processing in face recognition. At the simplest and lowest level of visual information, the ability to recognise faces is largely biased towards mid and low spatial frequencies (LSF), in contrast to high spatial frequencies (HSF) (Gao & Bentin, 2011; Peters & Kemner, 2017; Schyns & Oliva, 1999). However, research investigating the potential role of different spatial frequencies as a predictor of individual differences in face recognition is scarce, and it is unclear if the utilization of a specific SF band predicts face recognition ability (FRA) at an individual level.

While previous studies have indeed proposed the significance of specific bands of SF information in face recognition, they have not explicitly emphasized the crucial role of distinct SF bands in different stages of face recognition. For instance, LSF information has been demonstrated to convey global facial information that holds great importance during face encoding (Goffaux & Rossion, 2006; Peters & Kemner, 2017; Wenger & Townsend, 2000). In contrast, the role of HSF information has been shown to be important during the recognition of faces (Fiorentini et al., 1983; Goffaux & Rossion, 2006). This suggests the possibility that LSF information is important for face learning, while HSF information holds more relevance than LSF information in the later stages of face recognition. We addressed this by running two separate experiments, where we applied filters passing specific bands of SFs in the face learning (Experiment 1) or in the recognition (Experiment 2) stages. In the first experiment, participants learned SF-filtered faces and were subsequently required to recognize unfiltered versions of these same faces. In the second experiment, participants learned unfiltered faces and were required to recognize SF-filtered faces.

In contrast to previous literature (Peters & Kemner, 2017; Schyns & Oliva, 1999; Wenger & Townsend, 2000), we found that both LSF and HSF information are equally important and informative in face learning and recognition. Particularly, removing SF information reduces sensitivity to face identification. Indeed, the removal of either LSF or HSF information significantly impaired face learning and long-delayed recognition. Importantly, we found that the utilization of LSF or HSF information was not associated with FRAs measured with the Cambridge Face Memory Test – Chinese (CFMT-Chi). Specifically, our findings suggest that individual differences in FRA cannot be explained by variable reliance on a specific band of SF information during face learning and recognition.

As for higher-level processing of faces, some authors have proposed that holistic processing is necessary for face recognition (Jacques & Rossion, 2010; Rossion, 2008, 2013; Tanaka & Farah, 1993; Young et al., 1987). However, the concept of holistic processing itself (Farah et al., 1998; Gold et al., 2012; Maurer et al., 2002; Piepers & Robbins, 2012) and its relationship with face identification ability (DeGutis et al., 2013b; Konar et al., 2010; Richler et al., 2011a; Verhallen et al., 2017; Wang et al., 2012) remain an ongoing debate. Consequently, it is possible that this lack of consensus in the definition of holistic processing and mixed findings regarding the role of holistic processing in face recognition can be explained, at least partially, by the existence of different measures of holistic processing (Boutet et al., 2021; Rezlescu et al., 2017). In view of this, Chapters 3 to 5 aimed to investigate the following questions: Does holistic processing (1) predict individual differences in FRA, (2) is the concept of holistic processing universal (i.e., cognitive mechanism underlying holistic processing is consistent across cultures) and/or (3) unitary (i.e., different measures of holistic processing tap into the same cognitive mechanism)?

In Chapter 3, we aimed to explore the relationship between holistic processing and FRAs in Eastern and Western cultures. Culture has often been used to denote the distinct behaviours, customs and beliefs that characterize a social or ethnic group. Thus, culture represents a powerful deterministic force that might modulate visual perception (Chua et al., 2005; Nisbett & Miyamoto, 2005; McKone et al., 2010). This brings us to the question of whether face recognition and its underlying cognitive mechanisms are *universal*. Multiple cross-cultural studies involving oculomotor behaviour have argued that Western-Caucasians (WCs) and Eastern-Asians (EAs) have different eye movement strategies (Blais et al., 2008; Kelly et al., 2010), while others have found that they sample different ranges of low-level information during face recognition (e.g., spatial frequency; Blais et al., 2021; Tardif et al., 2017). Presumably, these cultural differences should also manifest in complex higher-level processes, such as holistic processing (e.g., Miyamoto et al., 2011). Nonetheless, how could individuals from one culture process a face more holistically than those from another, considering that holistic processing is a fundamental aspect of face recognition? One possibility is that holistic processing is mediated or modulated by distinct cognitive mechanism(s) unique to each culture.

