Running Head: EYE MOVEMENTS AND FACE RECOGNITION

Eye-Movement Strategies in Developmental Prosopagnosia and “Super” Face Recognition

Anna K. Bobak, Benjamin A. Parris, Nicola J. Gregory, Rachel J. Bennetts & Sarah Bate

Department of Psychology, Faculty of Science and Technology,
Bournemouth University, UK

Word count (main text): 8,989

Address for correspondence:
Anna Bobak
Department of Psychology
Faculty of Science and Technology
Poole House
Bournemouth University
Fern Barrow
Poole
BH12 5BB
United Kingdom

Telephone: +44 (0) 1202 961532
Fax: +44 (0) 1202 965314
Email: abobak@bournemouth.ac.uk

Abstract

Developmental prosopagnosia (DP) is a cognitive condition characterised by a severe deficit in face recognition. Few investigations have examined whether impairments at the early stages of processing may underpin the condition, and it is also unknown whether DP is simply the "bottom end" of the typical face-processing spectrum. To address these issues, we monitored the eye-movements of DPs, typical perceivers and "super recognizers" (SRs) while they viewed a set of static images displaying people engaged in naturalistic social scenarios. Three key findings emerged: (1) individuals with more severe prosopagnosia spent less time examining the internal facial region, (2) as observed in acquired prosopagnosia, some DPs spent less time examining the eyes and more time examining the mouth than controls, and (3) SRs spent more time examining the nose – a measure that also correlated with face recognition ability in controls. These findings support previous suggestions that DP is a heterogeneous condition, but suggest that at least the most severe cases represent a group of individuals that qualitatively differ from the typical population. While SRs seem to merely be those at the "top end" of normal, this work identifies the nose as a critical region for successful face recognition.

Keywords: prosopagnosia, super recognizers, face recognition, eye movements, individual differences.

Eye-Movement Strategies in Developmental Prosopagnosia and “Super” Face Recognition

Prosopagnosia is a neuropsychological disorder characterized by a failure to recognize familiar faces. While some individuals acquire the condition following neurological trauma (e.g. Damasio, Damasio, & Von Hoesen, 1982), it is thought that approximately two per cent of the population have developmental prosopagnosia (DP: Bennetts, Murray, Boyce, & Bate, under review for this review; Bowles et al., 2009). This form of the disorder has been attributed to a failure to develop the visual recognition mechanisms necessary for successful face recognition, despite intact low-level visual and intellectual functions (Susilo & Duchaine, 2013). Interestingly, there also appears to be a genetic component to the condition in at least some individuals (Duchaine, Germine, & Nakayama, 2007; Grueter et al., 2007). Due to considerable difficulties hindering early diagnosis of face recognition difficulties, it is essentially impossible to distinguish the former, developmental, from the latter, congenital, form of prosopagnosia. For the purpose of this paper we are thus referring to all types of prosopagnosia unrelated to known neurological trauma and without concomitant disorders known to affect face processing as “developmental”.

A multitude of work with both healthy and impaired participants has contributed to cognitive neuropsychological theories of face recognition, such that it is generally accepted that the process consists of a series of sequential stages that can selectively be damaged by neurological trauma (e.g. Bruce & Young, 1986). Specifically, Bruce and Young’s model posits that, after a period of early visual analysis, an incoming face is transformed from a view-dependent to a view-independent representation at the level of structural encoding, and face familiarity is then assessed in the face recognition units. Actual identification is subsequently thought to occur in the person identity nodes, whereas other aspects of face perception (e.g. the recognition of emotional expression or lip speech) operate in parallel to the identity pathway. While some caution must be exercised in interpreting developmental deficits within these models (e.g. Bishop, 1997), such theories nevertheless provide a framework for the assessment of face-processing in DP. As such, much work has examined the middle and latter stages of face-processing in DP participants (e.g. those at the level of structural encoding and beyond) in an attempt to locate the impairment in these individuals (e.g. Bate, Haslam, Jansari, & Hodgson, 2009; Bate & Cook, 2012; Bennetts et al., 2015; Duchaine et al., 2007; Lee, Duchaine, Nakayama, & Wilson, 2010). Yet, it is conceivable that the impairment occurs at a much earlier stage of processing, involving mechanisms that direct visual attention to faces: if DPs do not allocate adequate attention to faces, it is unsurprising that they fail to recognize them.

This issue can be addressed via the monitoring of spontaneous attention to faces within naturalistic social scenes, where it has been shown that the attention of unimpaired perceivers is rapidly drawn to people (and particularly faces) when they are seen in peripheral vision (Fletcher-Watson, Leekham Findlay, & Stanton, 2008). Although this process has not yet been examined in prosopagnosia, several studies have demonstrated that individuals with autism spectrum disorder (ASD: a condition that is often accompanied by impairments in facial identity recognition; Weigelt, Koldewyn, & Kanwisher, 2012) allocate less attention to faces in these paradigms. For instance, Riby and Hancock (2008) monitored the eye movements of ASD participants while they viewed images displaying people engaged in social activities (e.g. a group of friends eating a meal, or a bride and groom on their wedding day). The authors calculated the dwell time allocated to faces, bodies and the background of the scene, and noted that the ASD group spent less time studying faces compared to controls. It is conceivable that this paradigm may reveal a similar effect in DP participants, presenting evidence that abnormalities occurring early in the face recognition process may underpin the condition.

Importantly, the paradigm described above also lends itself to more specific analyses related to patterns of facial feature exploration. Given that eye movements are thought to be functional during the learning (Henderson, Williams & Falk, 2005) and recognition (Althoff & Cohen, 1999; Luria & Strauss, 1977) of faces many authors argue that they reflect actual information processing strategies. In a landmark study, Yarbus (1967) reported that humans view faces in an organised manner concentrating mainly on the inner features (eyes, nose and mouth). Many studies have subsequently reported that the eye region is particularly pivotal for the recognition of facial identity, given typical perceivers fixate on the eyes to a greater extent than any other facial region (e.g. Bate et al., 2009, 2010; Schyns, Bonnar & Gosselin, 2002; Slessor, Riby & Finnerty, 2013). These findings are bolstered by reports that individuals with acquired prosopagnosia spend less time examining the inner features of the face (i.e. the eyes, nose and mouth) than controls, (e.g. Caldara, Schyns, Mayer, Smith, Gosselin, & Rossion, 2005; Lê, Raufaste, & Demonet, 2003; Lê, Raufaste, Roussel, Puel, & Demonet, 2003; Stephan & Caine, 2009), and one study has reported the same effect in DP (Schwarzer et al., 2007). More specifically, some studies suggest that participants with acquired prosopagnosia (Caldara et al., 2005; Bate et al., in press; Stephan & Caine, 2009; Van Belle, Ramon, Lefevre, & Rossion, 2010) spend less time examining the eyes and more time examining the mouth than control participants.

Previous studies examining eye movement strategies in DP present some evidence of covert face recognition (i.e. recognition without awareness) in this population (Bate et al., 2008, 2009). Specifically, Bate and colleagues (2008) reported that DP participants present with reduced sampling of famous compared to unfamiliar faces in the absence of overt recollection of their identities - an eye movement strategy that is similar to that displayed by typical perceivers who are able to explicitly identify famous people. This pattern of findings was further replicated with newly learned faces, particularly those associated with positive affective valence (Bate et al., 2009).

While this pioneering work examined eye movement strategies in DP with a specific focus on the recognition of previously known (famous) or newly learned (unfamiliar) faces, more specific patterns of feature exploration, especially in a naturalistic context of social scenes, have not yet been explored in this form of the condition.

Investigation of this issue is timely, given it speaks to a theoretically important debate regarding the underpinnings of DP. While some authors indicate that DP bears some similarity to acquired prosopagnosia (Brundson, Coltheart, Nickels, & Joy, 2007; Schmalzl, Palermo, Green, Brundson, & Coltheart, 2008) others suggest that individuals with DP simply represent the “bottom end of normal” (Bowles et al., 2009; Russell, Duchaine, & Nakayama, 2009). The latter hypothesis is supported by recent evidence suggesting that face recognition skills within the typical population reside upon a continuum (Bowles et al., 2009; Russell et al., 2009), and the identification of so-called “super-recognizers” (SRs) who have extraordinary face recognition skills (Bobak et al., in press; Russell, Chatterjee, & Nakayama, 2012; Russell et al. 2009). Evidence suggests that the latter group are as good at face recognition as DPs are bad (Russell et al., 2009), supporting the hypothesis that individuals labelled as DP may simply represent those at the bottom end of a face recognition spectrum, rather than a disorder characterised by a qualitatively different pattern of processing. However, this issue has not yet been directly addressed within an empirical investigation.An innovative means of investigating the underpinnings of DP is via the analysis of individual eye-movement strategies. As reviewed above, there are several lines of evidence that suggest acquired prosopagnosia is characterised by reduced attention to the eye region of the face, and, in some cases, increased attention to the mouth. If a similar pattern of findings emerges in DP participants, this would suggest that the two forms of the condition are underpinned by similar impairments to visuo-cognitive mechanisms. However, this finding would be inconclusive without a full analysis of eye movement strategies in typical perceivers, complimented by an investigation into super recognition. Indeed, one would predict that, if there is a full spectrum of face recognition ability where DPs and SRs represent the bottom and top ends, respectively, patterns of eye movements would vary along the entire spectrum according to the same measure. If this holds true, the evidence discussed thus far indicates that the proportion dwell time allocated to the eye region is a likely candidate. That is, if DPs spend less time on the eyes than controls, SRs should spend more time on this region, and the measure should also correlate with face recognition ability within typical perceivers.

