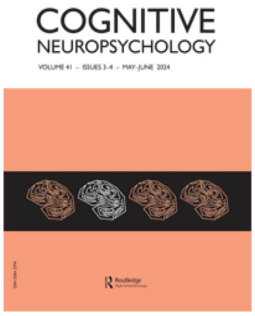

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Impairments for faces but not for abstract shapes in developmental prosopagnosia: Evidence from visual working memory tasks

John R. Towler[a], Margaret C. Jackson[b] and Jeremy J. Tree[a]

[a]School of Psychology, Faculty of Medicine, Health and Life Science, Swansea University, Singleton Park, Swansea, UK; [b]School of Psychology, University of Aberdeen, Old Aberdeen, UK

ABSTRACT

We investigated visual working memory (VWM) for faces and two novel non-face pattern types (Blobs and Mondrians) in individuals with developmental prosopagnosia (DP) and age-matched controls. Participants completed both simultaneous and sequential encoding tasks, judging whether a probe item matched one shown at encoding. DPs showed a consistent face disadvantage across both encoding types, while controls showed a face advantage, but only during simultaneous encoding. Compared to controls, DPs had impaired face VWM in both tasks but performed equivalently for abstract shapes and patterns. Face VWM impairments in DP were not exacerbated by increased memory load or updating demands, suggesting these deficits stem from face perception difficulties that affect encoding rather than general VWM mechanisms. Our group-based analyses were supplemented by individual case statistics. Overall, our findings indicate that DPs do not exhibit general VWM deficits, but rather specific difficulties with face processing across formats.

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Developmental prosopagnosia; face recognition; visual working memory; object recognition; abstract shapes

Introduction

Developmental prosopagnosia (DP) is a selective neurodevelopmental disorder characterized by a severe lifelong and persistent impairment for face recognition that is present in the absence of brain damage or wider intellectual disability (Susilo & Duchaine, 2013; Towler & Eimer, 2012; Towler et al., 2017). Individuals with DP are often diagnosed on the basis that they self-report face recognition problems and demonstrate severe difficulties recognizing both familiar and unfamiliar faces. However, there is some heterogeneity in the application of diagnostic criteria, with some groups focusing on unfamiliar face recognition (e.g., Djouab et al., 2020; Gerlach et al., 2022; Monzel et al., 2023), and others focusing more on subjective self-report over cognitive testing (see Burns et al., 2023; DeGutis et al., 2023). In addition, most individuals with DP demonstrate some degree of difficulty with face perception (e.g., Duchaine et al., 2007b; Le Grand et al., 2006; Towler et al., 2012). Some estimates based on traditional criteria suggest that approximately 2% of the general population has DP, although this estimate would be much higher with more liberal diagnostic criteria, and such individuals often suffer from social anxiety related to failures recognizing familiar people (Dalrymple et al., 2014a; Yardley et al., 2008).

Many investigations have been conducted on the specificity of face recognition impairments in DP (e.g., Behrmann et al., 2005; Duchaine & Nakayama, 2005; Gray et al., 2019). Such studies often utilize images of complex real-world objects as a comparison for faces and results are mixed regarding whether DPs show impairments or have normal performance (Geskin & Behrmann, 2017; Towler & Tree, 2018). Other studies have tested low-level vision using simple stimuli such as lines, and have participants make basic discriminations such as judgements of orientation, size, whether two lines are parallel to one another, or whether the gaps in two lines are in the same place (e.g., the BORB tests). One study estimated visual working memory capacity, visual search ability, and other attentional functions in DP (Gerlach & Starrfelt, 2021). These studies find that DPs have normal performance in these attentional, perceptual and visual

CONTACT John R. Towler j.r.towler@swansea.ac.uk School of Psychology, Faculty of Medicine, Health and Life Science, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

working memory (VWM) tasks with low-level simple visual stimuli. Similarly, a previous study tested lower-level visual processing in three DPs from the same family with the discrimination of radial frequency patterns and found normal performance in these individuals suggesting that face processing deficits emerged at higher levels of the visual processing stream (Lee, Duchaine, Wilson, & Nakayama, 2010).

While DPs show normal VWM other work has found impaired VWM for faces among DP compared to control participants. Shah et al. (2015a, 2015b) showed that face WM deficits in DP were not exacerbated by problems maintaining face information in VWM over time. Jackson et al. (2017) manipulated the number of faces to be encoded (between 1 and 4) to test load effects, and findings indicated that the problem does not lie with capacity limits in VWM per se but may be in part caused by face encoding difficulties, or difficulties in the comparison processes at retrieval. In terms of face-specificity, Shah and colleagues found no VWM deficits in DP for real-life non-face categories (chairs, butterflies, hands), again supporting the established finding of spared object recognition and processing in DP for real-world non-face items for which some familiarity exists. The question remains, however, as to what stage in the visual processing hierarchy is impaired in DP, or what level of visual complexity and familiarity is required to demonstrate recognition impairments in DP. To date there is an absence of studies investigating mid-level visual processing, or recognition of medium complexity and abstract visual images in DP for which there exists no prior specific familiarity (for studies of familar and complex objects in DP, see: Barton et al., 2019; Biotti et al., 2017; Burns et al., 2017). The current study aims to address this gap in understanding by employing two novel categories of medium complexity abstract visual shapes and patterns within a visual WM task and comparing these directly to face WM performance among DP individuals and a group of age-matched controls.

Two fundamental types of visual information that are crucial for effective real-world object recognition are the external boundaries (or contours) of individual objects, and their internal patterns or textures (e.g., Altmann, Bülthoff, & Kourtzi, 2003; Troje & Bülthoff, 1996; Wallace & Brodie, 1993). Previous research (Towler & Eimer, 2016; Towler et al., 2018) has indicated that DPs show a strong bias to encode the external features of faces (hair and external head outline) as compared to internal features (eyes, nose, mouth). Therefore, in addition to testing the face-specificity of VWM face impairments in DP, we also aimed to determine whether visual recognition deficits in DP could be accounted for by impairments for processing external shape outlines or for the internal local composition of abstract patterns. To this aim we used two classes of novel abstract object stimulus that differ in terms of either external contour (*"Blobs"*) or internal details (*Mondrions*) (see Figure 1). Blobs in the present study are two-dimensional shapes for which different exemplars vary in terms of their global external outline (also called BORTS – Blurred Outline Random Tetris Shapes; for previous use in VWM see Jackson et al., 2015). The internal composition of Blobs is uniformly black for all exemplars, offering no information about individual identity other than the outer contour. Mondrions are essentially the inverse of Blobs along these two

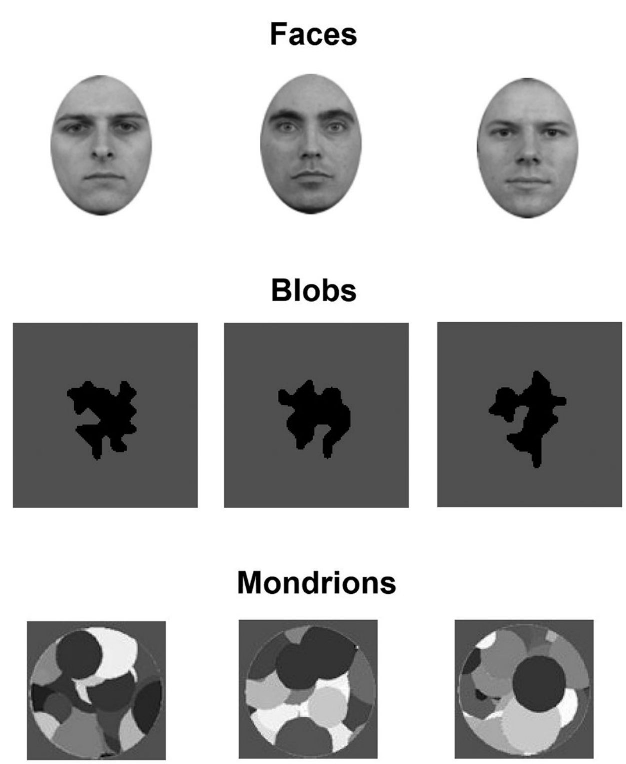


Figure 1. Examples of the three classes of stimuli used in the current experiments. Three examples each of Faces (top panel), Blobs (middle panel) and Mondrions (bottom panel) are shown. [To view this figure in colour, please see the online version of this journal.]

internal and external feature dimensions features. All Mondrions are uniformly circular in terms of their global external shape outline and offer no information about individual identity; instead, Mondrions differ in terms of the differently shaded and sized circles present within their internal composition (for previous use, see: Jackson & Raymond, 2006). Blobs, and Mondrions were considered good novel objects to use and compare to faces because they are simpler than real world objects, have no inherent familiarity, while also being more challenging to recognize than simple line orientations or colours often used in studies of VWM.

We used the same two VWM tasks that Jackson et al. (2017) employed to also examine the underlying cognitive processes involving VWM capacity (load manipulation), and VWM retention or updating (sequential presentation). Items were either simultaneously (Experiment 1) or sequentially (Experiment 2) encoded into VWM, and we measured VWM performance separately for faces, Blobs and Mondrions. The simultaneous encoding task (Experiment 1) manipulates VWM load by presenting 1–4 items at encoding followed after a short blank delay by a single probe item that matches one of the encoding items on 50% of trials. The sequential encoding task (Experiment 2) allowed us to probe memory for four items that have been maintained for different lengths of time (primacy and recency effects).

We calculated d′ memory sensitivity scores and response bias scores to rule out differences in response bias accounting for potential differences between DP and Control Groups. We also measured response times to provide an additional sensitive measurement of any potential deficits, and to investigate whether normal performance in our DP Group could be explained by an increase in response times at the group level.

In our analysis approach we firstly examined VWM across different category type (face/blobs/mondrions) separately within the DP group and the control group, to assess within-group face-specificity effects. Faces have been argued to be "special" and processed in ways unique from other non-face visual stimuli due to extensive expertize and individuation (e.g., Bruce & Young, 2012; Diamond & Carey, 1986; Gauthier & Tarr, 1997). In support of this account, prior studies directly comparing VWM for faces versus non-face common objects among healthy adults have shown a face-*advantage* (e.g., Curby & Gauthier, 2007; Curby et al., 2009). Therefore, we predicted that this face-advantage should be present for our age-matched control participants but disrupted in DP. Shah et al. (2015a, 2015b) did not directly statistically compare VWM for faces versus hands, chairs, or butterflies among DP individuals, although we can infer from their figures that DPs were likely worse for faces than chairs and butterflies but not for faces versus hands. Whether or not the VWM face-advantage is eliminated or merely diminished in DP in our study may provide some indication of whether residual face expertize is present in developmental prosopagnosia.