Considering the relevance of holistic processing in face recognition, one might think that this process is universal across different societies. Accordingly, in Chapter 3, group comparisons between EAs and WCs revealed comparable susceptibilities in the inversion, part-whole, composite and Navon's tasks. In other words, both EAs and WCs relied on holistic processing during face and non-face object recognition to a similar extent. Second, in line with previous literature, we found that holistic processing is associated with face recognition, measured by the CFMT (DeGutis et al., 2013b; Richler et al., 2011a). That is, the identification of faces is facilitated by the processing of holistic information, with a stronger reliance on holistic processing being associated with better FRAs. Specifically, both groups' FRAs were positively correlated with face inversion and part-whole effects (FIE and PWE, respectively), but not with the composite face effect (CFE). The strength and direction of these associations were also comparable between EAs and WCs. Interestingly, we found that FRA was weakly associated with the global precedence effect in the Navon's task too (GPE; Gerlach & Starrfelt, 2018b). However, when separated by groups, we found that the GPE was only associated with FRAs in WCs, but not in EAs. This finding suggests that delayed global processing of non-face objects might contribute to poor face recognition in WCs, but not EAs. However, here it is important to consider potential mediating factors too. In fact, our sample of EAs had higher object recognition abilities as measured with the Cambridge Car Memory test.

Furthermore, exploratory factor analyses identified one main component in face recognition ability and holistic processing (i.e., holistic face processing; *HF*), suggesting that the CFMT, FIE, and PWE tap into overlapping mechanisms. Surprisingly, we found that the CFE did not load onto the same component as FRA (measured with the CFMT) or other holistic indexes. This observation indicates that there are multiple processes reflecting the construct of holistic face processing, and they have distinct contributions to face recognition. Altogether our findings suggest that (1) the factor *HF* represents the holistic mechanism involved in FRA; (2) holistic processing is not a unitary process, as the three traditional measures of holistic processing cannot be explained by a single common mechanism; and (3) the FIE and PWE are measuring overlapping mechanisms, that are distinct from those of CFE. Interestingly, when cultural factors were taken into account, these loading patterns were different across societies. For example, PWE loaded into *HF* only for WCs, but not EAs. These findings suggest that the underlying cognitive mechanism of holistic processing involved in FRA is influenced by cultural factors. In line with previous studies, the processing of holistic facial information has a pivotal role in face recognition across societies, but the underlying mechanism of holistic face processing is culture-specific.

It is clear that the baffling concept of holistic processing and its relationship with FRA is partially explained by previous rigid attempts to define this higher-level processing as unitary. We suggest that this rationale may also extend to mixed findings observed at the extreme ends of the FRA spectrum – individuals with prosopagnosia. Developmental Prosopagnosics (DPs) are characterized by severe deficits in face recognition, despite having normal object recognition

(Fry et al., 2020; Hendel et al., 2019), normal vision and memory, with no obvious brain damage (Susilo & Duchaine, 2013). In contrast, Acquired Prosopagnosics (Aps) have a neuropsychological condition characterized by a severe deficit in the recognition of faces following brain injury or trauma (Barton, 2008b; Busigny et al., 2010; Rezlescu et al., 2012). If holistic processing is sufficient for face recognition, one would expect to see holistic processing impairments in DPs (e.g., Avidan et al., 2011; DeGutis et al., 2012; Esins et al., 2016; Liu & Behrmann, 2014; Susilo & Duchaine, 2013; Towler et al., 2018) and APs (Busigny et al., 2010, 2014; Busigny & Rossion, 2011; de Gelder et al., 2003; Rezlescu et al., 2012). However, this is not always the case for DPs (Bennetts et al., 2022; Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017) or APs (Finzi et al., 2016; Rezlescu et al., 2012).