However, other lines of evidence suggest the critical measure is not the proportion of dwell time spent on the eyes, but the time spent examining the nose. Hsiao and Cottrell (2008) reported that the optimal viewing position in face recognition (i.e. the location of the first fixation that a person makes to a face) is to the left of the centre of the nose. In addition, the preferred landing position (i.e. the location that participants fixate the most) is around the centre of the nose, rather than within the eye region. Similarly, Peterson and Eckstein (2012) found that the optimal viewing position on a range of face-processing tasks was below the eyes and towards the left side of the nose – in a remarkably similar position to that observed by Hsiao and Cottrell. Both sets of authors suggest that this viewing position may be the optimal location for holistic processing of the entire face to occur. Holistic processing is thought to be directly related to unfamiliar face recognition ability (Richler, Cheung, & Gauthier, 2011; Wang, Lin, Fang, Tian, &Liu, 2012; but see Konar, Bennett, & Sekuler, 2010). Pertinently, impaired holistic processing has been previously reported in acquired (Ramon, Busigny, & Rossion, 2010) and developmental (Avidan, Tanzer, & Behrman, 2011) prosopagnosia, and a recent study by DeGutis, Cohan, and Nakayama (2014) reported a successful training regime targeting the holistic processing deficit in a group of 24 DPs. If face recognition skills are related to holistic processing and the holistic processing itself is associated with the proportion of dwell time spent looking at the nose, one would predict that, if DP is simply the tail end of the face-processing spectrum, these individuals would spend less time looking at the nose than controls. Alternatively, if this measure is associated with face recognition ability in both typical participants and SRs, yet DPs mirror the performance of individuals with acquired prosopagnosia (i.e. by spending less time on the eyes and more time on the mouth), this would provide evidence that DP represents a qualitatively distinct group that is independent from the typical population.

It is, however, important to note that research has identified DP as a heterogeneous condition. Specifically, individuals differ in the severity of their impairment and often present with idiosyncratic perceptual deficits that exist even within the same family (Lee, Duchaine, Wilson, & Nakayama, 2009; Schmalzl, Palermo, & Coltheart, 2008). It is thus possible that any differences in the eye-movements may be associated with different patterns of perceptual deficiency.

The current study addresses the issues discussed above. In Experiment 1, we employed a social scenes eye-tracking paradigm to examine the scanning strategies used by 10 individuals with DP in comparison to age-matched control participants. This paradigm was selected because (a) it permits novel insights into the salience of faces in DP (i.e. by examining the time taken to initially fixate a face, and the proportion of dwell time allocated to faces versus bodies and background regions), and (b) previous work examining ASD suggests that analysis of featural fixation durations is more fruitful when faces are presented within their natural context rather than as individual static images (see Birmingham, Bischof, & Kingstone, 2008). This latter set of analyses looked at more specific patterns of feature exploration, examining fixation durations across the inner versus the outer facial features, and across the eyes, nose and mouth. Experiment 2 used the same paradigm to explore scanning strategies in eight individuals who meet the published diagnostic criteria for super recognition (see Bobak et al., in press). Given this group significantly differed to the DP group according to age, we conducted this as a separate experiment with an independent age-matched control group for each sample. However, the aims of this experiment were akin to those for Experiment 1: the paradigm allowed us to examine the salience of faces to SRs, and to examine their featural exploration of faces in comparison to matched controls - all within an ecologically valid context. Further analyses examined scanning strategies in the two control groups, to investigate (a) whether any differences between DPs and SRs could simply be attributed to age, and (b) whether attention to the eyes or nose correlated with face recognition skills in typical perceivers. Finally, we conducted a third experiment to attempt to replicate the SR findings using a different paradigm. Indeed, Experiment 2 represents the first eye-movement investigation into superior face recognition, and if its results are robust, we expected them to be reproduced within a more traditional single-face instruction-based encoding task.

EXPERIMENT 1

Our first experiment represents the first in-depth analysis of patterns of feature exploration in DP, and adoption of the "social scenes" paradigm also permitted analysis of visual attention to the entire face, and the critical region covering the inner features. Specifically, we replicated the methodology used by Riby and Hancock (2008), and asked 10 participants with DP and 20 matched controls to free-view a set of static images displaying social scenes while their eye movements were monitored.

Method

Participants

A group of 10 adults with DP took part in this study (7 female, mean age = 57.8 years, SD = 7.1). All participants had undergone neuropsychological testing prior to the investigation to confirm their prosopagnosia. These findings and participants' demographic information are summarised in Table 1. A full description of this battery of tests is reported elsewhere (Bate, Haslam, Tree, & Hodgson, 2008; Duchaine et al., 2007), and these tests are used by several laboratories for background neuropsychological assessments of DP participants (e.g. Bowles et al., 2009; Duchaine et al., 2007; Lee et al., 2010). Critically, all participants performed at least two standard deviations below published control means on the Cambridge Face Memory Test (CFMT: Duchaine & Nakayama, 2006) and a famous faces test that was created and standardized within our laboratory (see Bennetts et al., in press). Some participants were also impaired on the Cambridge Face Perception Test (CFPT: Duchaine et al., 2007), but it should be noted that impaired performance on this test is not required for a diagnosis of DP. As is noted for acquired prosopagnosia, the condition is heterogeneous in its cognitive presentation, and while some individuals experience deficits in face perception as well as face memory, others only experience difficulties in the latter (see Bate et al., 2014). None of the DPs reported socio-emotional or low-level visual or intellectual difficulties. Indeed, as summarised in Table 1, all of their IQs (estimated using the Wechsler Test of Adult Reading, WTAR: Holdnack, 2001) were high, and no atypical scores were noted on various tests of the Birmingham Object Recognition Battery (Riddoch & Humphreys, 1993). No abnormalities in basic low-level vision were observed using a standard Snellen letter chart (3m) or the Hamilton-Veale contrast sensitivity test.

< Insert Table 1 >

Twenty (10 female) control participants were also tested, and were matched to the DP group on the basis of age (M = 51.5 years, SD = 6.9) and estimated IQ (using the WTAR). All participants provided written consent and were rewarded with a small monetary payment in exchange for their time. Ethical approval for this experiment was granted by Bournemouth University's Ethics Committee.

Materials

Twenty-five colour images were purchased from an online image database for use in this study. Twenty of the images displayed the faces and bodies of people who were engaged in social activities (e.g. a group of friends in a bar, a family having a picnic, and work colleagues meetings in an office; see Figure 1). Between two and six individuals were present in each scene, and their positioning varied across the images. The characters were not facing the camera, and were naturally engaging with each other. The remaining five images depicted natural scenes (e.g. a woodland or coastal image) that did not contain people. These "filler" images were included to keep participants naïve to the aims of the experiment. All images were adjusted to 27.09cm in length and 18.07cm in height, and subtended 20.48 degrees of visual angle when viewed from a distance of 50cm.

< Insert Figure 1 >

Eye-movements were recorded using the Eyelink 1000 system (SR Research Ltd, Canada), a video-based pupil/corneal reflex tracking device sampled monocularly at 2000 Hz with spatial accuracy of between 0.25 and 0.5 degree of visual angle. Head movements were minimized by the requirement that participants placed their head within a chin rest for the duration of the experiment. Eye position was monitored through an infrared CCD video camera that was placed on the desk in front of the participant. In an initial calibration phase and during the actual experiment, eye position on the screen was sent to a Dell host computer, which also collected information about when the stimuli were presented.

Design and Procedure

Participants were seated in a quiet room and were asked to place their head within the chin rest. A nine point calibration of eye fixation position was conducted prior to the experiment. The calibration procedure began with the presentation of a white dot in the centre of a black computer screen. The dot moved consecutively around the edge of the screen until an adequate corneal lock was achieved in each position. Once each participant had successfully completed the calibration phase they immediately began the experiment. Because the test was administered in one continuous block recalibration was not required.

Participants were informed that they were going to view a set of images and that they should pay attention to each image and allow their eyes to naturally explore the stimuli. They viewed the sequence of 25 images (20 experimental and five filler images) in a random order, with an exposure time of five seconds per image (following the protocols of Riby and Hancock, 2008). They were not required to make a response and the visual scanpath was recorded for the entire duration of the experiment. The initial point of retinal attention for each trial was controlled by the presentation of a centrally positioned fixation dot before the stimulus appeared.

Eye Movement Parameters and Statistical Analyses

Eye movements were analysed using Eyelink Data Viewer software (SR Research Ltd), which allows periods of fixation to be identified and user-defined areas of interest to be determined within the images. To investigate visual attention to faces, areas of interest (AOIs) were drawn onto the 20 experimental images using a freehand marquee tool (analyses were not performed on the five filler images). Three sets of AOIs were drawn onto each image (see Figure 1). The first set contained three AOIs: the background of the image (all areas other than the bodies and faces of the characters), the bodies of each character (taken from below the chin), and the faces of each character (including outer features such as the ears and hair). Second, the latter region was further divided into two separate AOIs, in order to investigate attention to the inner (i.e. the area covering the eyes, nose and mouth, and the spaces immediately between them) versus the outer (i.e. all remaining facial areas, including the ears and hair) facial regions. Finally, the "inner" AOI was subdivided into specific features, covering the eyes, nose and mouth.