Second, we compared VWM performance between DPs and controls for each category of faces, Blobs, and Mondrions. If face VWM deficits in DP are face-specific, we expect to see impaired face VWM across the two experiments for DPs vs controls (replicating Jackson et al., 2017), but no DP impairment for Blobs and Mondrions. Alternatively, if visual impairments are present for abstract patterns and shapes such as Blobs and Mondrions in the DP group that are like those underpinning faces, we predict a similar pattern of VWM impairments among DPs as compared to controls for these novel categories as for faces. By using abstract shapes that differ in their external outline (Blobs) or internal features (Mondrions), we can further determine whether any VWM differences exist between DPs and controls according to these visual elements, and whether any face-advantage observed within or between groups is general or in specific relation to a certain object type. Bayesian analyses on mean performance for Faces, Blobs, and Mondrions were conducted in order to provide a quantitative estimate of confidence in the null hypothesis – that DPs are unimpaired with non-face stimuli. This will help advance our understanding of the role of lower-level visual information processing mechanisms that may underly face and object recognition deficits in DP.

Finally, we conducted single subject analyses of the DP Group for performance for faces and non-face objects, as well as the differential performance between faces and non-face items using Z-score calculations in comparison with the Control Group. These analyses were substantiated by single case t-test methods (Crawford & Howell, 1998) which allowed us quantify impairments for separate measures, and to identify classical neuropsychological dissociations between performance on two tests.

Methods

Participants

We recruited 13 individuals with Developmental Prosopagnosia (DP) from the Swansea City and County area (mean age = 43.87, SD = 13.27; 5 males) and 13 age–matched controls (mean age = 44.69, SD = 11.51; 4 males) from Swansea University, control participants were individually age-matched ± 4 years to each DP participant. Ethical approval was granted by the School of Psychology Ethics Sub-Committee at Swansea University. In terms of sample size, our previous study (Jackson et al., 2017) showed significantly poorer WM for faces in DPs as compared to Controls among a sample of 10 DPs versus multiple samples of 10 controls with an observed power of 0.81 (Experiment 1) and 0.86 (Experiment 2), using the same two experimental procedures employed here. These observed Power values are higher than the traditionally recommended 0.80 power. The current sample is larger than our previous work (13 DPs and 13 Controls) and therefore, this sample size was deemed sufficient to detect impairments of this magnitude. In addition, a power analysis suggested that with $\eta p2 = .2$ (large effect size) as seen in the previous study, a total sample size of 26 would be sufficient for a two-group comparison. None of the participants reported neurological injury, or psychiatric history, and all demonstrated normal to high performance on general verbal intelligence screening (Wechsler Test of Adult Reading – WTAR; Wechsler, 2001). All DP participants self-referred to our laboratory due to subjective day-to-day problems with face recognition. DPs subjective difficulties with face recognition were confirmed by scores on the standardized prosopagnosia index (PI-20) questionnaire (Shah et al., 2015a, 2015b). DP participants were given a battery of standardized tests to objectively assess their face recognition difficulties: a UK-appropriate Famous Face Recognition Test – FFT (Bate et al., 2019), the Cambridge Face Memory Test – CFMT (Duchaine & Nakayama, 2006) and the Cambridge Face Perception Test – CFPT (Duchaine et al., 2007a, 2007b). To test for basic visual impairments, DPs were given general basic object recognition tests (e.g., sub-tests from the Birmingham Object Recognition Battery, BORB; Riddoch & Humphreys, 1993). Wider social and emotional difficulties were also assessed in DP cases. DPs were screened for autistic traits using the Autism Quotient questionnaire (Baron-Cohen, Wheelwright, Hill, et al., 2001b) and the Reading the Mind in the Eyes Test (RMET; Baron-Cohen, Wheelwright, Skinner, et al., 2001a), and for alexithymic traits using the Toronto Alexithymia Scale (TAS-20; Bagby et al., 1994).

All DPs were impaired on standardized measures of famous face recognition (FFT) and face recognition memory (CFMT). Performance on the CFPT ranged from normal to impaired performance for different DP cases. Only one DP in our sample had clinically relevant levels of autistic and alexithymic traits (consistent with the distribution of these traits in the general population). Full details of the DP group are reported in Tables 1 and 2, along with z-scores or raw scores of performance on different tests. Z-scores and clinically relevant levels of autistic and alexithymic traits are calculated by comparing DP performance to control

Table 1. Details of individual performance on a battery of neuropsychological tests and questionnaires for each DP participant.

DP	Age	Gender	FFT	CFMT	CFPT	PI20	AQ-50	TAS-20	RMET
ER	19	F	−4.18	−2.52	−2.24	3.78	-	43	−1.44
HB	60	F	−7.11	−2.9	−1.09	3.32	18	40	−2.28
KL	31	F	−2.09	−2.01	−0.11	3.59	14	47	−0.06
RK	39	M	−6.48	−2.01	−0.52	3.96	14	50	−0.06
NH	57	F	−3.97	−2.27	−1.42	3.32	15	49	−1.17
RH	30	M	−4.6	−3.78	−2.57	3.59	14	50	−0.06
SR	56	F	−1.78	−2.64	−1.58	3.32	22	47	1.06
JD	54	F	−2.82	−2.27	−1.25	3.96	15	32	1.33
AT	52	F	−6.38	−2.01	−2.24	4.24	19	23	−2
GE	49	M	−5.12	−2.14	−2.73	4.15	20	50	0.78
JG	53	F	−4.18	−2.27	−1.91	2.86	28	55	0.78
RW	39	M	−4.81	−2.77	−1.34	3.87	12	46	−0.06
GM	49	M	−3.45	−3.53	−4.7	4.88	38*	67*	−0.89
Mean	**45.23**		**−4.38**	**−2.55**	**−1.82**	**3.76**	**17.36**	**44.33**	**−0.31**

*AQ-50 and TAS-20 scores that are in the clinically relevant range (>60 for TAS-20, >32 for AQ-50).

Table 2. Details of individual performance on a battery of neuropsychological tests for each DP participant.

DP	BORB length	BORB size	BORB orientation	BORB gap	BORB object decision	WTAR (/50)
ER	0.06	−0.96	0.46	−0.03	0.42	40
HB	0.69	0.71	1.23	0.23	0.21	49
KL	0.69	−0.13	0.46	−0.03	0.63	46
RK	0.69	−0.54	0.46	0.23	1.25	40
NH	0.69	−0.13	−0.31	−0.03	1.25	45
RH	0.69	−0.54	0.46	0.23	1.25	40
SR	0.69	0.29	0.85	0.73	0.42	50
JD	−0.56	−1.79	0.08	0.73	1.04	31
AT	−1.19	−0.13	0.85	−0.28	0.63	50
GE	−1.19	−0.96	1.23	0.98	1.04	45
JG	−2.44	−0.96	0.46	−0.28	−0.42	49
RW	−1.81	−0.96	0.08	−0.28	−0.21	49
GM	0.06	−0.13	0.08	−3.78	1.46	48
Mean	**−0.23**	**−0.48**	**0.49**	**−0.12**	**0.69**	**44.77**

performance from these studies (CFMT: Duchaine et al., 2006; CFPT: Duchaine et al., 2007a, 2007b; PI-20: Shah et al., 2015a, 2015b; AQ-50: Baron-Cohen, Wheelwright, Hill, et al., 2001b; AS-20: Bagby et al., 1994; RMET: Baron-Cohen, Wheelwright, Skinner, et al., 2001a). Table 2 contains Z-scores for each subtest of the BORB that was completed, and raw WTAR scores (/50) for each DP. DP cases were within the normal range for basic visual functions and basic-level object recognition ability as assessed across the BORB, and for verbal intelligence as assessed by the WTAR.

Standardized tests

The Cambridge Face Memory Test (CFMT) (Duchaine & Nakayama, 2006) is a widely used measure of face recognition ability. Participants are required to memorize and then identify unfamiliar male faces presented under varying conditions, including changes in viewpoint and lighting. The test includes three sections of increasing difficulty, where the faces are presented in similar conditions from different viewpoints, followed by different lighting conditions, and then under more challenging conditions involving superimposed visual noise. The CFMT provides a reliable assessment of individual differences in face memory ($\alpha = 0.89$), making it a standard tool in prosopagnosia research.

The Cambridge Face Perception Test (CFPT) (Duchaine et al., 2007a, 2007b) is a measure designed to assess face perception abilities. In this test, participants are presented with a target face and asked to arrange six faces in order of similarity to the target. This version of the task was performed with upright faces only. Performance is scored based on the accuracy of the arrangements. The CFPT is a robust tool for investigating individual differences in face perception and related cognitive processes.

The Famous Faces Test (FFT) is a widely used tool in developmental prosopagnosia research to assess face recognition ability (e.g., Duchaine & Nakayama, 2005; Garrido et al., 2009). Participants are shown a series of 60 images of well-known individuals and are asked to identify each one. The test measures the ability to recognize and name familiar faces, providing a valuable metric for assessing deficits in face processing. It has been applied extensively to diagnose and study prosopagnosia and related conditions.

The Prosopagnosia Index 20 (PI-20) is a 20-item self-report questionnaire that assesses face recognition difficulties, commonly associated with developmental or acquired prosopagnosia (Shah et al., 2015b). Participants rate their experiences with face recognition tasks on a Likert scale and the scale has been found to have good internal consistency ($\alpha = 0.87$). Higher scores suggest more severe face recognition impairments.

The Reading the Mind in the Eyes Test (RMET) measures social-cognitive ability by assessing participants' capacity to infer mental states from photographs of the eye region of faces (Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001b). This revised version consists of 36 items, each presenting an image of a pair of eyes alongside four mental state descriptors. Participants select the descriptor that best matches the emotion or mental state portrayed. Higher scores indicate greater theory of mind proficiency.

The Autism Spectrum Quotient (AQ-50) is a self-report measure designed to quantify traits associated with the autism spectrum in adults (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001a). It consists of 50 items spanning five domains: social skills, attention switching, attention to detail, communication, and imagination, and this scale has been found to have good internal consistency ($\alpha = 0.82$). Participants respond on a four-point scale, with higher scores indicating greater expression of autism-related traits.