Accordingly, in Chapter 4, we investigated whether face recognition deficits in developmental and acquired prosopagnosia can be explained by distinct cognitive mechanisms of holistic processing, across two different experiments. Particularly, we examined whether the heterogeneous nature of DPs’ (Experiment 1) and APs’ (Experiment 2) deficit would be reflected by different underlying mechanisms of holistic processing. Here, we have three possibilities. First, not all holistic face paradigms are measuring the same aspect of holistic processing, leading to impaired performance in some but not other aspects of holistic processing across all individuals with prosopagnosia. We call this account the *universal holistic processing deficit hypothesis*. Second, different prosopagnosics may present qualitatively different holistic processing impairments. We call this the *heterogeneous holistic processing deficit hypothesis*. Third, prosopagnosics' deficits in face identification may not be explained by holistic processing impairments. Similar to Chapter 3, we employed the three gold-standard measures of holistic face processing and the Navon’s task to explore the first and third possibilities, and individually compared each prosopagnosics' performance to their corresponding age-matched NT group to examine the second possibility.

From our first experiment, we found some group-level effects. Specifically, DPs were less susceptible to the inversion and part-whole effects compared to NTs but were comparable in the composite and Navon tasks. In short, across the three traditional measures of holistic processing of faces, NTs showed stronger holistic face processing compared to DPs only in the inversion and part-whole effects. This was in line with previous studies (Avidan et al., 2011; Behrmann et al., 2005; DeGutis et al., 2012; Duchaine et al., 2007b; Klargaard et al., 2018). Our current findings are also consistent with previous literature that found normal holistic processing in DPs when indexed with the composite task (Bennetts et al., 2022; Biotti et al., 2017; Le Grand et al., 2006; Susilo et al., 2010; Ulrich et al., 2017). Importantly, the results from our single-case analyses revealed that holistic processing deficits in DPs, rather than being universal, are heterogeneous. For instance, none of the DPs was impaired in all the three holistic indexes, which suggests that holistic processing, although impaired in some ways, is not totally absent in DPs (DeGutis et al., 2012). In brief, our findings suggest that holistic processing impairments in DPs present both quantitative and qualitative differences across distinct individuals (Corrow et al., 2016; Le Grand et al., 2006; Tardif et al., 2019)

In our second experiment, we used single-case analysis to examine the holistic profiles of two APs (Case RM and DS). Our single-case analyses revealed that the performance of Case RM and DS were comparable to their age-matched controls in the part-whole, composite and Navon’s task, but not for the inversion task, partially replicating the findings of previous studies (Busigny et al., 2010, 2014; Busigny & Rossion, 2011; Finzi et al., 2016; Rezlescu et al., 2012). This suggests that APs have impaired holistic processing as reflected by the inversion, but not the part-whole and composite effects, and this holistic deficit is specific to faces (as reflected by normal GPE). Notably, our findings also indicate some cognitive mechanisms underlying holistic processing may be preserved in APs, wherein none of our APs were characterized by impairment in all three measures of holistic face processing. Our current findings provide further support for the notion that holistic representations of faces are constituted by multiple underlying mechanisms of the face processing network, in which holistic processing can be spared in some form of AP (Finzi et al., 2016). While we found that APs' holistic processing deficits are consistent, the sample size is too small to make any generalization claims. Overall, the findings of the current chapter propose two main implications: (1) holistic processing deficits in DPs are heterogeneous and (2) holistic processing is not a unitary process wherein there is no common mechanism explaining what is captured by the three traditional measures of holistic processing (Boutet et al., 2021; Rezlescu et al., 2017).

The findings in the Chapter 4 also provide an alternative possibility – DPs' impairment extends to both holistic and featural processing (Bennetts et al., 2022; Verfaillie et al., 2014; Yovel & Duchaine, 2006). For instance, despite being poorer in the conditions of interest, DPs were also poorer in the control conditions, which often reflects the featural processing of faces (Bennetts et al., 2022; Tsantani et al., 2020). Even though holistic processing can explain individual differences in face recognition (for the most part), it is not the only higher-level process facilitating FRA (DeGutis et al., 2013b). When featural processing is reliably measured in recent studies, it was found that featural processing was comparable, if not better, than holistic processing in predicting face recognition ability (e.g., featural but not holistic processing is impaired in DPs; Tsantani et al., 2020).