Data were accordingly entered into three analyses of variance (ANOVAs). To examine visual attention to faces, a 3 (region: faces, bodies, background) x 2 (group: DP, control) mixed factorial ANOVA with repeated measures on the 'region' factor was performed. Second, to examine whether DPs spend less time on the inner features than controls, a 2 (facial region: inner, outer) x 2 (group: DP, control) mixed factorial repeated measures ANOVA was carried out. To examine fixation durations across facial features, and to investigate previous findings that individuals with prosopagnosia spend less time on the eyes and (in some instances) more time on the mouth in comparison to controls, we carried out a 3 (feature: eyes, nose, mouth) x 2 (group: DP, control) mixed factorial ANOVA. Finally, a univariate ANOVA investigated whether DPs take longer to initially fixate a face than controls.

Effects involving a repeated measures factor are reported with *p* corrected for departures from sphericity using the Huynh-Feldt correction, where appropriate. Effect sizes are calculated using partial eta squared ($\eta\rho^2$). For each variable, participants are also compared to the control group on a single case level, using modified t-tests for single case comparisons (SINGLIMS, Crawford, Garthwaite, & Porter, 2010). Holmes' sequential Bonferroni procedure was used to correct for multiple comparisons where appropriate.

Results

Analysis of the regional distribution of fixations throughout the entire image revealed that all participants spent longer looking at faces (M = 58.52%, SE = 2.00) than either bodies (M = 24.35%, SE = 1.12) or the background of the images (M = 17.30%, SE = 1.14), $F(2,56)$, = 148.920, $p = .001$, $\eta\rho^2 = .842$. The difference in time spent on the bodies versus the background was also significant, $F(1,28) = 38.223$, $p = .001$, $\eta\rho^2 = .577$. A significant interaction between region and group was also observed, $F(2,56) = 4.754$, $p = .027$. Follow-up analyses indicated that while there was no difference in the time spent studying the background, DPs spent more time looking at bodies and less time looking at faces than controls: $F(1,28) = 2.506$, $p = .125$, $F(1,28) = 5.732$, $p = .024$, $\eta\rho^2 = .170$, and $F(1,28) = 5.170$, $p = .031$, $\eta\rho^2 = .156$, respectively (see Figure 2a). No main effect of participant group was noted in the ANOVA, suggesting DPs spent a similar length of time as controls in fixating on each image, and the findings did not result from a lack of engagement with the task, $F(1,28) = .043$, $p = .837$.

< Insert Figure 2 >

The second set of analyses examined the proportion dwell time spent on the inner versus the outer regions of the face. A main effect of region indicated that all participants spent longer looking at the inner (M = 41.10%, SE = 2.23) versus the outer (M = 17.42%, SE = 1.29) region, and this factor did not interact with participant group: $F(1,28) = 60.523$, $p = .001$, $\eta\rho^2 = .684$ and $F(1,28) = .002$, $p = .965$, respectively (see Figure 2b). A main effect of group was observed, indicating that DPs spent less overall time attending to faces (regardless of region)

(M = 26.99%, SE = 1.63) than controls (M = 31.53%, SE = 1.15), $F(1,28) = 5.170$, $p = .031$, $\eta\rho^2 = .156$.

Analyses of patterns of facial feature exploration also indicated differences between DP and control participants. While no main effect of feature was noted, this factor did interact with participant group: $F(2,56) = 2.069$, $p = .143$ and $F(2,56) = 6.208$, $p = .006$, $\eta\rho^2 = .181$, respectively. Follow-up analyses indicated no differences in the proportion dwell time spent on the nose, but DPs spent less time on the eyes and more time on the mouth than controls: $F(1,28) = .323$, $p = .575$, $F(1,28) = 10.334$, $p = .003$, $\eta\rho^2 = .270$ and $F(1,28) = 4.848$, $p = .036$, $\eta\rho^2 = .148$, respectively (see Figure 2c). No main effect of group was noted in this analysis, in line with the above finding that DPs did not spend less time looking at the inner facial features than controls, $F(1,28) = .598$, $p = .446$.

A final analysis indicated that DPs did not take longer (M = 1024.17ms, SE = 62.77) than controls (M = 973.12ms, SE = 36.10) to first fixate upon a face, $F(1,28) = .572$, $p = .456$.

Because there is considerable heterogeneity in DP, and individuals often present with distinct patterns of perceptual impairment (Lee et al., 2009; Schmalzl et al., 2008), it is prudent to examine data on a case-by-case as well as at a group-based level. Each individual's score on each measure was therefore compared to the control mean and standard deviation, using modified *t*-tests for single-case comparisons (see Table 2). With reference to the main group-based findings, only two of the 10 DPs spend significantly less time viewing the face than controls (DPs 1 and 10), and four spent a longer time viewing bodies (DPs 1, 2, 8 and 10). Although the proportion dwell time spent viewing the eye region was significant at the group level, no individual DP spent significantly less time than controls fixating this region. The proportion dwell time spent viewing the mouth was also greater in the DPs than controls at the group-level, yet significant case-by-case analyses were only observed in DPs 2 and 4, and a trend towards this pattern was observed in DP6. Finally, only one DP (DP2) took a significantly longer time than controls to initially fixate a face.

One might predict that DPs with impairments in face perception (i.e. those scoring poorly on the CFPT, see Table 1) would be the individuals to show significant abnormalities on the eye-movement measures. However, this pattern did not emerge: only one (DP 2) of the five DPs who were significantly impaired on an eye-tracking measure also presented with a deficit in face perception. This observation is supported by the absence of a correlation between any eye-tracking measure and performance on the CFPT in the DP group. Strikingly, however, DP performance on the CFMT did negatively correlate with the proportion of dwell time directed towards the entire face (r = -.633, p = .050), and specifically the inner features (r = -.678, p = .031). That is, DPs with more severe deficits in face recognition tend to spend less time viewing the inner features of the face.

Summary of Experiment 1

Group-based analyses revealed no differences in the time that DPs and controls spent looking at the background of the images, but the DP group as a whole spent more time looking at bodies and less time looking at faces. While no group-based difference was found in the time they spent looking at the inner compared to the outer facial regions, a significant correlation indicated that DPs with more severe face recognition deficits spent less time viewing the inner facial features. At the group-based level, differences in more specific patterns of feature exploration were observed. Specifically, while the DP group spent a similar amount of time looking at the nose as controls, they spent less time fixating on the eyes and more time examining the mouth. However, no individual DP significantly differed in the time spent on the eyes compared to controls, and only two on the time spent on the mouth.

The group-based findings reported here are remarkably similar to those previously observed in acquired prosopagnosia, suggesting similar underlying impairments in both forms of the condition. However, these findings alone do not rule out the possibility that DPs are simply the individuals that reside at the bottom end of the face recognition continuum, given these measures may also be associated with face recognition ability in typical perceivers, and those at the very top end of the spectrum. To address this issue, a second experiment was conducted.

EXPERIMENT 2

In order to examine whether DPs and SRs represent individuals at the extreme ends of the typical face recognition continuum, our second experiment adopted the same paradigm as used in Experiment 1. This time, participants were eight individuals who met the published criteria for super recognition and a new group of 20 controls. The latter group was necessary because the SRs significantly differed in age to the DP group. In addition to performing the same analyses for the SR group as described above for the DPs, the two control groups were also combined for a series of analyses that considered scanning strategies within typical perceivers. The combination of controls across both Experiments provided greater statistical power for these analyses, while permitting examination of the influence of participant age on the key findings. Given the difference in age between the DP and SR groups, this comparison was required in order to infer that any findings related to group membership (i.e. identification of each individual as a DP or a SR) as opposed to participant age.

Method

Identical protocols were used as described in Experiment 1, but different participants were tested. Following widespread media coverage about super recognition, eight individuals who believed they had extraordinary face recognition ability contacted our laboratory (see Table 3). Following published procedures for identifying SRs, a short interview was initially conducted with each SR to enquire about their everyday experiences with face recognition. All eight participants reported extraordinary face recognition skills that had been present from an early age. They described instances where they were able to recognise people even after a brief encounter or after many years have passed (for instance, childhood friends). One participant explained: “I recently saw a girl who I taught for a couple of swimming lessons when I was a teenager. I recognised her immediately, despite the fact that I had not seen her since she was 6, and she is now 18.”

Each participant was also screened using the Cambridge Face Memory Test-Long Form (CFMT+; Russell et al., 2009), and all SRs achieved scores that were above 90/102 (criteria that were used in previously published research to confirm super recognition, given this cut-off is two standard deviations above the control mean: Bobak et al., in press; Russell et al., 2009, 2012; see Table 3). Table 3 also reports CFPT data for the SR sample. However, it should be noted that, as stated above for the diagnosis of DP, it follows that super recognition may also be heterogeneous in its presentation, and superior performance on the CFPT is not necessary for diagnosis. That is, in line with the predictions of dominant models of face-processing (e.g. Bruce & Young, 1986), superior face memory skills are not necessarily dependent on superior face perception skills. In addition, the large variability in control performance on the CFPT results in a large standard deviation, making significant differences on single-case analyses near impossible to achieve. Hence, in line with the procedure followed by Russell et al. (2009), we performed only a group-based analysis and found that our SR group also significantly outperformed the reported control norm on this test (Duchaine et al., 2007; $F(1, 27) = 15.54$, $p = .001$), $\eta\rho^2 = .575$.