The Toronto Alexithymia Scale (TAS-20) is a self-report measure designed to quantify trait alexithymia (Bagby et al., 1994). It consists of 20 items spanning three correlated domains (difficulty identifying feelings, difficulty describing feelings, and an externally oriented thinking style), and this scale has been found to have good internal consistency (α = 0.81). Participants respond on a five-point scale, with higher scores indicating higher levels of alexithymic traits.

The Birmingham Object Recognition Battery (BORB) includes tests of low-level visual processing to evaluate basic perceptual abilities (Riddoch & Humphreys, 1993). For this study, participants had to judge whether two items were the same or different on various visual features including: tests of length, size, orientation, and the presence of a gap. The object decision task was also performed where participants had to make decisions about real or imaginary objects.

Materials & stimuli

Face stimuli were taken from the Radboud faces database (Langner et al., 2010). Six males showing a neutral expression were selected, transformed to greyscale, and cropped into an oval to remove hair and other external outline features (Jackson et al., 2017). Mondrions were 10 computer-generated greyscale patterns of 20 small circles of varying sizes, cropped into a circular shape (see Jackson & Raymond, 2006). Blobs were 10 computer-generated black abstract shapes on a grey background, which varied in their external contour but had no internal features (Jackson et al., 2015). Image sizes were constructed so that the objects appeared to be similar sizes. Face images were 73×101 pixels, Blobs were 133×133 pixels, and Mondrions were 100×100 pixels. Participants had a standard viewing distance of 50 cm. Figure 1 shows examples of faces, Blobs, and Mondrions. There were 6 face exemplars and 10 Blob/Mondrian exemplars within each set; however, this small difference in exemplars is highly unlikely to influence the between-group findings. We made the decision to have a small number of possible exemplars to focus our tasks moreso on WM processes such as capacity and retrieval rather than on the precision with which items had to be maintained in WM. Relatedly, we wanted to increase the chances that the face processing task was manageable for DP individuals and so opted for a smaller number of exemplars.

Design and procedure

All participants (DP and control groups) completed all VWM tasks in a fully within-subjects design. There were two Experiments which consisted of 3 tasks in total. Experiment 1 was a simultaneous VWM procedure where all items were shown concurrently for memory encoding on each trial. Experiment 2 was a sequential VWM procedure where all items were shown one after the other for memory encoding (see section below for further details). In both Experiments participants completed face, Blob, and Mondrion versions of each task in a randomized order. The simultaneous and sequential procedures were the same as in Jackson et al. (2017), unless specified otherwise, and were counterbalanced across two sessions.

Experiment 1: Simultaneous encoding

In the simultaneous VWM tasks of Experiment 2 memory load was manipulated so that participants had to encode one, two, three, or four items on each trial, and the face, Mondrion, and Blob tasks were delivered separately. Each session began with twenty practice trials which were not retained for the reported statistical analysis. In the main session for each task there were 120 trials in total – 30 trials for each of the four load conditions. These 120 trials were segmented into 6 blocks of 20 trials. Each trial was initiated by pressing the space bar. Each trial began with an initial blank screen (2000 msec duration). One, two, three, or four items were presented for memory encoding in a 2×2 grid in the centre of the screen (see Figure 2) and the memory encoding screen duration was increased by 500 msec for each additional item that was present (load 1 = 500 msec duration; load 2 = 1000 msec duration; load 3 = 1500 msec duration; load 4 = 2000msec duration). When fewer than 4 items were shown, other grid locations were filled with either a scrambled face image (for the faces task) or a scribble image (for Mondrions and Blobs tasks – see Figure 2). Immediately after the memory encoding display a blank maintenance interval was present for 2000ms (this maintenance interval duration was chosen to closely match the average maintenance interval of the sequential procedure in Experiment 2). A single test probe item was then shown in the centre of the screen and participants had to respond whether it matched or not with one of the items shown on that trial during memory encoding. There were 50% match trials and 50% non-match trials for each memory load condition and these trial types were fully randomized. The

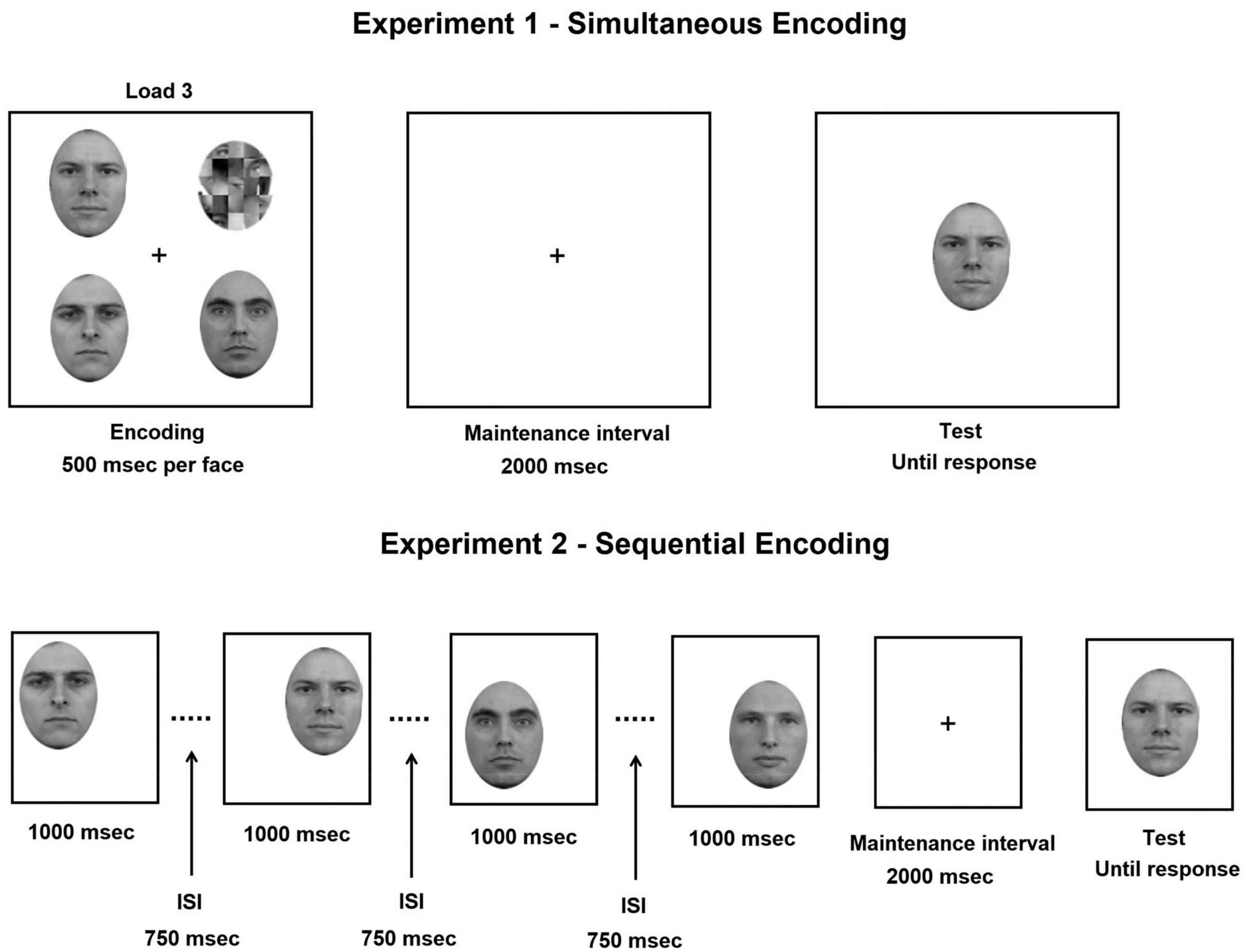


Figure 2. Trial structure for Experiment 1 (top panel) and Experiment 2 (bottom panel). For Experiment 1 a Load 3 trial is given as an illustration, and Encoding, Maintenance and Test screens are shown with details about timing, these displays are followed by a self-paced interval after response (not shown). For Experiment 2 each individual face encoding display is followed by a blank ISI display. The Test display is followed by a self-paced interval after response (not shown). [To view this figure in colour, please see the online version of this journal.]

probe item remained on screen until participants made a response.

Experiment 2: Sequential encoding

In the sequential VWM task of Experiment 2, four items were always shown on each trial (i.e., load 4). Twenty practice trials preceded each main session, and these practice trials were excluded from the statistical analysis. In the main session there were 120 trials in total (50% match trials, 50% non-match trials, randomized) split across 6 blocks of 20 trials for each of the faces, Mondrions, and Blobs tasks. Each trial was initiated by pressing the space bar. After an initial blank screen (750 msec duration), each of the 4 items was serially presented in the centre of the screen for 1000 msec, with each item jittered slightly off centre in an imagined 2×2 grid so that the exact foveal position for each was different (see Figure 2). The encoding time provided here was 1000 msec per item which was double the length of time that was previously given per face presentation (500 ms) in Jackson et al.'s (2017) sequential WM task in order to try and reduce encoding difficulty, as sequential task performance was previously found to be lower than simultaneous performance. There was a blank inter-stimulus interval of 750 msec between each item presentation. The serial position of the to-be-tested probe item on match trials was manipulated to have appeared in First, Second, Third or Fourth Position on an equal numbers of trials (40 trials each), randomized. After the final encoding item disappeared the screen returned to its blank state for a 1000 msec maintenance interval. A single test probe item was then shown in the exact centre of the screen (so that it never completely overlapped with foveal encoding locations) and participants stated whether it matched or not with one of the items just shown at encoding. The probe item on each trial was surrounded by a light grey rectangle in order to differentiate it from memory encoding items, and remained on screen until a response was made.

Data analysis

For our main analysis we converted hit and false alarm (FA) rates into d′ values ($_{Z}$Hits – $_{z}$FA) and used d′ signal detection scores as a measure of perceptual sensitivity for the primary VWM accuracy analysis. Extreme Hits and FA values of 1 and 0 were adjusted to 0.99 and 0.01 respectively to enable d′ computation. In d′ the maximum score of 4.66 reflects 100% accuracy while the minimum score of −4.66 reflects 0% accuracy; a d′ score of zero reflects 50% chance performance. We also computed response bias by calculating c values [($_{Z}$Hits + $_{z}$FA)/2], where more positive c values correspond to a more conservative response bias (more misses than false alarms) and more negative c values correspond to a more liberal response bias (more false alarms than misses). We calculated and analysed mean response times for each task and condition in order to examine whether there were subtle impairments in the DP group that would be demonstrated by increased response times. We computed Group (DP, control) by Stimulus Type (Faces, Mondrions, Blobs) by Memory Load (One, Two, Three, Four)/Target Position (First, Second, Third, Fourth) mixed ANOVAs and single group ANOVAs. Group by Stimulus Type interactions were of primary interest and where this was significant, we explored further by examining (1) within-group stimulus effects and (2) between-group effects for each stimulus type. Bonferroni-corrected pairwise comparisons were used to examine significant main effects, and further ANOVAs or t-tests were computed to examine significant interactions.