Theoretically, if holistic information facilitates learning and storage of unfamiliar faces, it is likely to also facilitate discrimination of similar-resembling faces. However, whole face information may seem less useful compared to capturing identify-specific facial features (i.e., mole; Fysh & Bindemann, 2022) when comparing face memory representations with visual inputs, particularly when all faces contain similar configurations (e.g., a pair of eyes above the nose). Additionally, some face perception tasks permit matching strategies (e.g., sampling "back-and-forth"), in which global information may be less dependable compared to identity-specific information. As described by Rossion (2013, p.10): "Facial parts are the building blocks of our ability to individualize faces." Thus, we proposed that *featural processing*, which is often disregarded in face processing literature, also has a distinct functional role in the later stages of face recognition.

For this reason, in the fifth chapter, we investigated the extent to which individual differences in FRAs are quantitatively associated to holistic and featural processing in typical adults, during face learning and face recognition stages, using the fixed-trajectory aperture paradigm (FTAP; Murphy & Cook, 2017; Murphy et al., 2020; Tsantani et al., 2020). Across two experiments, we found that forcing observers to view faces through a dynamic aperture during face learning (Experiment 1) and recognition (Experiment 2) reduced recognition accuracy. This result lent further support to the notion that holistic processing facilitates accurate face recognition (Jacques & Rossion, 2010; Rossion, 2008, 2013). Furthermore, we showed that both holistic and featural processing contribute independently to individual differences in FRAs. However, the significant associations between featural processing and FRAs were task-dependent. Specifically, featural processing was only associated with FRA during face recognition, but not face learning. This suggests that holistic processing contributes to individual differences for both face learning and recognition, but featural processing only contributes to individual differences in face recognition.

The disparities in the association between featural processing and FRAs could be the result of our viewing manipulations. In Experiment 1, the FTAP constrained all observers to learn faces in a similar fashion, which could interfere with unique perceptual encoding strategies used by good recognizers. For instance, Dunn et al. (2022) found that super recognisers (SRs) had broader gaze distributions and more fixations than typical observers, but these differences were more apparent during face learning. If that is the case, applying the aperture during face learning not only minimised holistic processing, but may have also interfered with how good recognisers process features. Nonetheless, Chapter 5 was able to provide reliable insights into the contribution of holistic processing to face learning and face recognition, as well as the contribution of featural processing to later face recognition stages.

In conclusion, across four empirical chapters, we found that individual differences in face recognition can be accounted for by qualitative and quantitative differences. We found that along the FRA spectrum, individuals have both similar and distinct processes they utilise during face processing. As for low-level processing, we found that FRA was not facilitated by better utilisation of low or high SF information during face learning and recognition. However, in higher-level processing, we found that holistic and/or featural processing facilitates face recognition across the spectrum. Notably, the mechanisms underlying this holistic facilitation are culture-specific. Furthermore, individuals with specific deficits in face recognition (i.e., DPs and APs) also showed impaired holistic processing of faces. Nonetheless, at an individual level, our findings indicated that these holistic impairments are heterogeneous. Specifically, individual DPs have impaired performance across distinct measures of holistic processing. Together, these findings imply that the concept of holistic processing is not universal, nor is it unitary. Overall, the current thesis has provided an in-depth exploration of factors, from low-level to higher-level processing, that may underly individual differences in FRAs.

6.2 Theoretical Implications

The findings of this thesis have clear theoretical implications for accounts of individual differences in FRAs. Despite finding significant correlations between the recognition performance of faces with only low spatial frequencies and FRA in Chapter 2, the findings revealed that when the “Noise” stage in the CFMT-Chi was excluded, this association disappeared. This pattern of results suggests that the influence of low spatial frequency processing on FRA is primarily driven by the “Noise” trials in the CFMT-Chi and does not actually facilitate face recognition. This indicates that future studies need to be cautious when interpreting factors underlying individual differences in FRA measured with the CFMT, such that different stages of the CFMT may reflect distinct processes of face recognition.