It should be noted that we did not follow the protocol of Russell et al. (2009) in screening the SRs using the “Before They Were Famous” test (a test presenting photographs of celebrities that were taken some time before they became famous). Indeed, the previously reported correlations between the BTWF and the CFMT and CFMT+; $r = .70$, $p < .001$ and $r = .71$, $p < .001$, respectively, suffer from a sampling error that makes their meaningful interpretation difficult, if not impossible. Namely, within 29 subjects, four SRs in Russell et al.’s study make up 13.8% of the sample. While there are no published reports on the prevalence of super recognition in the general population, it is highly unlikely that such a high proportion of individuals would possess extraordinary face recognition skills. Ultimately, the top end of the score distribution in the original report on SRs is artificially inflated and the conclusion that the BTWF test correlates with the CFMT and CFMT+ should be seen as tentative, at least until appropriate control data is published. Instead, our previous work using two alternative face recognition tasks provide additional evidence of extraordinary face recognition skills in four of the SRs reported here (SR2, SR3, SR7 and SR8: Bobak et al., in press).

< *Insert Table 3* >

A new group of 20 (10 female) control participants also participated in this study, and were matched to the SRs according to age (M = 24.7 years, SD = 5.7) and estimated IQ. All control participants reported typical face recognition skills, and this was confirmed via completion of the CFMT (standard form), where all participants performed within the “typical” range (M =58.0, SD = 8.0). These participants were all Bournemouth University students and staff members who participated in exchange for course credits or a small monetary payment. Ethical approval for this study was granted by Bournemouth University's Ethics Committee.

Results

SR Participants

As observed in Experiment 1, analysis offixation durations throughout the entire scenes revealed that all participants spent longer looking at faces (M = 67.70%, SE = 2.00) than either bodies (M = 18.80%, SE = 1.12) or the background of the images (M = 12.70%, SE = 1.20), F(2,52), = 262.200, p = .001, $\eta\rho^2$ = .910. The difference in time spent on the bodies versus the background was also significant, F(1,26) = 38.436, p = .001, $\eta\rho^2$ = .587. A significant interaction between region and group was again observed, F(2,52) = 3.900, p = .026, $\eta\rho^2$ = .130, and follow-up analyses indicated that while there was no difference in the time spent studying the background or faces, controls spent more time than SRs looking at bodies F(1,26) = 2.597, p = .119, $\eta\rho^2$ = .091, F(1,26) = 3.959, p = .057, $\eta\rho^2$ = .132, and F(1,26) = 4.946, p = .035, $\eta\rho^2$ = .160, respectively (see Figure 3a). However, it should be noted that there was a main effect of participant group, suggesting that SRs (M = 33.30%, SE = 0.01) spent more time than controls (M = 32.90%, SE = 0.01) fixating on each image component, F(1,26) = 6.390, p = .018, $\eta\rho^2$ = .197.

< *Insert Figure 3* >

As in Experiment 1, the second set of analyses examined the proportion dwell time spent on the inner versus the outer regions of the face. A main effect of region indicated that all participants again spent longer looking at the inner (M = 55.70%, SE = 2.50) versus the outer (M = 12.00%, SE = 1.20) region, and this factor interacted with participant group: F(1,26) =

172.364, p = .001, $\eta\rho^2$ = .869 and F(1,26) = 9.749, p = .004, $\eta\rho^2$ = .273 respectively. Follow-up analyses indicated that SRs spent more time looking at the inner features and less time looking at the outer features of faces than controls: F(1,26) = 8.456, p = .007, $\eta\rho^2$ = .246 and F(1,26) = 6.943, p = .014, $\eta\rho^2$ = .211 respectively (see Figure 3b). The main effect of group approached significance, indicating that SRs spent more time attending to faces (regardless of region) (M = 35.90%, SE = 1.70) than controls (M = 31.80%, SE = 1.11), F(1,26) = 3.959, p = .057, $\eta\rho^2$ = .132.

Analysis of patterns of facial feature exploration also indicated differences between SRs and control participants. While participants in both groups spent longer looking at the nose (M = 24.20%, SE = 1.60) than either the eyes (M = 12.70%, SE = 1.80) or the mouth (M = 9.40%, SE = 1.40), F(2,52), = 18.899, p = .001, $\eta\rho^2$ = .421, the “feature” factor also interacted with participant group F(2,56) = 5.804, p = .005, $\eta\rho^2$ = .182. Follow-up analyses indicated no differences in the proportion dwell time spent on the eyes and mouth, but SRs spent more time on the nose than controls: F(1,26) = .557, p = .462, F(1,26) = .385, p = .540 and F(1,26) = 17.937, p = .001, $\eta\rho^2$ = .408, respectively (see Figure 3c). There was also a main effect of group, indicating that SRs spend more time looking at the inner features of the face than controls, F(1,26) = 9.153, p = .006, $\eta\rho^2$ = .260.

A final group analysis indicated that SRs were also faster (M = 794.17ms, SE = 31.68) than controls (M = 934.08ms, SE = 36.38) in first fixating upon a face, F(1,26) = 5.199, p = .031, $\eta\rho^2$ = .167.

Finally, case-by-case analyses were also performed on the data, given there is reason to suspect that super recognition may also be characterised by cognitive heterogeneity (see Table 4). As in Experiment 1, we performed modified *t*-tests for single-case comparisons for all the eye-tracking measures (Crawford et al., 2010). Although there was a group-based difference in the proportion dwell time spent studying bodies, this measure did not significantly differ in any of the case-by-case comparisons. Likewise, the significant group comparisons noted for the proportion dwell time spent on the inner and outer facial features only resulted in one significant single-case comparison (for SR7). However, four participants (SR1, SR2, SR4, and SR7) spent significantly longer than controls looking at the nose, and an additional participant performed above two standard deviations from the mean on this measure (SR6). Finally, although the SRs as a group elicited their first fixation to a face more rapidly than controls, this finding was not supported in any case-by-case comparisons.

It is more difficult to discern whether the eye-movement measures are indicative of any cognitive variation in the SR group. Indeed, all the SRs achieved high scores on the CFMT+ and the CFPT, and unsurprisingly the cluster of scores at near-ceiling levels and the small sample size prohibited any potential correlations from emerging.

< Insert table 4 >

Control Participants

In order to examine whether the different patterns of performance observed in the DP versus the SR group could simply be attributed to age (the DP group were significantly older than the SR group), we performed a final set of analyses on the control data to examine whether age interacted with any of the eye-tracking measures or our measure of face recognition ability (i.e. performance on the CFMT). Data for the control groups were combined across Experiment 1 and Experiment 2, and no effect of age was observed on any of the eye-movement variables (all *p*s > .05). Unsurprisingly, performance on the CFMT was lower in the older (M = 49.15, SE = 1.92) compared to the younger (M = 57.95, SE = 1.92) participant group, $F(1,38) = 10.474$, $p = .003$, $\eta\rho^2 = .216$ (see Bowles et al., 2009). Hence, the differing pattern of performance in the DP (i.e. less time spent on the eyes and more on the mouth) versus the SR (i.e. more time spent on the nose) group cannot simply be attributed to participant age.

This pattern of findings raises a final question: which measure used in this study best reflects the typical face-processing continuum? That is, does the face recognition ability of typical perceivers vary according to the time spent on the eyes and mouth as observed for DPs, or the nose as observed for SRs? While it would be too simplistic to assume that regional distribution of fixations is the only marker of typical face perception, the face-processing literature largely concentrates on the processing of inner features as the function of face recognition. Pertinently, this final analysis addressed this question by performing three correlations on the collapsed control data. While no significant correlation was observed between control CFMT performance and the proportion dwell time spent on the eyes (r = .179, p = .268), there was a marginal negative correlation with the time spent on the mouth (r = -.309, p = .052) and a stronger positive correlation with the time spent on the nose (r = .408, p = .009).

Summary of Experiment 2

This experiment investigated the eye-movement patterns of SRs and typical perceivers in the same eye-movement task as used in Experiment 1. At the group level, SRs spent less time examining bodies and more time examining the inner features of faces than controls. While case-by-case analyses mostly failed to reach significance on these measures, a more consistent pattern emerged for the proportion dwell time spent on the nose. In group and four individual analyses, the SRs spent a significantly longer time looking at the nose. Given this finding does not simply mirror those of Experiment 1 (where DPs were found to spend less time on the eyes and more time on the nose), one could argue that DPs and SRs do not merely represent individuals at the opposite ends of the typical face recognition spectrum. Analysis of the control data revealed a correlation between face recognition ability and the proportion dwell time spent on the nose, indicating that SRs may simply be those at the top end of the spectrum, whereas DPs may reside on a qualitatively different continuum.

Experiment 2 therefore lends support to the findings of Hsiao and Cottrell (2008) and Patterson and Eckstein (2012), indicating that the nose may represent an optimal viewing position in face recognition, possibly underpinning successful holistic processing of faces. However, as this is the first eye movement investigation examining super recognition, we sought to replicate the findings in a final experiment.