Single case t-test statistics were calculated using the methods described in Crawford and Howell (1998), the software package Singlims_ES.exe was used to calculate impairments on single tasks by comparing D′ values for each DP case to the Control Mean and SD. The software package Dissocs_ES.exe was used to calculate whether there was a significant difference between face test scores and object test scores, combined with a significant impairment on the faces task and this would constitute a classical impairment in cognitive neuropsychology. We flag significant differences (one and two tailed tests) in Table 3 alongside Z-scores for each DPs performance on that task.

Table 3. Z-scores for Mean Faces, Mondrions, and Blobs performance (averaged across Simultaneous and Sequential task versions) for each individual DP participant as compared to the Control Group Mean and SD. Object Mean Z-scores are calculated based on the mean of the Mondrions and Blobs d′ as compared to the mean and SD of the Control group.

DP	Faces	Mondrions	Blobs	Object Mean	Face Advantage
ER	−1.28	0.26	−0.66	−0.23	−1.50
HB	−1.49	−0.11	0.85	0.45	−1.23
KL	−1.11	0.38	−0.57	−0.10	−1.89*
RK	−0.78	1.05	0.41	0.91	−1.67
NH	−1.65*	0.52	−0.08	0.29	−2.41
RH	−3.24**	−1.46	−0.58	−1.28	−3.75**
SR	−1.46*	−1.31	−1.46	−1.71	−0.96
JD	−1.79**	−1.10	−0.70	−1.12	−2.88**
AT	−0.45	0.62	−0.60	0.03	−0.63
GE	−0.83	0.27	−0.93	−0.39	−1.58
JG	−1.16	0.69	2.67**	2.04**	−2.70**
RW	−1.96**	−0.45	−1.02	−0.90	−3.47**
GM	−1.47	0.93	0.88	1.12	−2.67**
DP Group Mean	−1.44	0.02	−0.14	−0.07	−1.81

Notes: Face Advantage Z-scores are calculated based on the difference score between Faces Mean d′ and Object Mean d′ as compared to the mean and SD of the Control group. Negative Face Advantage Z-scores indicate an increased tendency towards a face disadvantage. Crawfords modified single case t-tests were performed on individual DP participants scores. **indicates significant impairment compared to the control group (two-tailed), *indicates significant impairment compared to the control group (one-tailed).

Results

Experiment 1: Simultaneous encoding

Signal detection analysis – sensitivity (d′)

The mixed ANOVA with Group, Stimulus Type, and Memory Load as factors showed that there was a significant interaction between Group and Stimulus Type (F(2, 48) = 11.296, p<.001, ηp^2 = .320), and the main effect of Group was not significant (F(1, 24) = 3.985, p = .057, ηp^2 = .142). First, we explored this interaction by comparing faces versus non-face shapes within each group separately (using Stimulus Type by Load ANOVAs), to determine whether there was a face-advantage within the controls group but not within the DP group, as would be predicted from prior literature (see Figure 3). The control

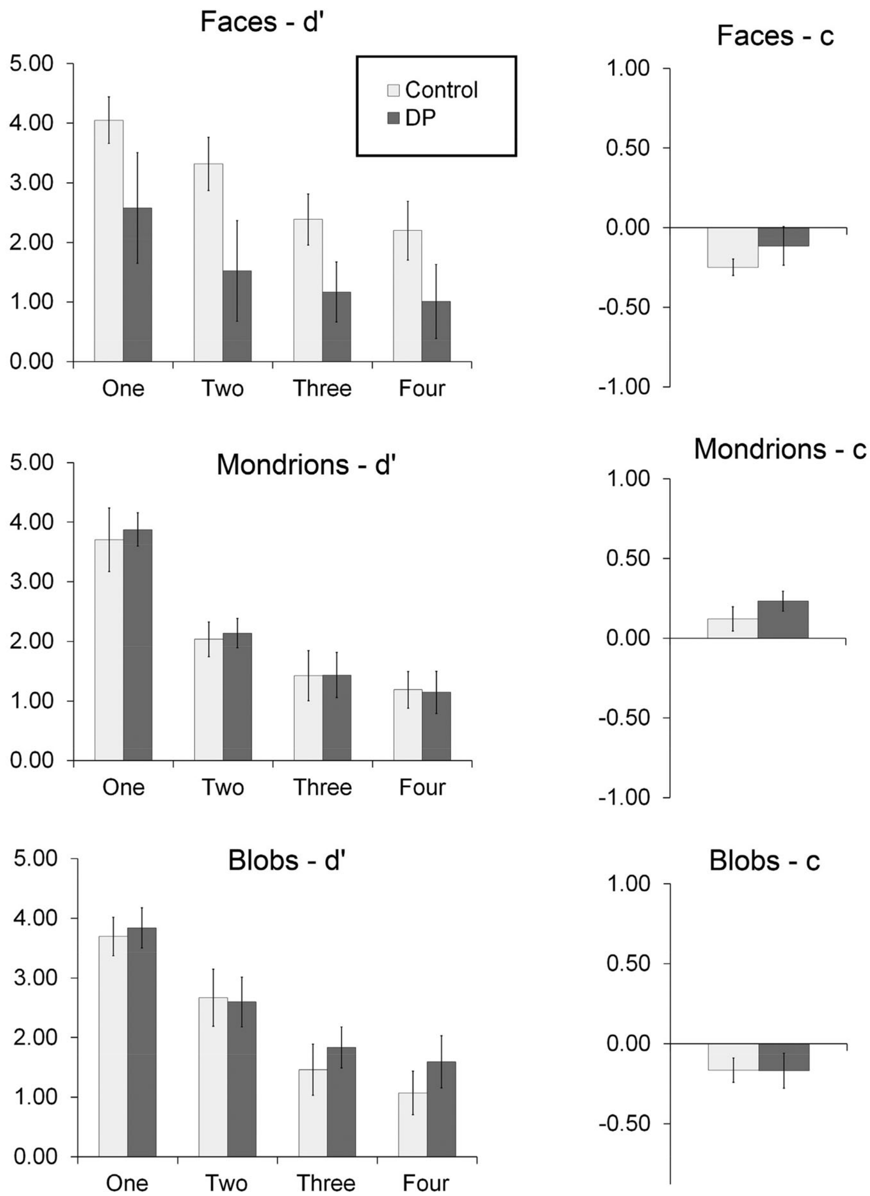
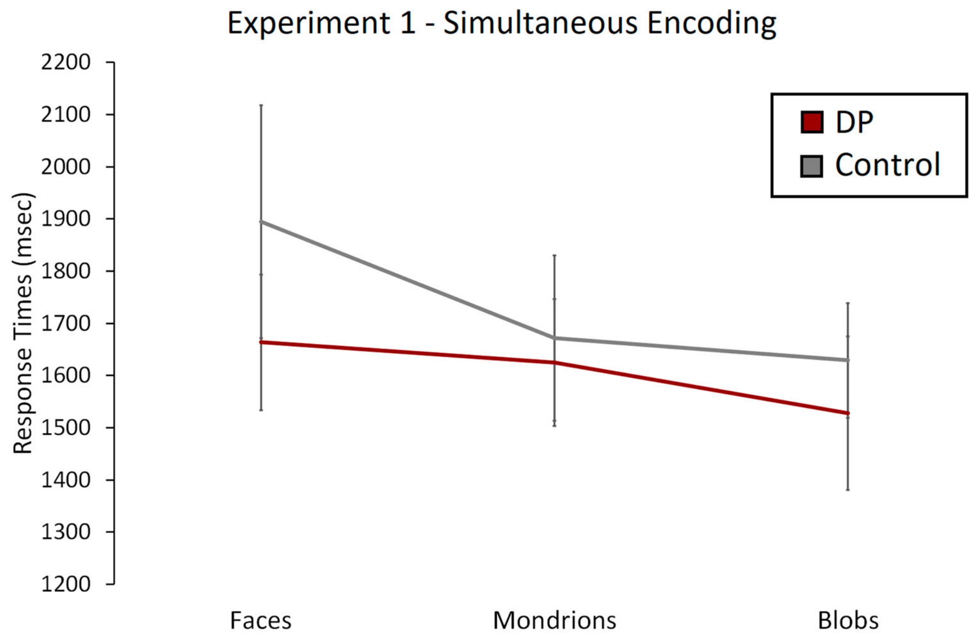


Figure 3. Mean d′ values for each stimulus category (Faces, Mondrions, and Blobs) for both the DP and Control Groups are shown separately for the Simultaneous Encoding Task (Experiment 1 – top panel) and the Sequential Encoding Task (Experiment 2 – bottom panel). The face-advantage for Control participants in Experiment 1, and its absence in Experiment 2 can be observed. The DP group tends to have a general face-disadvantage. Error bars represent 1 SEM. [To view this figure in colour, please see the online version of this journal.]

group showed a significant face-advantage as compared to Mondrions ($F(1, 12) = 18.741$, $p = .001$, $\eta p^2 = .610$) and a significant face-advantage as compared to Blobs ($F(1, 12) = 15.802$, $p = .002$, $\eta p^2 = .568$). There were no significant differences between Blobs and Mondrions ($F(1, 13) = 0.366$, $p = .557$, $\eta p^2 = .030$) among controls, suggesting that these non-face stimuli were matched for difficulty in the simultaneous encoding task. By contrast, DPs had significantly *poorer* VWM accuracy for Faces as compared to Blobs ($F(1, 12) = 5.33$, $p = .040$, $\eta p^2 = .308$). Although Faces were poorer overall than Mondrions this difference was not significant ($F(1, 12) = 2.560$, $p = .136$, $\eta p^2 = .176$). DPs showed a non-significant difference between Blobs and Mondrions ($F(1, 13) = 3.705$, $p = .078$, $\eta p^2 = .236$) although numerically they were better with Blobs than Mondrions.

The Group by Stimulus Type interaction was then further explored by running mixed ANOVAs (Group by Memory Load) for each Stimulus Type separately to assess stimulus-specific differences in VWM performance between DPs and controls (see Figure 4).