Across Chapters 3 to 5, we consistently showed that disrupting holistic information reduces an individual’s ability to accurately identify faces. In real-world scenarios, faces are often dynamic, in which they must be learnt rapidly from different viewpoints, lighting and distances (Hancock et al., 2000). However, learning and storage of multiple identity-specific features and their configuration may appear redundant compared to capturing the gist of these vigorous unfamiliar faces. Consequently, encoding a global (holistic) percept would provide a more stable representation than its local features (Peters & Kemner, 2017). Given that there is less variation in the global information of faces, holistic processing can also significantly decrease cognitive load and allow efficient long-term storage of a larger number of face identities (e.g., Fysh, 2018; Weigelt et al., 2014). Overall, the current thesis suggests that individual differences in FRA are facilitated by holistic processing, during both face learning and face recognition.

Our findings also have implications regarding the use of the composite face effect (CFE) as a measure of holistic face processing. We found that the CFE was not associated with FRA across both EAs and WCs in Chapter 3, nor was it impaired in Prosopagnosics in Chapter 4. Together, our findings suggest that the underlying mechanism measured by the CFE is not related to individual differences in FRA. The first possibility is that the CFE might be measuring an aspect of holistic processing that is uniform across individuals with different FRAs. A second possibility is that the CFE may not be measuring holistic face processing at all, particularly, the CFE may tap into other underlying cognitive mechanisms that involve general perceptual abilities (Fitousi, 2015, 2020). Another possibility is related to the version of the composite task used. Some studies have proposed that the complete version or full design of the composite task is a more reliable (e.g., reduced susceptibility to response biases) and robust method for measuring *holistic interference* (Richler et al., 2012). The version we used (i.e., original, standard, or partial design) is believed to involve both featural and holistic processing, as it compares the target halves rather than the composite as a whole (Richler & Gauthier, 2014). Conversely, the complete design requires participants to process the composite faces as a unitary whole. However, the complete design has also been criticised that it is not always reflecting face-specific mechanisms (McKone et al., 2013). In brief, we do not condemn the use of the CFE as a measure of holistic face processing in future studies despite the large number of criticisms in recent years. Instead, we lend further support to the notion that holistic processing measured with the CFE is independent from face memory.

Moreover, some past studies have directly attributed SRs' high FRA (Abudarham et al., 2021; Nador et al., 2021) and DPs' low FRA (Tsantani et al., 2020) to efficient and impaired featural processing during face recognition, respectively. Building upon our earlier discussions in Chapter 5, our findings offer a potential implication for this attribution, particularly given that some of our participants were sitting at both extreme ends of the FRA spectrum. Specifically, the ability to accurately recognize individual features may be dependent on good holistic processing during face learning. It is plausible that SRs' superior face recognition ability might stem from their enhanced holistic representations during face learning. In contrast, DPs' struggle with featural processing could be linked to their impaired holistic representations formed during face learning. Thus, holistic processing might underlie SRs' exceptional perceptual encoding, which could subsequently facilitate the recognition of facial features of learnt faces (Belanova et al., 2021; Dunn et al., 2022). Possibly, DPs could be as bad at extracting and learning facial descriptions (via holistic processing) and recognising these identity-specific features (via featural processing) as SRs are good.

Lastly, it is crucial to acknowledge that relying on one cognitive process (e.g., holistic processing) does not necessarily hinder the other (e.g., featural processing), but rather, it can facilitate it. As emphasized in Sergent's (1986) paradigm, to distinguish between different faces, a holistic percept needs to capture fine-grained information related to the unique characteristics of each face (see also course-to-fine strategy; Bar, 2004; Hegdé, 2008). Accordingly, we propose that holistic processing facilitates the processing of individual facial features. For instance, holistic processing might not only aid in the encoding of second and/or higher-level (i.e., holistic and configural) facial information but also promote the encoding of first-order featural information, albeit indirectly. Specifically, early face processing involves efficient holistic encoding of the entire face (i.e., gist) to form a stable “face template”, consequently allowing identity-specific features to be efficiently embedded into it (McKone & Yovel, 2009; Richler et al., 2012; Rossion, 2013). This holistic template provides a stable representation of learnt faces in memory, which enhances the consolidation and retrieval processes. In short, holistic processing indirectly facilitates the differentiation of faces during later recognition stages, through featural processing. Our implications also integrate well into existing models of face recognition, e.g., the holistic/part-based model (McKone & Yovel, 2009; Rossion, 2008), in which holistic processing codes *all* information in the face. According to this model, both holistic and featural processes work in parallel and facilitate face recognition independently. Together, our findings imply that FRA relies on distinct yet related higher-level processes.