EXPERIMENT 3

While the social scenes paradigm is a relatively novel and highly ecologically valid method of investigating patterns of eye-movements, most research looking at face learning and recognition to date employed single-face stimuli. In order to allow comparability between studies and replicate the findings of Experiment 2, our last experiment provided an additional investigation of eye-movements in SRs, using an alternative face learning paradigm. This time we used single-face stimuli and asked participants to view each face and encode it for a later recognition test (that was never presented).

Method

Participants

Two of the SRs described in Experiment 2 (SR4 and SR7) agreed to return to the laboratory and took part in this study. Additionally, in accordance with the Russell et al. (2009, 2012) criteria, we recruited two new SRs (SR9 and SR10), a 35 year-old male (92/102 faces identified correctly in the CFMT+ and 20 errors made in the CFPT upright) and a 35 year-old female (97 faces identified correctly in the CFMT+ and 20 errors made in the CFPT upright). Both participants contacted our research group independently and reported instances of extraordinary face recognition since childhood. These individuals also participated in another investigation in our laboratory, where their performance on two further face-processing tests significantly exceeded that of controls (Bobak et al., in press). A new group of 20 (10 female) control participants also participated, and were matched to the SRs according to age (*M* = 24.9 years, *SD* = 4.6) and estimated IQ. All control participants reported typical face recognition skills, and this was again confirmed via completion of the CFMT, where all participants performed within the “typical” range (*M* = 56.05, SD = *6*.75). These participants were all Bournemouth University students and staff members who participated in exchange for course credits or a small monetary payment. Ethical approval for this study was granted by Bournemouth University’s Ethics Committee.

Materials

Colour photographs of 24 (12 female) white Caucasian adults were taken from the Glasgow Unfamiliar Face Database (Burton, White, & McNeill, 2010). In all photographs the person was looking directly at the camera (direct gaze) and had a neutral facial expression. Faces were cropped to remove excess hair, but were not cropped around the hairline. The faces were presented against a white background and measured approximately 10 x 9cm, so that each face subtended 11.42 x 10.28 degrees of visual angle when viewed from a distance of approximately 50 cm. Gaze behaviour was recorded using the same eye-tracker has described in Experiment 1.

Procedure

Participants were seated approximately 50 cm from the screen, and placed their head within the chin rest. The experiment was preceded by a nine-point calibration procedure. Each trial began with the presentation of a central fixation cross, and each face was presented centrally on a single occasion and in a randomized order. Each face was displayed for five seconds, and participants were instructed to memorize the faces for a later recognition test (that was not presented).

Eye Movement Parameters and Statistical Analyses

Scanning behaviour was examined for the entire 5-second period. To investigate fixations to specific regions, a freehand tool was used to draw three AOIs onto each facial image, covering the eyes, nose and mouth. The proportion dwell time elicited to each AOI was calculated for each participant. Due to the very small size of the experimental group, only case-by-case (modified *t*-tests for single-case comparisons: Crawford et al., 2010) statistical procedures were performed on all measures.

Results

Case-by-case analyses (see Table 5) of SRs and control participants revealed that the difference in scanning strategy between these groups is related to the nose region, where all four SRs spent a significantly longer time examining this area compared to control participants. SR7 spent also more time scanning the mouth region of the studied faces than controls.

< Insert Table 5 >

Summary

The results of Experiment 3 provide further support for the findings observed for the SR participants in Experiment 2, using an alternative paradigm. Specifically, when required to memorise a set of faces, all four SRs spent significantly more time than control participants viewing the nose. Surprisingly, SR7 also spent significantly more time than controls looking at the mouth region, although a similar trend did not emerge in any of the other SR participants, nor for this individual in Experiment 2.

DISCUSSION

This investigation monitored the eye-movements of DP, SR and control participants while they viewed images of people engaged in natural social scenes. Findings in the DP group suggest that, in some cases, the condition may be underpinned by reduced attention to faces. Indeed, while the DPs as a group did not take a longer time to initially fixate upon a face than controls, they did spend less overall dwell time examining faces and more time viewing bodies. Further, in contrast to previous work, the DP group did not spend less time on the inner facial features than controls, but this measure did correlate with their score on the CFMT, indicating that individuals with more severe prosopagnosia spent less time examining the inner region of the face. As observed in previous work examining acquired prosopagnosia, the DP group spent less time viewing the eyes and more time viewing the mouth than controls. In contrast, across two experiments, SRs spent more time viewing the nose, suggesting these individuals are not merely the “opposite” of DP. Instead, analysis of control data indicated that the face recognition ability of typical perceivers is also associated with the time spent examining the nose, and therefore that SRs represent individuals at the top end of the typical face-processing system, whereas DPs may be a qualitatively different group.

First, the DP findings will be addressed. One aim of the investigation was to examine whether DP may result from a lack of attention to faces. While the DPs as a group did not take a longer time to initially fixate a face, a disparate pattern of findings emerged in single-case analyses. Indeed, one DP took a significantly longer time than controls to initially fixate on a face (DP2), and another (DP1) performed at 1.77 standard deviations above the control mean. Although three other DPs were slower than controls but within one standard deviation of the control mean, the mean scores of the remaining five DPs were quicker than controls. These findings converge with previous work suggesting that DP is a heterogeneous condition, and that impaired face detection mechanisms may underpin the face recognition difficulties in only a subset of individuals (Garrido, Duchaine, & Nakayama, 2008; Dalrymple & Duchaine, 2015). Indeed, in their recent paper with a group of seven children with DP, Dalrymple and Duchaine (2015) reported that four participants had impaired face detection, but in three children the mechanism was spared and performance remained on par with that of controls. This finding converges with some earlier work with adults (Garrido et al., 2008) where four DPs (out of a group of 14) also had intact face detection mechanisms. The authors attributed this heterogeneity to occurrence of ectopias, regions of cortical disorganisations produced by impaired neural migration (Dalrymple & Duchaine, 2008). Specifically, they suggested that ectopias affecting brain areas responsible for face detection may result in atypical attention to faces and failure to develop a functional face recognition system, leading to DP. On the other hand, ectopias at higher levels of visual system (i.e., occipital and temporal areas of the brain) could result in DPs with impaired face recognition and perception, notwithstanding intact face detection. Finally, a pervasive ectopia of the entire face processing system may lead to face perception and recognition problems that are concomitant but not necessarily resulting from face detection abnormalities. It is thus possible that in the study presented here, DP1 and DP2, but not the other eight DP participants, had partial or widespread ectopias resulting in slower orienting towards faces within social scenes. To assess this heterogeneity fully, future work should endeavour to combine standard behavioural tasks of face detection with more ecological paradigms, such as the social scenes task described in this study.

Further insight into the hypothesis that reduced attention to faces may underpin some cases of DP comes from the measures examining the proportion of dwell time to the background of the images, bodies and faces. It is striking that there was no difference between DPs and controls in the proportion dwell time spent on image background, but group-based analyses indicated that DPs spent more time examining bodies and less time examining faces. Single-case analyses found supporting evidence for this pattern in three DPs (DP1, DP2 and DP10), and similar non-significant trends were noted in all other DPs with the exception of DP6 and DP9. While these findings may indicate that reduced attention to faces underpins DP in some individuals, it is also possible that this measure reflects a social consequence of the disorder. That is, because faces provide little information to people with DP, they rely on alternative sources of information (e.g. bodies or movement, Bennetts et al., in press) to make identity judgments.

The proportion dwell time spent on the inner and outer features has been used in many previous investigations to indicate reduced attention to the core facial features in acquired prosopagnosia (Le et al., 2003), and in one investigation using developmental cases (Schwarzer et al., 2007). The findings reported here are therefore in contrast to previous reports, given we did not find any differences on this measure between the DP and control groups as a whole, or in any single-case comparisons. This finding may result from the different, more ecologically valid paradigm that was used here compared to previous work, where single faces were typically presented against plain backgrounds. However, it is striking that two DPs tended to spend a longer time viewing the inner features: DPs 6 and 9. Without wishing to place too much emphasis on non-significant results, it is nevertheless of interest that these were the same individuals who tended to initially fixate on faces more rapidly than controls. Further, the finding that CFMT scores in the DP group correlated with the time spent on the inner features may account for the pattern of findings reported here: it is possible that DPs with milder prosopagnosia (i.e. those with higher CFMT scores) may represent those at the bottom end of normal rather than membership of a qualitatively separate group. Future work might address this possibility, and the identification of different phenotypes of the condition is likely to have important implications for the development of remediation techniques (see Bate & Bennetts, 2014).

It is also of interest that group analyses revealed that DPs spent less time fixating the eyes and more time fixating the mouth than control participants. Although case-by-case analyses did not reach significance for any individual DP with regard to the "eyes" measure, the trend was in the same direction in all but one participant (DP10). The reduced time spent on the mouth significantly differed for two individual DPs (DP2 and DP4), and the trend was present for all other individuals with the exception of DP10. It is therefore possible that DP10's prosopagnosia has different underpinnings to the rest of the group, but the few significant case-by-case analyses suggests that these patterns of feature exploration may not serve as reliable biobehavioural indicators of the condition.

Notably though, the group-based patterns of feature exploration reported here converge with previous reports of acquired prosopagnosia (Le et al., 2003; Stephan & Caine, 2009), which have typically been attributed to a reduced ability to process faces in a "holistic" or "configural" manner (Stephan & Caine, 2009). Indeed, it is generally accepted that configural processing requires analysis of the particular presentation of the inner features of the face and the spatial relations within them (e.g. Maurer, Le Grand, & Mondloch, 2002), and it is possible that the increased focus on the mouth region may distract attention from the more informative eye region and from employing optimal configural processing mechanisms.