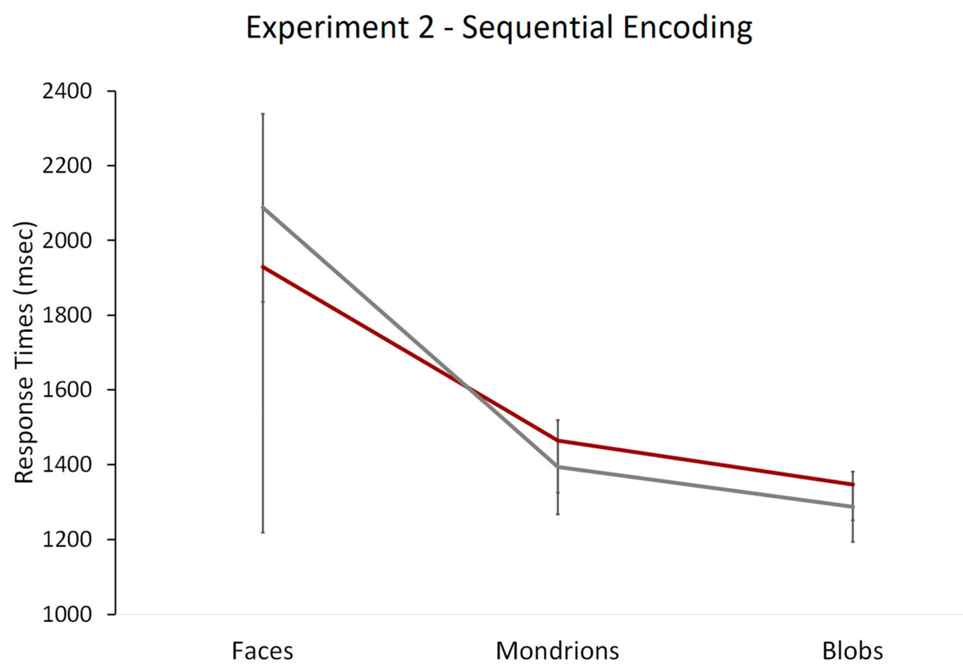


Figure 4. d′ sensitivity values for each Load condition (left panels) and mean c response bias values (right panels) for the Simultaneous Encoding VWM task (Experiment 1) are reported for DP and Control Groups. Faces (top panels), Mondrions (middle panels), and Blobs (lower panels) are shown separately. Error bars represent 1 SEM. [To view this figure in colour, please see the online version of this journal.]

DPs showed significantly impaired VWM for faces compared to the age-matched control group ($F(1, 24) = 12.303$, $p = .002$, $\eta p^2 = .339$) (Faces DP: M = 1.570, SE = 0.286; Faces Controls: M = 2.987, SE = 0.286), but not for either Mondrions ($F(1, 24) = 0.091$, $p = .765$, $\eta p^2 = .004$) or for Blobs ($F(1, 24) = 1.221$, $p = .280$, $\eta p^2 = .048$) (Mondrions DP: M = 2.147, SE = 0.140; Mondrions Controls: M = 2.087, SE = 0.140; Blobs DP: M = 2.466, SE = 0.155; Blobs Controls: M = 2.224, SE = 0.155). Clearly, compared to the control group, DPs had impaired VWM for faces but not for Mondrions or Blobs, indicating a face-specific deficit when items had to be encoded simultaneously.

In the main ANOVA there was a non-significant main effect of Stimulus Type ($F(2, 48) = 0.749$, $p = .478$, $\eta p^2 = .030$), importantly showing that there was no overall difference in difficulty between faces and the two novel object categories tested. There was a significant main effect of Memory Load ($F(3, 72) = 175.052$, $p<.001$, $\eta p^2 = .879$) confirming the predicted general decrease in memory sensitivity as Memory Load increases for all categories. Further main effects and interactions were not significant or were not relevant to our main hypotheses but are reported here for completeness. The Group by Memory Load interaction ($F(3, 72) = 1.048$, $p = .377$, $\eta p^2 = .042$) was not significant. A significant Stimulus Type by Memory Load interaction was present ($F(6, 144) = 3.383$, $p = .004$, $\eta p^2 = .124$) but follow-up analyses revealed no significant main effects of Stimulus Type at each Memory Load (all ps>.122). The 3-way interaction between Group, Stimulus Type, and Memory Load was similarly not significant ($F(6, 144) = 0.597$, $p = .732$, $\eta p^2 = .024$).

Signal detection analysis – response bias (c)

Here we ran a similar mixed ANOVA to the d′ analysis but for response bias (*c*) values. Overall, these analyses confirmed that decreased memory sensitivity in the DP group was due to genuinely increased overall error rates (for both hits and false alarms) as compared to the control group and not due to differences in response biases. Positive c values indicate a conservative response bias whereby more targets are missed than false alarms are made. Negative c values indicate a liberal response bias whereby participants report more false alarms than missed targets. Importantly, the main effect of Group and all interactions involving Group were non-significant (Fs<1.13) confirming that the differences observed for perceptual sensitivity in the main d′ analysis above were not due to specific response biases for DPs to either make more false alarms or miss more targets than control participants. Overall, participants had relatively liberal response biases for faces ($c = -.18$) and Blobs ($c = -.17$), indicating a tendency towards more false alarms than misses, and a more conservative response bias for Mondrions ($c = .18$), indicating a tendency towards more misses than false alarms (see Figure 4, right panels). These observations were confirmed by a significant main effect of Stimulus Type ($F(1, 24) = 11.273$, $p<.001$, $\eta p^2 = .32$), whereby responses for Mondrions were significantly more conservative than for faces ($p<.001$), and for Blobs ($p<.001$), while faces and Blobs did not differ from one another in terms of response bias ($p = .875$). The main effect of Memory Load was not significant ($F<1.71$).

Response times – RTs

Overall, the RT analyses showed that RT differences could not explain group differences in memory sensitivity between controls and DPs. The main ANOVA for mean RTs showed a non-significant main effect of Group ($F(1, 24) = 0.001$, $p = .976$, $\eta p^2<.001$) and non-significant interactions between Group and all other factor combinations (all ps>.102). The differences in VWM sensitivity found between groups are not due to slower response times accompanying higher VWM sensitivity, and that there is no overall difference in response times between DPs and controls. As expected based on previous research the main effect of Load was significant ($F(3, 72) = 61.269$, $p < .001$, $\eta p^2 = .719$) where responses to Load 1 were faster than Load 2 ($p < .001$) and Load 2 was faster than Load 3 ($p = .002$), but there was no significant difference in RTs between Loads 3 and 4 ($p = .664$). The Load by Stimulus Type interaction was not significant ($p = .256$). There was an overall significant main effect of Stimulus Type ($F(2, 48) = 3.550$, $p = .036$, $\eta p^2 = .129$), where RTs were numerically fastest for Blobs, middling for Mondrions, and slowest for Faces, but all Bonferroni pairwise comparisons were non-significant (all *p*s>.109).

Experiment 2: Sequential encoding

Signal detection analysis – d′

The main overall mixed ANOVA had the within subject factors of Stimulus Type (faces, Mondrions, Blobs) and Target Position (first, second, third, fourth),[1] and the between subject factor Group (DP, controls). DPs ($M = 1.329$, $SE = 0.151$) performed significantly worse than controls ($M = 1.799$, $SE = 0.151$) overall on the sequential VWM task ($F(1, 24) = 4.868$, $p = .037$, $\eta p^2 = .169$). However, and as predicted if DPs had a more selective impairment for faces and not for Blobs and Mondrions in the task, we found a significant interaction between Group and Stimulus Type, ($F(2, 48) = 5.397$, $p = .008$, $\eta p^2 = .184$). The 3-way interaction between Group, Stimulus Type, and Target Position ($F(6, 144) = 1.274$, $p = .273$, $\eta p^2 = .050$) was non-significant.

We first explored the Group by Stimulus Type interaction by comparing faces versus non-face shapes within each group separately (using Stimulus Type by Target Position ANOVAs) (see Figure 5). The control group showed no significant difference in VWM performance for Faces versus Mondrions (F(1, 12) = 0.297, p = .596, ηp^2 = .024). Surprisingly controls showed significantly superior VWM performance for Blobs compared to Faces (F(1, 12) = 7.151, p = .020, ηp^2 = .373). VWM performance for Blobs was also significantly better than for Mondrions (F(1, 12) = 10.001, p = .008, ηp^2 = .455) in the control group. Thus, we find no evidence of a face-advantage in VWM among control participants as found in Experiment 1. In contrast and as anticipated, the DP group had significantly poorer VWM performance for Faces as compared to Blobs (F(1, 12) = 21.900, p = .001, ηp^2 = .646) and significantly poorer VWM for Faces as compared to Mondrions (F(1, 12) = 13.533, p = .003, ηp^2 = .530). There was no significant difference between Blobs and Mondrions (F(1, 12) = 2.374, p = .149, ηp^2 = .165) in the DP group.

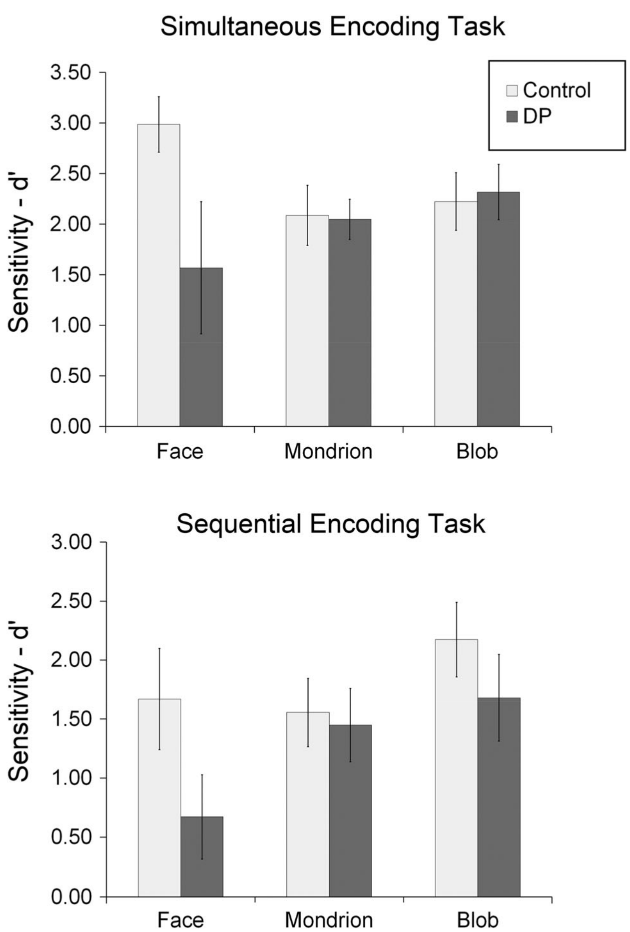


Figure 5. d′ sensitivity values (left panels) for each Load condition and mean c response bias values (right panels) for the Sequential Encoding VWM task (Experiment 2) are reported for DP and Control Groups. Faces (top panels), Mondrions (middle panels), and Blobs (lower panels) are shown separately. Error bars represent 1 SEM. [To view this figure in colour, please see the online version of this journal.]