6.3 Limitations and Future Directions

The current thesis is not without limitations. In Chapter 2, we found that performance in the old/new recognition memory tasks, specifically sensitivity in the unfiltered condition, was correlated with CFMT-Chi in Experiment 1, but not in Experiment 2. This is surprising, given that the constraints imposed by our tasks in the unfiltered conditions are the same across both experiments. This discrepancy may be due to the recognition of a combination of faces that includes unfiltered, high SF-filtered, and low SF-filtered. This mix of SF-filtered faces could lead to repulsive face after-effects, where recognizing low SF-filtered faces could result in subsequent faces being perceived with a bias towards their finer details (e.g., HSF information) while reducing sensitivity towards coarse details (e.g., LSF information), and *vice versa* (Webster, 2005; Webster & MacLeod, 2011). As a result, the presentation of SF-filtered faces could affect the strategy used to recognise subsequent faces. Nonetheless, it is unclear why these after-effects were more prevalent during face recognition than face learning. One possibility is that recognizing faces with varying SFs could lead participants to switch between perceptual strategies across each trial (Gold et al., 1999). In contrast, the strategy used in Experiment 1 remains consistent because only full-band faces are presented during the recognition stages of the memory tests. In fact, studies have shown that face sampling strategies during face learning and recognition differ between cultures as a result of relying on different bands of SF information (Miellet et al., 2013). Thus, future research should, therefore, further investigate the dissociation between face learning and recognition in SF processing.

As mentioned, previous research has suggested that individuals from Eastern and Western societies differ in the way they allocate their attention over space, with Easterners relying more on global, lower SF information (see review by Blais et al., 2021). In Chapter 2, however, our results did not indicate selective tuning to low SF information in Easterners. For instance, our results showed that Easterners use both low and high SF information equally during face learning and recognition. While direct testing of cultural differences was not within the scope of our current study, our findings propose that Easterners did not show a bias towards global information in face recognition. Furthermore, it is also unclear if SF processing has different weights on individual differences in FRA across cultures. For instance, our findings indicated that LSF processing was not associated with FRA in Easterners. Consequently, these patterns may not be the same for Westerners, such that the FRAs of Western participants may be predicted by the reliance on a specific band of SF information. Future research should also further examine the role of SF processing and FRA in both WCs and EAs.

Nonetheless, how can WCs and EAs achieve comparable performances in different holistic tasks while using different strategies of visual sampling? Studies have found that

Western and Eastern societies can switch to similar strategies when visual sampling is constrained (Caldara, 2010). Caldara (2010) showed that when EA observers' fixations are constrained with a gaze-contingent aperture, they were still able to switch their default fixation strategy (e.g., central processing of the nose) to those of WCs (e.g., more fixations near the eyes and mouth). In view of this, we speculate that different cultures may use multiple distinct holistic processing strategies, as reflected by different holistic indexes, and can flexibly switch among these strategies based on task constraints. Nonetheless, this speculation has not been examined. To strengthen our implication, future research could expand upon the current methodology by incorporating measures of gaze. If the speculation above holds true, it will likely manifest as inconsistent oculomotor behaviour during distinct holistic processing tasks for both EAs and WCs. For example, as shown by our factor analysis, while holistic processing measured by the FIE loaded onto holistic face processing in both groups, the PWE loaded onto holistic face processing in WCs but not in EAs. Consequently, we would expect that EAs would switch their gaze patterns during the PWE task compared to WCs.