However, this interpretation is challenged by previous work that has identified the nose as an optimal viewing position in face recognition (Hsiao & Cottrell, 2008; Peterson & Eckstein, 2012), and provides evidence against a body of other work that suggests the eyes are pivotal in face recognition (Schyns et al., 2002; Sekiguchi, 2011). Both Hsiao and Cottrell (2008) and Peterson and Eckstein (2012) suggested that the nose may be the optimal viewing position because it is the best location for holistic and configural processing of the entire face. Interestingly, the findings in our SR and control sample indicate that the proportion dwell time spent on the nose has a positive association with face recognition ability, although we cannot comment on whether the proportion dwell time spent on the nose is representative of configural or holistic processing skills. A consistent finding in the word reading literature is that there is an optimal viewing position (just to the left of a word's centre) when intentionally processing words (O'Regan & Jacobs, 1992) and when word reading proceeds automatically (Smilek, Solman, Murawski, & Carriere, 2009; Parris, Sharma & Weeks, 2007). In this literature the optimal viewing position is accounted for lexically (Stevens & Grainger, 2003), but has been shown to influence the spatial distribution of attention across non-lexical stimuli (Ducrot & Pynte, 2002). Since better distribution of spatial attention across a face does not necessarily imply better configural processing, it is possible that better face recognition in SRs results from a more efficient spread of spatial attention across faces.

Notably, it seems that this finding is a relatively reliable indicator of super recognition, given it emerged in four of the eight SRs in Experiment 2 (with one other SR exceeding control performance by more than two standard deviations) and all four of the SRs in Experiment 3 (note that one of the latter participants was the same as one who did not significantly differ from controls in Experiment 2). Nevertheless, the finding that it did not emerge in all SR participants leaves open the possibility that superior face recognition may also be characterised by cognitive heterogeneity, and it may have different underpinnings in different individuals. This is perhaps supported by the unexpected finding that one SR (SR7) spent more time examining the mouth than controls in Experiment 3, although the same effect did not emerge for this participant in Experiment 2.

However, it is relevant that our combined analyses of control performance across Experiments 1 and 2 indicates that SRs may simply be those at the top end of the typical face-processing system. Indeed, the proportion dwell time that controls spent on the nose correlated with their face recognition skills, whereas no correlation was noted with the time spent examining the eyes, and only a mild correlation emerged for the time spent on the mouth. Alternatively, given the trends towards a qualitatively different pattern of processing in DPs (where no participant differed from controls on the time spent on the nose, but various effects emerged for the eyes and mouth), our data supports the hypothesis that the condition is comparable to acquired prosopagnosia, and most of these individuals do not simply represent the bottom end of the typical face-processing spectrum.

In sum, this paper presents evidence that (a) some cases of DP may be underpinned by reduced attention to faces, and (b) that at least some individuals with the condition represent a qualitatively different group to typical perceivers, rather than simply being the "bottom end" of normal. Conversely, individuals who meet the criteria for super recognition appear to be those at the "top end" of normal, and the work presented here suggests that the nose (as opposed to the eyes) appears to be a critical region involved in successful face recognition. Future work should endeavour to further partition DP, and to establish whether the nose region is also associated with heightened configural or holistic processing skills.

References

Althoff, R. R., & Cohen, N. J. (1999). Eye-movement-based memory effect: a reprocessing effect in face perception. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(4), 997-1010.

Bate, S., & Bennetts, R. J. (2014). The rehabilitation of face recognition impairments: a critical review and future directions. *Frontiers in Human Neuroscience*, *8,* 491.

Bate, S., & Cook, S. J. (2012). Covert recognition relies on affective valence in developmental prosopagnosia: Evidence from the skin conductance response. *Neuropsychology*, *26*(5), 670-674.

Bate, S., Haslam, C., Jansari, A., & Hodgson, T. L. (2009). Covert face recognition relies on affective valence in congenital prosopagnosia. *Cognitive Neuropsychology, 26*(4), 391-411.

Bate, S., Haslam, C., Tree, J. J., & Hodgson, T. L. (2008). Evidence of an eye movement-based memory effect in congenital prosopagnosia. *Cortex, 44*(7), 806-819.

Bennetts, R. J., Butcher, N., Lander, K., Udale, R., & Bate, S. (2015). Movement Cues Aid Face Recognition in Developmental Prosopagnosia. *Neuropsychology*.

Bennetts, R. J., Murray, E., Boyce, T., & Bate, S. (under review). Prevalence of developmental prosopagnosia in middle childhood. *Quarterly Journal of Experimental Psychology*.

Birmingham, E., Bischof, W. F., & Kingstone, A. (2008). Gaze selection in complex social scenes. *Visual Cognition, 16*(2-3), 341-355.

Bishop, D. V. (1997). Cognitive neuropsychology and developmental disorders: Uncomfortable bedfellows. *The Quarterly Journal of Experimental Psychology: Section A*, *50*(4), 899-923.

Bobak, A., Hancock, P. J., & Bate, S. (in press). Super-Recognizers in Action: Evidence from Face Matching and Face Memory Tasks. *Applied Cognitive Psychology*.

Bowles, D. C., McKone, E., Dawel, A., Duchaine, B., Palermo, R., Schmalzl, L., ... & Yovel, G. (2009). Diagnosing prosopagnosia: Effects of ageing, sex, and participant–stimulus ethnic match on the Cambridge Face Memory Test and Cambridge Face Perception Test. *Cognitive Neuropsychology*, *26*(5), 423-455.

Brunsdon, R., Coltheart, M., Nickels, L., & Joy, P. (2006). Developmental prosopagnosia: A case analysis and treatment study. *Cognitive Neuropsychology*, *23*(6), 822-840.

Burton, A. M., White, D., & McNeill, A. (2010). The Glasgow face matching test. *Behavior Research Methods*, *42*(1), 286-291.

Caldara, R., Schyns, P., Mayer, E., Smith, M. L., Gosselin, F., & Rossion, B. (2005). Does prosopagnosia take the eyes out of face representations? Evidence for a defect in representing diagnostic facial information following brain damage. *Journal of Cognitive Neuroscience*, *17*(10), 1652-1666.

Crawford, J. R., Garthwaite, P. H., & Porter, S. (2010). Point and interval estimates of effect sizes for the case-controls design in neuropsychology: Rationale, methods, implementations, and proposed reporting standards. *Cognitive Neuropsychology*, *27*(3), 245-260.

Damasio, A. R., Damasio, H., & Van Hoesen, G. W. (1982). Prosopagnosia Anatomic basis and behavioral mechanisms. *Neurology*, *32*(4), 331-331.

Dalrymple, K. A., & Duchaine, B. (in press). Impaired face detection may explain some but not all cases of developmental prosopagnosia. *Developmental Science*.

Duchaine, B., Germine, L., & Nakayama, K. (2007). Family resemblance: Ten family members with prosopagnosia and within-class object agnosia. *Cognitive Neuropsychology*, *24*(4), 419-430.

Duchaine, B., & Nakayama, K. (2006). The Cambridge Face Memory Test: Results for neurologically intact individuals and an investigation of its validity using inverted face stimuli and prosopagnosic participants. *Neuropsychologia*,*44*(4), 576-585.

Ducrot, S., & Pynte, J. (2002). What determines the eyes' landing position in words? *Perception & Psychophysics*, *64*(7), 1130-1144.

Fletcher-Watson, S., Leekam, S. R., Findlay, J. M., & Stanton, E. C. (2008). Brief report: Young adults with autism spectrum disorder show normal attention to eye-gaze information—Evidence from a new change blindness paradigm. *Journal of Autism and Developmental Disorders*, *38*(9), 1785-1790.

Garrido, L., Duchaine, B., & Nakayama, K. (2008). Face detection in normal and prosopagnosic individuals. *Journal of Neuropsychology*, *2*(1), 119-140.

Grueter, M., Grueter, T., Bell, V., Horst, J., Laskowski, W., Sperling, K., ... & Kennerknecht, I. (2007). Hereditary prosopagnosia: The first case series. *Cortex*, *43*(6), 734-749.

Henderson, J. M., Williams, C. C., & Falk, R. J. (2005). Eye movements are functional during face learning. *Memory & Cognition*, *33*(1), 98-106.

Holdnack, H. A. (2001). *Wechsler Test of Adult Reading: WTAR*. Psychological Corporation: San Antonio, TX

Hsiao, J. H. W., & Cottrell, G. (2008). Two fixations suffice in face recognition. *Psychological Science*, *19*(10), 998-1006.

Jones, R. D., & Tranel, D. (2001). Severe developmental prosopagnosia in a child with superior intellect. *Journal of Clinical and Experimental Neuropsychology, 23*(3), 265- 273.

Kane, M. J., & Engle, R. W. (2003). Working-Memory Capacity and the Control of Action: The Contributions of Goal Neglect, Response Competition, and Task Set to Stroop Interference. *Journal of Experimental Psychology: General*, 132(1), 47-70.

Konar, Y., Bennett, P. J., & Sekuler, A. B. (2010). Holistic processing is not correlated with face-identification accuracy. *Psychological Science*, *21*(1), 38-43.