The Group by Stimulus Type interaction was further examined by mixed ANOVAs with Group and Target Position as factors for each Stimulus Type separately, these analyses allowed us to qualify whether DPs impaired performance was due to the faces condition alone or was due to a more general impairment across the three categories. As expected, DPs had impaired VWM performance for Faces compared to the control group (Faces DP: M = 0.672, SE = 0.219; Faces Controls: M = 1.669, SE = 0.219) (F(1, 24) = 10.387, p = .004, ηp^2 = .302), but were crucially unimpaired for both Mondrions (F(1, 24) = 0.29, p = .867, ηp^2 = .001) and Blobs (F(1, 24) = 1.911, p = .180, ηp^2 = .074) compared to controls (Mondrions DP: M = 1.515, SE = 0.166; Mondrions Controls: M = 1.555, SE = 0.166; Blobs DP: M = 1.801, SE = 0.190; Blobs Controls: M = 2.173, SE = 0.190). These results confirm that DPs had a face-specific deficit in VWM compared to age-matched controls when items had to be encoded sequentially.

As expected, there was a significant main effect of Target Position (F(3, 72) = 72.743, p <.001, ηp^2 = .752), reflecting the fact that participants VWM accuracy increased as the target face was closer in time to presentation of the test face – a clear recency effect in VWM (see Figure 5). VWM sensitivity was similar at the first and second target positions (p = .110), improved significantly from the second to the third target positions (p <.001), and improved again from third to fourth target positions (p <.001) (First: M = 1.126, SE = 0.113; Second: M = 1.254, SE = 0.106; Third: M = 1.603, SE = 0.126; Fourth: M = 2.274, SE = 0.128). The interaction between Group and Target Position was not significant (F(3, 72) = 0.134, p = .939, ηp^2 = .006), showing that the recency effect was robust across both groups.

Although not relevant to our current hypotheses, we also observed a significant main effect of Stimulus Type (F(2, 48) = 15.287, p <.001, ηp^2 = .389), and further qualified by a significant Target Position by Stimulus Type interaction (F(6, 144) = 2.889, p = .011, ηp^2 = .107). Participants had superior VWM sensitivity for Mondrions as compared to Faces at the first and fourth target positions only (both *ps* <.018), and superior performance for Blobs as compared to Mondrions at the second target position only (*p* <.001; all other *ps* >.084).

To summarize, the results of Experiment 2 confirm and extend the findings of Experiment 1 in relation to DP impairments in face VWM. Here DPs showed impaired VWM sensitivity for Faces compared to Blobs and Mondrions, and showed poorer face-specific VWM performance compared to controls (no group differences for Mondrions or Blobs). DPs impairment with faces is therefore not specific to the conditions under which faces are encoded and is present for both simultaneous and sequential encoding conditions.

Signal detection analysis – response bias (c)

We ran a similar mixed ANOVA to the d' analysis but for response bias (*c*) values. Positive c values indicate a conservative response bias whereby more targets are missed than false alarms are made. Negative c values indicate a liberal response bias whereby participants report more false alarms than missed targets. Importantly, the main effect of Group and all interactions involving Group were also not significant (Fs<1.3) confirming that the differences observed for sensitivity in the main d' analysis above were not due to specific response biases for DPs to either make more false alarms or miss more targets than control participants. Similarly to the simultaneous encoding task in Experiment 1, decreased sensitivity in the DP group was due to genuinely increased overall error rates (for both hits and false alarms) as compared to the control group.

In general, Figure 5 (left panels) shows that in the sequential encoding task participants had relatively conservative response biases for faces (c = .19), no clear response bias for Mondrions (c = −.01) and a relatively liberal response bias for Blobs (c = −.19). These response bias differences were confirmed by a significant main effect of Stimulus Type, F(1, 24) = 8.144, *p*<.001, $\eta p^2 = .253$. The relatively conservative response bias for faces significantly differed from the relatively liberal response bias for Blobs (*p*<.001), and responses for Blobs were also significantly more liberal than for Mondrions (*p*<.01). Response biases for faces and Mondrions did not significantly differ from one another (*p* = .079). The main effect of Stimulus Position was highly significant (F(1, 24) = 72.42, *p* <.001, $\eta p^2 = .751$), reflecting the fact that response biases were generally conservative at the first position (c = .21) and became gradually more liberal from position one to two (c = .15, *p* <.017), position two to three (c = −.03, *p* <.001), and position three to four (c = −.37, *p* <.001). Because in the sequential encoding task false alarm rates remain constant across Target Positions, this finding is therefore simply the result of increased hit rates with Target Position (a recency effect), rather than true changes in response bias.

Response times – RTs

The RT analysis confirms that group level response speed cannot explain the observed differences in VWM sensitivity. The main mixed 2 (Group) x 3 (Stimulus Type) x 4 (Target Position) ANOVA for mean RTs from match trials showed a non-significant main effect of Group (*F*(1, 24) = 0.532, *p* = .473, $\eta p^2 = .022$) and non-significant interactions between Group and all other factor combinations (all ps >.518). As in Experiment 1 there are no speed-accuracy trade-offs that could account for any group differences in WM accuracy, and there is no difference in retrieval speed between DPs and controls.

As expected, there was a significant main effect of Target Position (*F*(3, 72) = 35.702, *p* <.001, $\eta p^2 = .598$), where retrieval responses to items encoded at Fourth position were faster than First, second and Third positions (all *ps* <.001) supporting the recency effect observed for VWM sensitivity. All other position comparisons were non-significant (all ps >.322). Although not relevant to our main hypotheses, there was also a significant main effect of Stimulus Type (F(2, 48) = 3.402, *p* = .042, $\eta p^2 = .124$), where RTs were numerically fastest for Blobs, middling for Mondrions, and slowest for faces, but all Bonferroni pairwise comparisons were non-significant (all *ps* > .109). The Target Position by Stimulus Type interaction was non-significant (*p* = .604). For non-match trials with no position information there were non-significant main effects of Group (F(1, 24) = 0.274, *p* = .606, $\eta p^2 = .011$) and Stimulus Type (F(2, 48) = 0.248, *p* = .781, $\eta p^2 = .010$), and their interaction was also not significant (F(2, 48) = 1.687, *p* = .196, $\eta p^2 = .066$).

Category analysis, Bayesian statistics, and individual differences

In order to examine individual differences and to directly focus on performance for the three object

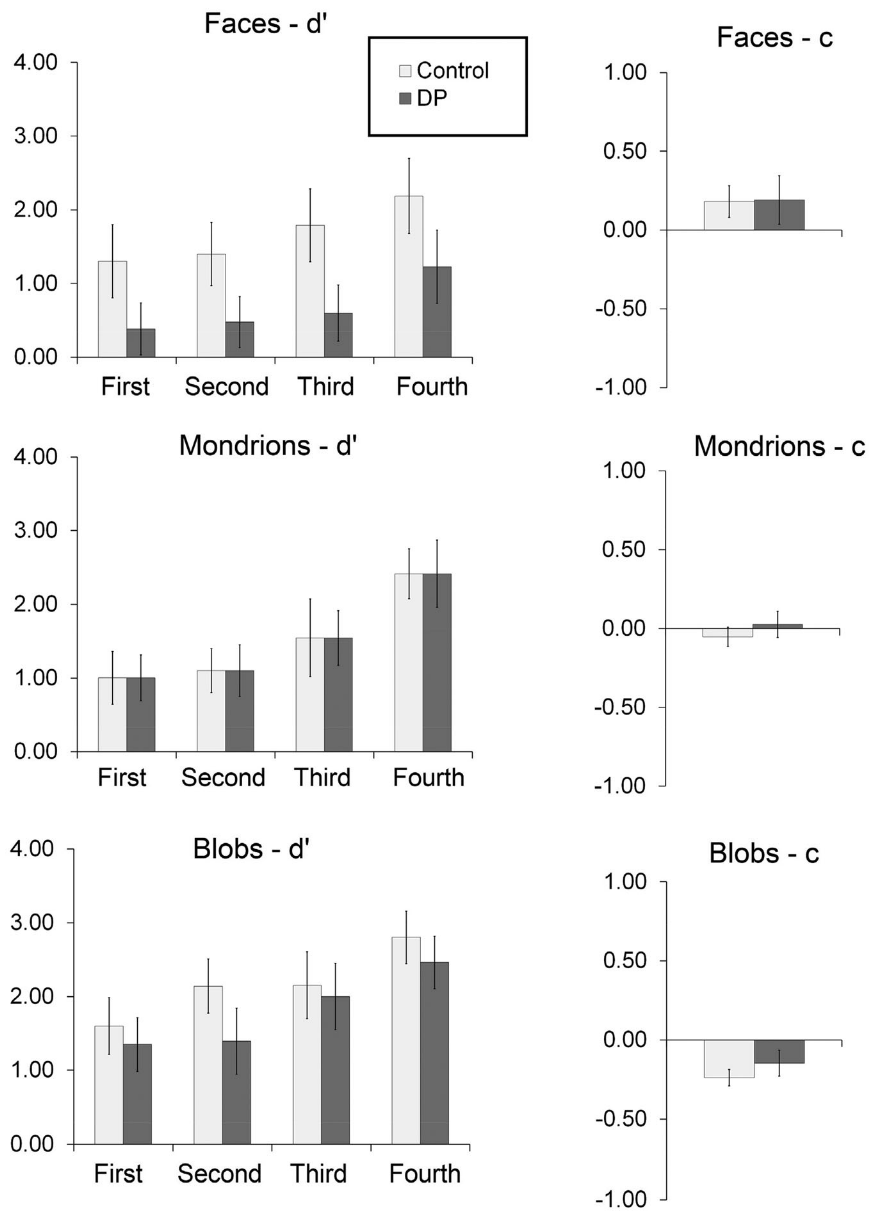


Figure 6. The distribution of individual DP participants and control participants mean d′ scores for faces, Mondrions, and Blobs with box, whisker, and violin plots detailing quartiles, range, and median scores. [To view this figure in colour, please see the online version of this journal.]

categories used we computed mean category d′ scores by calculating the average of simultaneous and sequential tasks for each category (faces, Mondrions, Blobs). Figure 6 shows the distribution of individual DP participants and control participants mean d′ scores for faces, Mondrions, and Blobs with box-plots and violin plots. Both groups have similar means, ranges and variability for Blobs and Mondrions. For faces DP participants tend to score within or below the lower range of the control group or below the worst performing control participant with no individual DP participants scoring above the control mean. Bayesian independent samples t-tests (with a standard Cauchy prior of .707) were conducted on mean category d′ scores which showed that there was very strong evidence for a significant difference between DP and control participants for the category of faces ($BF_{10} = 69.92$). By contrast, Bayesian independent samples t-tests were almost three times in favour of the null hypotheses that DP and control participants did not differ from each other as compared to the hypotheses that the groups differ in performance for Blobs ($BF_{10} = .38$) and for Mondrions ($BF_{10} = .36$).