In addition, the presence of cultural differences in holistic face processing within the domain of neuroimaging research also remains unclear. For instance, studies have reported selective activation of the face fusiform area (FFA) and occipital face area (OFA) during face recognition. Specifically, the OFA was suggested to reflect featural processing, whereas the FFA has been associated with the holistic processing of faces (Nichols et al., 2010). Importantly, cultural differences were shown in the activation of the FFA between EAs and WCs, wherein EAs showed more right lateralization in the FFA compared to bilateral activation seen in WCs (Goh et al., 2010). Building upon our findings, it is possible that these culture-specific lateralization(s) reflect different holistic mechanisms. In fact, neural investigations have shown distinct activation patterns of the FFA between the part-whole and composite face tasks (Li et al., 2017). However, to date, no studies have explicitly explored these possibilities.

While most previous studies typically confirm Prosopagnosia using at least two objective memory tests of faces (e.g., CFMT and famous face memory tests), as recommended by DeGutis et al. (2023), our study was limited by the inclusion of only the CFMT for assessing FRAs in our sample of suspected DPs. This approach is important because relying on a single measure may not always provide a reliable basis for making a diagnosis (Sachdev et al., 2014). Therefore, to further confirm the heterogeneity of holistic deficits in DPs, future research should include more stringent inclusion criteria in selecting DPs, preferably using the CFMT and CCMT together with the famous face memory tests and the 20-questions prosopagnosia index (PI20; Shah et al., 2015b).

Our attempt to measure featural and holistic processing with the novel FTAP paradigm is also not without limitations. For instance, when viewing faces through an aperture, there is a possibility that some holistic processing is spared. Specifically, participants may have integrated individual facial features into a whole, as compared to embedding individual parts onto a stable template, during face encoding (Gold et al., 2012). In other words, the sequential presentation of featural information would hinder the formation of a holistic "face template" (Richler et al., 2012; Rossion, 2013), however, the aperture may spare the integration process of different sections of the aperture faces into a coherent whole (Gold et al., 2012; Murphy & Cook, 2017). As described by Murphy and Cook (2017), this would explain the observed summative effects was when the inversion effect was used in conjunction with the FTAP (e.g., viewing faces through an aperture impaired recognition of inverted faces to a similar extend as those of upright faces).

One solution to address the aforementioned issue is to adopt the FTAP in conjunction with the part-whole task, as studies have proposed that the PWE measures the holistic integration of facial features (Boutet et al., 2021). Together, these adopted tests could explore if encoding through an aperture would also result in diminished PWE during recognition. Two interpretations can be acquired by adopting the FTAP in the part-whole task: (1) If PWE is reduced when faces are learnt through an aperture, compared to when faces are learnt in full, it supports the notion that holistic processing facilitates face encoding and represents the perception of a whole-face template; (2) If not, this argues that face encoding relies on the integration of individual features into a whole, wherein a whole face percept is probably nothing more than the sum of the features and its configurations (Gold et al., 2012).

Finally, the current thesis also has practical applications in clinical settings. Previous studies have shown that FRA is related to the duration of overt attention paid to facial features (Bobak et al., 2017; Peterson et al., 2019; Tardif et al., 2019; Towler et al., 2018). Assuming these fixations represent encoding featural information, it appears that better FRA is associated with spending more time looking at specific features (i.e., eyes and nose). Our current study was able to further contribute to this hypothesis. For instance, using the FTAP, all participants were forced to learn faces largely in a featural manner. During face learning, good recognisers were unable to spend more time at critical regions that contained important identity information, and this resulted in them performing poorly like poor recognisers. Taken together, these findings suggest that visual sampling indeed varies quantitatively across the spectrum of FRA. This leads us to the question: Can visual sampling be trained to improve face recognition? While the visual sampling behaviours of individuals with superior or impaired face recognition have been assessed at a behavioural level, the potential of oculomotor behaviour for training individuals is less understood. For example, gaze data from SRs can be used to design training programs aimed at enhancing face recognition skills, particularly involving the FTAP. By understanding the areas where good recognizers tend to fixate and which feature(s) they prioritize, targeted interventions can be developed to enhance FRA in those who struggle with it. For instance, we can encourage poor recognizers (or clinical cases such as Prosopagnosics) to adapt their sampling behaviour to emulate those of SRs during learning and recognition of unfamiliar faces.

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