Le, S., Raufaste, E., & Demonet, J. F. (2003). Processing of normal, inverted, and scrambled faces in a patient with prosopagnosia: behavioural and eye tracking data. *Cognitive Brain Research*, *17*(1), 26-35.

Lê, S., Raufaste, E., Roussel, S., Puel, M., & Démonet, J. F. (2003). Implicit face perception in a patient with visual agnosia? Evidence from behavioural and eye-tracking analyses. *Neuropsychologia*, *41*(6), 702-712.

Lee, Y., Duchaine, B., Wilson, H. R., & Nakayama, K. (2010). Three cases of developmental prosopagnosia from one family: Detailed neuropsychological and psychophysical investigation of face processing. *Cortex, 46*(8), 949-964.

Luria, S. M., & Strauss, M. S. (1977). *Comparison of eye movements over faces in photographic positives and negatives*. Naval Submarine Medical Research Lab Groton CT.

Maurer, D., Le Grand, R. L., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences*, *6*(6), 255-260.

O'Regan, J. K., & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance, 18*(1), 185.

Parris, B.A., Sharma, D., & Weekes, B.S. (2007). An Optimal Viewing Position Effect in the Stroop Task When Only One Letter Is The Colour Carrier. *Experimental Psychology*, *54*(4), 273-280.

Peterson, M. F., & Eckstein, M. P. (2012). Looking just below the eyes is optimal across face recognition tasks. *Proceedings of the National Academy of Sciences*, *109*(48), E3314-E3323.

Riby, D. M., & Hancock, P. J. (2008). Viewing it differently: Social scene perception in Williams syndrome and autism. *Neuropsychologia*, *46*(11), 2855-2860.

Richler, J. J., Cheung, O. S., & Gauthier, I. (2011). Holistic processing predicts face recognition. *Psychological Science, 22*, 464-471.

Riddoch, M. J., & Humphreys, G. W. (1993). *BORB: Birmingham object recognition battery*. LEA.

Russell, R., Chatterjee, G., & Nakayama, K. (2012). Developmental prosopagnosia and super-recognition: No special role for surface reflectance processing. *Neuropsychologia*, *50*(2), 334-340.

Russell, R., Duchaine, B., & Nakayama, K. (2009). Super-recognizers: People with extraordinary face recognition ability. *Psychonomic Bulletin & Review*, *16*(2), 252-257.

Schmalzl, L., Palermo, R., & Coltheart, M. (2008). Cognitive heterogeneity in genetically based prosopagnosia: A family study. *Journal of Neuropsychology*, *2*(1), 99-117.

Schmalzl, L., Palermo, R., Green, M., Brunsdon, R., & Coltheart, M. (2008). Training of familiar face recognition and visual scan paths for faces in a child with congenital prosopagnosia. *Cognitive Neuropsychology*, *25*(5), 704-729.

Schwarzer, G., Huber, S., Grüter, M., Grüter, T., Groß, C., Hipfel, M., & Kennerknecht, I. (2007). Gaze behaviour in hereditary prosopagnosia. *Psychological Research*, *71*(5),583-590.

Schyns, P. G., Bonnar, L., & Gosselin, F. (2002). Show me the features! Understanding recognition from the use of visual information. *Psychological Science*, *13*(5), 402-409.

Slessor, G., Riby, D. M., & Finnerty, A. N. (2013). Age-related differences in processing face configuration: the importance of the eye region. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *68*(2), 228-231.

Smilek, D., Solman, G.J.F., Murawski, P., & Carriere, J.S.A. (2009). The eyes fixate the optimal viewing position of task-irrelevant words. *Psychonomic Bulletin and Review*, *16*(1), 57-61.

Stephan, B. C. M., & Caine, D. (2009). Aberrant pattern of scanning in prosopagnosia reflects impaired face processing. *Brain and Cognition*, *69*(2), 262-268.

Stevens, M., & Grainger, J. (2003). Letter visibility and the viewing position effect in visual word recognition. *Perception & Psychophysics*, *65*(1), 133-151.

Susilo, T., & Duchaine, B. (2013). Advances in developmental prosopagnosia research. *Current opinion in neurobiology*, *23*(3), 423-429.

Van Belle, G., Ramon, M., Lefèvre, P., & Rossion, B. (2010). Fixation patterns during recognition of personally familiar and unfamiliar faces. *Frontiers in Psychology*, *1*(20), 1–8.

Wang, R., Li, J., Fang, H., Tian, M., & Liu, J. (2012). Individual differences in holistic processing predict face recognition ability. *Psychological Science*,*23*(2), 169-177.

Weigelt, S., Koldewyn, K., & Kanwisher, N. (2012). Face identity recognition in autism spectrum disorders: a review of behavioral studies. *Neuroscience & Biobehavioral Reviews*, *36*(3), 1060-1084.

Yarbus, A.L. 1967. *Eye Movements and Vision.* Plenum Press: New York.

Table 1. Demographics of DPs and performance in standard deviation units on tests of face-processing, lower-level vision and object recognition. 'CFMT' refers to the Cambridge Face Memory Test (Duchaine & Nakayama, 2006), 'CFPT' to the Cambridge Face Perception Test (Duchaine et al., 2007), 'Mind in the Eyes' to the Reading the Mind in the Eyes Test (Baron-Cohen et al., 2001), and 'BORB' to the Birmingham Object Recognition Battery (Humphreys & Riddoch, 1993). DP scores are compared to published norms for each test (see each paper for control demographics). Note that the CFPT scores represent the number of errors, rather than the number of correct responses.

	Control Mean (SD)	**DP1**	**DP2**	**DP3**	**DP4**	**DP5**	**DP6**	**DP7**	**DP8**	**DP9**	**DP10**
Age		52	49	66	57	64	60	58	59	46	67
Gender		F	M	F	F	M	F	F	M	F	F
Hand		L	R	R	R	R	L	R	R	R	R
IQ		120	117	66	120	119	123	120	120	120	123
Face processing tests:											
CFMT	59.6/72 (7.6)	-2.3*	-2.7*	-2.7*	-3.5*	-4.2*	-4.6*	-2.6*	-4.03*	-3.2*	-2.8*
CFPT	36.7 (12.2)	-0.1	-4.9*	-2.2*	-0.9	-1.3	-5.2*	-4.2*	-1.42	-2.4*	-1.8
Famous faces	90.4% (7.7)	-6.8*	-2.2*	-4.9*	-6.7*	-6.1*	-9.2*	-9.1*	-8.67*	-9.3*	-7.2*
Mind in eyes	26.2 /36(3.6)	0.5	0.5	-1.4	0.2	-1.4	-0.9	0.5	-1.44	-0.3	0.2
Lower-level vision (BORB):											
Length match	26.9/30 (1.6)	-1.2	-1.8	-1.8	0.1	0.1	0.1	-1.2	-0.56	0.1	1.9
Size match	27.3/30 (2.4)	0.7	-1.0	-1.8	0.3	0.7	-1.8	0.3	0.71	0.7	-1.0
Orientation match	24.8/30 (2.6)	0.9	-0.7	0.5	0.1	0.5	-0.3	0.1	0.46	1.2	0.9
Position of gap	35.1/40 (4.0)	0.5	-0.5	1.0	0.5	-0.5	-0.3	1.0	0.48	0.7	1.0
Object decision test	52.4/64 (3.9)	0.2	-0.1	-0.4	0.9	-0.1	-1.1	-0.6	0.15	1.4	1.7

* indicates impaired performance

Table 2. Performance of DPs and controls on each measure in Experiment 1. Performance of the DPs is expressed in the numbers of standard deviations away from the control mean.

	Controls		Individuals with DP									
	Mean	SD	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
Eye-movement measures												
% dwell time faces	63.1	9.5	-2.7*	-0.8	-0.5	-0.7	-0.9	1.6	-1.5	-1.3	-0.1	-2.7*
% dwell time on bodies	21.7	4.9	2.3*	2.3*	0.6	1.4	0.7	-1.7	0.8	2.1	-0.7	3.1*
% dwell time on background	15.5	5.6	2.1	-0.8	0.3	0.0	1.0	-1.2	2.0	0.3	0.8	2.1
% dwell time on inner features	43.3	11.5	-1.6	-0.6	0.1	-0.3	-0.6	1.8	-1.2	-0.4	0.4	-1.5
% dwell time on outer features	19.8	7.8	-0.8	-0.1	-0.7	-0.4	-0.3	-0.7	-0.1	-1.1	-0.7	-1.1
% dwell time on eyes	13.1	8.6	-0.9	-0.7	-1.4	-1.4	-1.4	-1.2	-1.0	-0.9	-0.8	0.1
% dwell time on nose	12.7	6.3	-1.3	-1.5	1.1	-1.3	-1.2	1.2	-0.2	0.4	1.3	-0.9
% dwell time on mouth	9.2	9.1	0.7	2.2*	0.9	2.6*	1.5	1.9	-0.4	0.4	0.1	-0.9
First fixation to a face (msec)	973.1	161.4	1.8	2.6*	0.9	-0.6	0.8	-1.3	-0.9	0.7	-0.3	-0.5

*significantly different performance to control participants at the .05 level.

Table 3. Demographical information, CFMT+ and CFPT scores for the SR participants used in this study and SR and control norms described by Russell et al. (2012).