We used Pearson correlations to specifically address the question whether Blob and Mondrion performance were related to one another, and whether performance for these non-face categories was related WM performance for Faces. We calculated total category D′ scores by averaging across the Simultaneous and Sequential versions of the VWM Tasks for Blobs, Mondrions, and Faces respectively. Correlations were performed across DP and Control groups in order to achieve a larger sample size (N = 26). Pearson's correlation analyses on mean scores showed that performance for the three categories was positively correlated across both groups. Mondrion and Blob performance were significantly correlated with one another ($r(24) = .41$, $p = .037$), and face performance was significantly correlated with Mondrions ($r(24) = .44$, $p < .025$), but only showed a non-significant trend with Blobs ($r(24) = .32$, $p = .11$). These correlations generally suggest that the VWM tasks tap into a shared general underlying VWM ability across DP and control participants. The absence of differences between DPs and Controls for the Blobs and Mondrions conditions suggests that this shared underlying ability is not generally impaired in DP, but that the face specific ability is impaired when we consider the clear difference in performance for Faces in our DP and Control groups in our previous analyses.

To provide additional evidence for the lack of relationship between DP and the Mondrion and Blob task performance, and to account for fact that there is some shared variance in performance between the face, Blob, and Mondrion tasks, Bayesian linear regressions with the covariates mean Faces d′, mean Mondrions d′, and mean Blobs d′ predicting group membership (DP, control) were performed. All models including faces as a covariate (Faces only, Faces + Mondrions, Faces + Blobs, Faces + Mondrions + Blobs) showed strong or very strong evidence for correctly distinguishing between DP and control groups compared to the standard null model (BF_{10} range = 30.15–133.36). Models excluding faces (Mondrions only, Blobs only, Mondrions + Blobs) were instead approximately three to five times in favour of the null hypotheses that these non-face tests are unable to correctly classify group membership as compared to the standard null model (BF_{10} range = .19–.38).

To examine whether VWM task performance was related to distinct aspects of face processing within the DP group, Mean Face d′, Mondrion d′ and Blob d′ scores were correlated with the standardized face processing tasks (CFPT, CFMT, FFT) in this group only. These correlations revealed that Blob and Mondrion performance was unrelated to performance on these face processing tasks (all Ps >.23), suggesting that they measure different underlying abilities. Mean Faces d′ correlated significantly only with the CFMT ($r = .77$, $p = .002$), providing additional evidence that face VWM tasks tap into an underlying face processing ability which is compromised in DP.

Table 3 clearly shows that all 13 DPs had performance lower than the control mean on the Face VWM task as compared to the Control group. Ten out of 13 DPs individual DPs had face processing difficulties that were 1 SD or more below the control mean and one of these DPs had face processing difficulties that were 2 SD or more below the control mean. In contrast, Blob and Mondrion tasks (and the combined Object mean) had a range of scores encompassing both above and below average performance. For example, three DP individuals had Object mean scores that were more than 1 SD below the control mean, and two had scores that were over 1 SD above the control mean – most scores were well within the centre of the control range. Strikingly, all DP participants had face advantage scores below the mean of the Control group, confirming their previously reported and consistent face disadvantages across task contexts. Ten out of 13 DPs had face advantage scores that were 1 SD or more below the control mean, and five of those individuals had scores that were 2 SD or more below the control mean. To provide statistical support for these hypotheses, these data were subject to Crawfords modified single case t-tests and dissociation analyses (Crawford & Howell, 1998) using means and SDs for the Control Group for each of the test scores (Blobs, Mondrions, Faces, Face Advantage), one and two-tailed outcomes are reported. These analyses revealed that three DPs (RH, JD, RW) were significantly impaired on their average faces scores (two-tailed), and these same three DPs also showed strong evidence for classical dissociations between face and object recognition ability on the dissociation analysis. Two further DPs (NH, SR) were significantly impaired on their faces scores using a one-tailed analysis. No single DP was significantly impaired on either the Blob or Mondrion tasks or the combined object score. Interestingly, one

DP (JG) performed significantly above the control group scores on the Blob and combined object scores suggesting that superior object recognition can occur in the context of face recognition difficulties. JG and GM were observed to have significant dissociations between face and object recognition scores, but did not meet the criteria for classical dissociations because they were not sufficiently impaired on their face scores. Similarly, an additional DP (KL) showed a significant dissociation between faces and object scores using a one-tailed t-test analysis but was not sufficiently impaired on the faces score to warrant a classical dissociation. In total, 8/13 DPs showed evidence for either classical dissociations or disproportionate difficulties with face VWM tasks as compared to non-face VWM tasks. These data will be discussed in more depth in the General Discussion.

General discussion

To investigate whether individuals with DP have impairments processing abstract shapes and patterns we had DP and Control participants perform visual working memory (VWM) tasks with faces and with two artificial novel object categories – Blobs and Mondrions. These categories were selected as they are not face-like (unlike some other novel objects used to test face-specificity deficits in DP, e.g., greebles), have no associated familiarity (unlike common objects), and to determine whether DPs have feature-selective recognition impairments for the external outlines (Blobs) or the internal details of visual objects (Mondrions). We employed separate simultaneous (Experiment 1) and sequential (Experiment 2) memory encoding tasks to measure the effects of increasing memory load, and retention interval length, on VWM performance in DP and control participants.

The main results from both tasks were clear cut. As predicted, compared to age-matched control participants without face recognition impairments, individuals with developmental prosopagnosia showed face VWM deficits on both the simultaneous and sequential encoding tasks. Importantly, VWM performance for Blobs and Mondrions was indistinguishable for DPs compared to matched control participants. Prior studies comparing face recognition to novel (unlearned) object recognition (e.g., greebles) are mixed in whether face-specific deficits are present in DP or not (Duchaine et al., 2004; Fry et al., 2020). Our findings clearly add to the literature suggesting that individuals with DP are unimpaired at recognizing abstract visual patterns and shapes.

Our results also show that individuals with DP do not have general impairments discriminating the external global contour, or the internal fine details of these complex novel visual shapes and patterns. Previous findings showing that DPs have a strong bias towards encoding the external features of faces accompanied by a deficit for encoding the internal features (Towler et al., 2018) do not generalize to abstract patterns and shapes and may be face-specific. A reliance on the external facial features such as the hair and external head shape is a maladaptive compensatory recognition strategy that could lead to atypical and inefficient face learning in day-to-day contexts for individuals with DP (e.g., Adams et al., 2020; Bobak et al., 2017) and the present results show that this bias does not extend to these kinds of non-face objects. The current findings constrain theories of the cognitive locus of visual recognition difficulties in DP. Some authors have suggested that face recognition impairments may be caused at a lower-level stage of visual processing that feeds into both higher-level category-selective face recognition and object recognition mechanisms (e.g., Gerlach et al., 2022). Our current findings clearly show that some lower-level stages of recognizing complex external outlines, or the internal patterns of visual objects are not generally impaired in DP. Where observed in other studies, object recognition impairments in DP are likely present at higher-level stages of visual processing or memory than tested for here.

A key additional hypothesis that we investigated was whether control participants would show evidence for a VWM face-advantage as compared to Blobs and Mondrions (e.g., Curby & Gauthier, 2007) and whether this would also be the same for DPs. For the control group, a face-advantage was clear from the simultaneous encoding task of Experiment 1 but was absent from the sequential encoding task (Experiment 2, see Figure 3). DPs showed an overall *disadvantage* for faces relative to the other visual categories of Blobs and Mondrions in both experiments (see Figure 3 upper panel). The lack of face advantage in Experiment 2 for controls indicates that there are some task-specific effects at play. The sequential encoding task introduces the potential for retroactive interference which is suggested to degrade WM representations and thus substantially disrupt the WM system (Allen et al., 2006; Kool et al., 2014), therefore this could potentially account for the lack of a group-level face-advantage in this task here among controls.

In addition to the group-level analyses, we also conducted individual differences correlation analyses based on the three categories of stimulus tested in this study averaged across task version. These correlation analyses showed that VWM performance for Blobs and Mondrions was related, suggesting that they measure an underlying general VWM ability. Additionally, Mean Faces performance significantly correlated with Mean Mondrion performance and showed a trend to be correlated with Mean Blob performance. Taken together, these results suggest that the different stimulus categories all tap into an underlying general VWM ability across the DP and Control Groups. Additionally, we found a significant correlation between CFMT accuracy and mean VWM Faces performance across both VWM tasks, but the Blob and Mondrion tasks were unrelated to any face processing measures. When considered alongside the clear impairments with the standardized face processing tasks and the Faces VWM tasks in individuals with DP we find evidence for both a general VWM ability which is generally unimpaired in the DP group, and a face specific ability which is impaired across tasks.

To bolster our claims that DPs are unimpaired with processing abstract shapes and patterns we performed additional Bayesian analyses at the level of stimulus categories. These Bayesian analyses included both Bayesian t-tests and Bayesian Linear Regression and both analysis types confirmed the main results of the standard inferential statistics. The Bayesian t-tests showed that DPs performance for Blobs and Mondrions favours the null hypothesis of there being no difference between DPs and Controls by approximately three to one. The Bayesian linear regression used Faces, Blobs and Mondrion mean performance as predictors and showed that all models which included Faces as a predictor differentiated between DP and Control Groups with a very strong degree of confidence. On the other hand, models that did not include Faces supported the null hypothesis by between approximately three and five to one. Future studies with larger sample sizes may be able to provide even stronger evidence for this dissociation between Face and non-face VWM performance in DP.