	Russell et al. (2012) (N = 6)		The current study								
	SRs (N = 6)	Controls (N = 26)	SRs (N = 8)	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
Age	40.7 *(9.9)*	42.2 *(14.1)*	24.5 *(4.2)*	20	29	21	20	33	19	27	27
Gender	-	-	M = 5	F	M	M	M	M	F	M	F
Hand	-	-	R = 8	R	R	R	R	R	R	R	R
CFMT+	95.0 *(1.9)*	75.2 *(11.6)*	95.62 *(2.44)*	96	97	100	97	100	96	101	94
CFPT (upright)	24.7 *(10.3)*	35.4 *(12.9)*	18.5 *(7.2)*	10	22	16	12	16	32	16	24

Table 4. Performance of the SRs and controls on each measure in Experiment 2. Performance of the SRs is expressed in the numbers of standard deviations away from the control mean.

	Controls		Super-Recognizers							
	Mean	SD	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
Eye-movement measures										
% dwell time faces	63.7	10.3	0.6	0.7	-0.8	1.29	1.0	1.1	1.8	0.6
% dwell time on bodies	21.5	6.5	-1.2	-0.7	0.2	-1.01	-1.3	-0.9	-1.3	-0.5
% dwell time on background	14.6	5.8	-0.1	-0.6	1.1	-1.15	-0.8	-1.2	-1.7	-0.8
% dwell time on inner features	48.5	12.4	1.2	1.4	-0.5	1.74	0.9	1.4	2.3*	0.9
% dwell time on outer features	15.2	6.3	-1.3	-1.6	-0.4	-1.29	-0.0	-1.0	-1.6	-0.8
% dwell time on eyes	14.1	8.9	-0.8	-1.0	-0.2	-1.14	1.5	-0.9	-0.1	0.3
% dwell time on nose	17.2	7.6	2.6*	2.2*	0.1	3.40*	0.8	2.1	2.6*	0.9
% dwell time on mouth	8.5	7.2	0.6	1.3	-0.4	0.63	-0.9	0.2	0.9	-0.5
First fixation to a face (msec)	934.1	162.7	-1.0	-1.2	-1.0	-1.25	0.2	-0.6	-1.5	-0.5

*significantly different performance to control participants at the .05 level.

Table 5: Performance of the SRs and controls on the eye-tracking task. Performance of the SRs is expressed in the numbers of standard deviations away from the control mean.

	Controls		Super-Recognizers			
	Mean	SD	SR4	SR7	SR9	SR10
Eye-movement measures						
% dwell time on eyes	45.6	17.7	-1.0	-1.9	-0.4	-1.0
% dwell time on nose	21.7	9.2	4.2**	2.7*	2.2*	4.8**
% dwell time on mouth	9.8	5.5	-1.4	2.4*	-1.7	-1.8
% dwell time on inner features	77.1	12.5	1.1	0.4	0.3	1.4

*significantly different performance to control participants at the .05 level.
**significant different performance to control participants at the .001 level.

Figure 1. Example stimuli from Experiments 1 and 2. Black lines represent AOIs. In both experiments the images were displayed in colour.

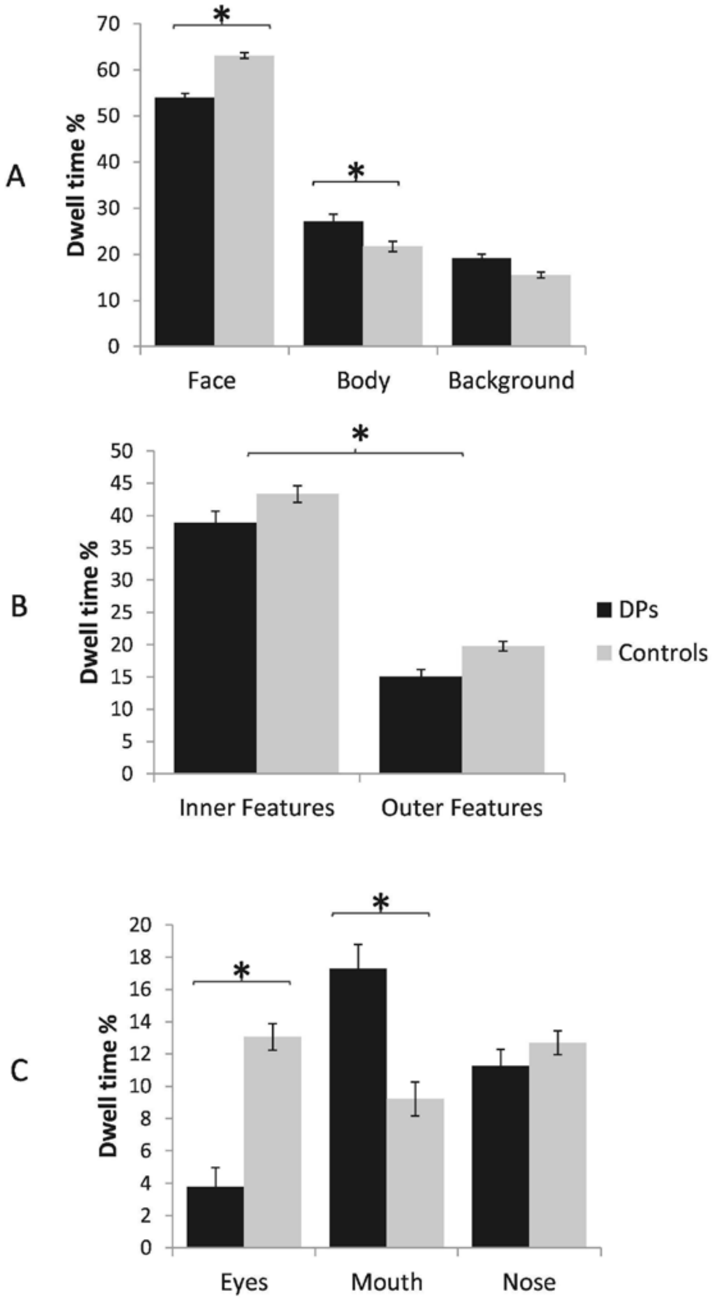

Figure 2. The percentage dwell time spent by DPs and controls on each region in Experiment 1. Error bars represent the standard error of the mean.

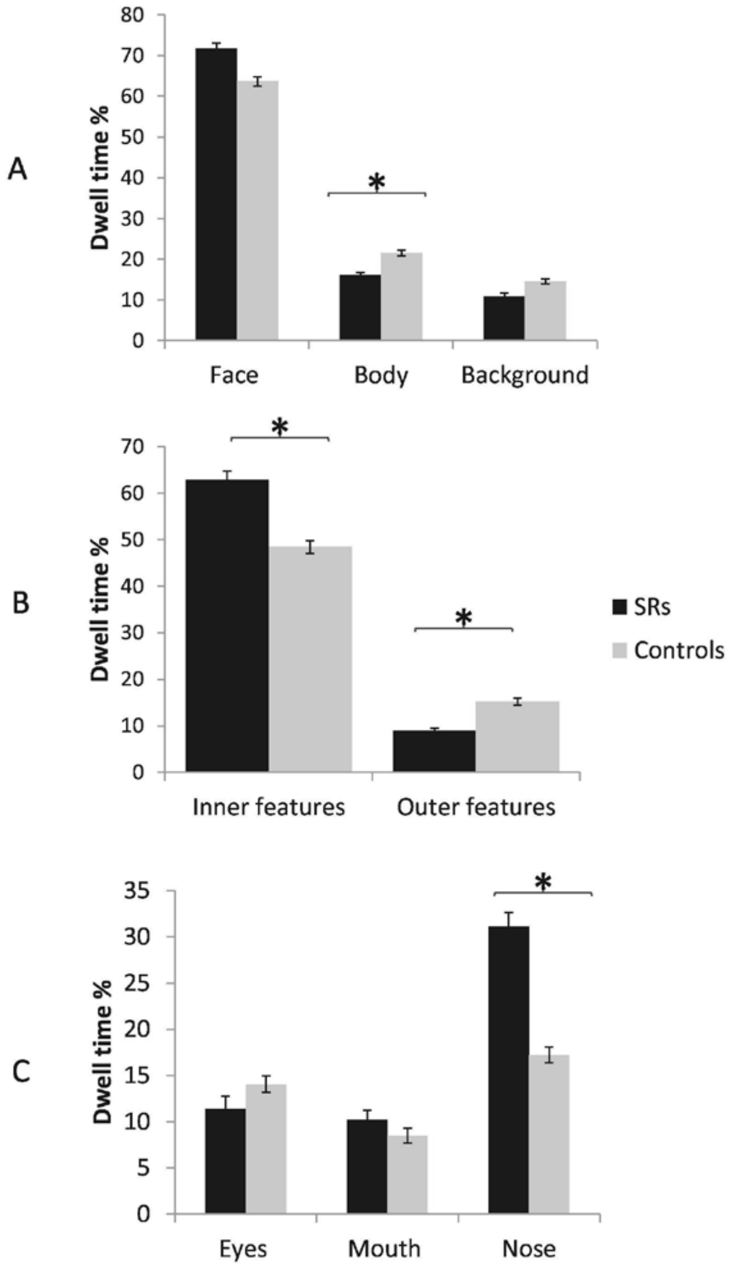

Figure 3. The percentage dwell time spent by SRs and controls on each region in Experiment 2. Error bars represent the standard error of the mean.