We took a closer look at individual DP participants by calculating Z-scores for individual DPs based on Faces, Blobs and Mondrion mean performance and compared to norms from the Control Group (see Table 2). We also calculated a Mean Object Z-score by averaging d′ scores for Mondrions and Blobs and calculating Z-scores on this basis, and then we created an individual Face Advantage Z-score by subtracting the Mean Object d′ from the Faces d′, and calculating Z-scores for individual DPs with reference to the norms of the Control Group. These analyses showed that DPs were −1.44 Z-scores below the mean on average on the Faces VWM tasks, with performance varying from individual to individual. Z-scores for Blobs and Mondrions were very close to the Control Group mean. Interestingly, calculation of Face Advantage scores provided some further insights into different profiles for individual DPs. While these analyses showed that *all DP participants* had face disadvantages overall (negative Z-scores) as compared to the Control Group, there were some interesting differences between individual cases. For example, while only DP participant RH had Z-score −2 or more below the mean for the Faces score, Crawfords single case t-tests revealed that three DPs had significantly impaired faces scores compared to the control group, with an additional two DPs showing face task impairments if a one-tailed threshold was applied. Importantly, no single DP was impaired on the Blob, Mondrion, or combined object scores for either one or two tailed tests. Interestingly, one DP had significantly superior Blob scores compared to the control group, suggesting that object VWM can be superior in the context of face recognition difficulties. In terms of dissociations between face and object scores, five individual DPs (HB, NH, RH, JG, and GM) had Face disadvantages that were significantly lower than the control group using the same criteria. Of these five, the three DPs with significantly impaired faces scores showed strong evidence for classical dissociations between face and object scores. These five participants showed clear Face disadvantages because this analysis accounts for their relative above average performance on the Blob and Mondrion tasks. JG is a particularly pronounced example here, because she had combined Blob and Mondrion VWM performance over 2 SD above the Control mean, while at the same time having Faces VWM performance −1.16 Z-scores below the mean. When we take non-face scores into account, we can observe a very clear deficit with Faces as compared to other visual categories in this case. These kinds of individual level statistical analyses can identify DP participants that may perform unexpectedly well on some face processing tasks because they are particularly good at specific task formats or have above average general cognitive ability. Importantly, eight out of 13 DPs showed some significant evidence for face processing related difficulties (either the Faces score, or Face Advantage score), and no individual DP was significantly impaired on the Blob or Mondrion tasks. At the same time, other individual DPs such as SR appear to have more general VWM difficulties, with low Z-scores for both Faces (−1.46) and Objects (−1.71), resulting in a relatively small deficit for the Face Advantage score (Z-score = −0.53). It may be of importance to note that case SR was a more borderline case on our standardized testing, and did not perform as poorly on the Famous Faces Test as other DPs. SRs face processing deficits may be more pronounced on other standardized tasks because they are complicated by more general VWM deficits. This is an important issue because our face and non-face VVM tasks correlate with one another and so are both influenced to some extent by a general underlying VWM ability. In other words, some individuals can perform relatively poorly on face-based tasks because they have poor underlying VWM ability but have relatively normal face processing ability. It remains to be seen the extent to which self-reported face recognition complaints can in some cases be largely accounted for by more general cognitive difficulties rather than by more face-specific impairments.

The current findings also address the important issue of the cognitive locus of apparent VWM impairments in DP in terms of whether DPs have specific difficulties with memory capacity or memory maintenance. We found that DPs showed clear impairments for faces in both VWM tasks. However, and importantly, the pattern of performance for different memory load conditions in Experiment 1 indicated that DPs have comparable VWM impairments for faces for each of the load conditions (from one to four items). Crucially, VWM performance was impaired for DPs when only a single face had to be encoded, and the degree of VWM impairment did not increase with increasing memory load as would be predicted by a reduced VWM capacity account (replicating Jackson et al., 2017). This consistent pattern of VWM impairments across all load conditions indicates that VWM impairments for faces in DP do not originate from a reduced capacity to simultaneously maintain multiple face representations in visual working memory. Instead, it appears that DPs have a clear and persistent deficit with face perception and the precision of stored VWM representations of each individual face (e.g. Ma et al., 2014, even in easier tasks with a reduced number of possible face exemplars (here, six possible faces).

A similar pattern of results was obtained in Experiment 2. Here DP participants had impaired VWM performance for faces, but no impairment was present for Blobs or Mondrions. Importantly, VWM impairments for faces compared to the control group were present to a similar degree for all retention interval lengths. This pattern of results indicates that individuals with DP do not have general VWM maintenance difficulties and that the observed VWM impairments for faces in DP do not originate from or become exacerbated by VWM maintenance stages. We can therefore rule out the hypothesis that DP participants have a more rapid decay of VWM face representations over time than control participants without face processing impairments (for similar findings, see: Jackson et al., 2017; Shah et al., 2015a, 2015b). Instead, the results from our two experiments can be parsimoniously explained by persistent face processing impairments in DP participants which compromise the precision of stored individual face representations (e.g., Biotti et al., 2019; Fisher et al., 2016, 2017).

A key challenge to the claim that individuals with DP have normal general object recognition ability is that they may use unusually time-consuming compensatory strategies to achieve normal accuracy in object recognition tasks. For this reason, we measured response times for each of the visual working memory tasks (see Figure 7). The results of this analysis clearly revealed that response times in the DP group did not differ from those of age-matched control participants for faces, Blobs or Mondrions for either the simultaneous or sequential encoding tasks. These results confirm that normal accuracy was not accompanied by slower response

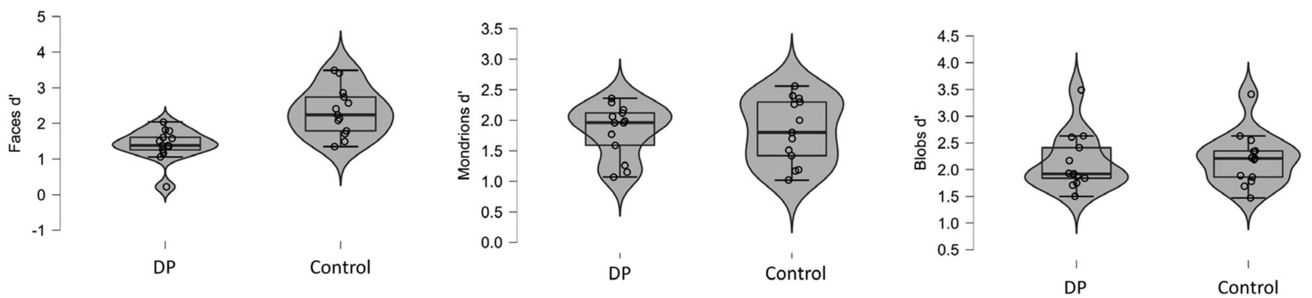


Figure 7. Mean response times for Faces, Mondrions, and Blobs for the Control and DP Groups. Experiment 1 (upper panel), and Experiment 2 (lower panel) are shown separately. No significant differences are observed between Groups. Error bars represent 1 SEM. [To view this figure in colour, please see the online version of this journal.]

times at the group level in the DP group and show that DPs were both as fast and accurate as Control participants with Blobs and Mondrions. Additionally, differences and similarities between DPs and Control participants cannot be explained by differences in response bias that were measured by our signal detection theory criterion analyses. Instead, observed differences in VWM performance for Faces were explained by decreased d' sensitivity scores, and normal performance for Blobs and Mondrions in the DP group was accompanied by response biases that did not significantly differ from the Control Groups response biases.

As is common in studies of prosopagnosia that use a combination of self-report and traditionally conservative cut-off criteria on cognitive tests, our DP participants were impaired on the CFMT and have clearly far below average performance as a group on the CFPT (see Table 1), and we suggest that these perceptual difficulties during unfamiliar face processing experienced by the DPs in the present study are linked to the specifically impaired performance on the face VWM tasks. Consistent with this claim we find that the CFMT and Faces VWM scores significantly correlate in our DP Group, even though these two tests differ in terms of format, and perceptual and cognitive demands. Interestingly, DPs perceptual impairments do not appear to impact on all aspects of face processing. We find that performance on the Reading the Mind from the Eyes Test (RMET) where participants must decipher complex emotional states from the eye region was unimpaired in the DP group. These findings are consistent with several studies that have found no difficulties with emotional expression processing in DP (Duchaine et al., 2003; Palermo et al., 2011; Fisher et al., 2017; Towler et al., 2017; although for evidence of expression recognition impairments in DP, see: Biotti & Cook, 2016; Bennetts et al., 2024; note that holistic interference during facial expression processing was found to be impaired in Palermo et al., 2011). These findings are largely consistent with models of face processing which posit separate visual pathways for the encoding of identity and the encoding of dynamic aspects of face perception including facial expression recognition (e.g. Calder & Young, 2005; Haxby et al., 2000). Relatedly, in our study we document an overall absence of high levels of alexithymia and autistic traits in the DP group that are often associated with impaired expression recognition ability (with only one DP participant having potentially clinically relevant scores on the AQ).

In conclusion, the present study provides clear evidence that individuals with DP have face-specific recognition impairments in VWM but not for novel shapes and patterns. These face recognition impairments are highly consistent and selective and are present across two variations of VWM task (simultaneous and sequential encoding). Individuals with DP do not appear to have general VWM impairments for processing abstract visual shapes and patterns. Based on our individual differences analyses, we suggest that using unfamiliar or abstract stimulus classes alongside face and object recognition tasks can help to identify cases of DP that do not have VWM difficulties and to help estimate face-specific impairments. Future work could explore recognition ability for other features and dimensions of object structure in developmental prosopagnosia that may not have been captured by the current study (e.g., Bao et al., 2020). Our findings are consistent with high-level face perception impairments in developmental prosopagnosia and suggest that where object recognition impairments are present in DP, they may primarily manifest for complex visual object categories for which a large amount of visual experience or familiarity has been acquired (e.g., Gauthier et al., 2014).

Note

1. Note that there is only one False Alarm (FA) value per participant as this cannot relate to target position on target absent trials. So each d′ calculation used the Hits for each target position with the singular FA value per participant.

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