Delayed processing of global shape information is associated with weaker top-down effects in developmental prosopagnosia

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Abstract

In previous studies we have shown that a group of individuals with developmental prosopagnosia (DP): (i) were impaired at recognizing objects when presented as silhouettes or fragmented forms; stimuli which place particular demands on global shape processing, (ii) that these impairments correlated with their face recognition deficit, (iii) that they showed a reduced global precedence effect in Navon’s paradigm, and (iv) that the magnitude of their global precedence effect correlated with their face and object recognition performance. This pattern of deficits points towards a delay in the processing of global shape information; a delay that may weaken top-down influences on recognition performance. Here we show that the DPs show reduced real object superiority effects (faster responses to real objects than nonobjects) compared with controls. Given that real object superiority effects reflect top-down processing, these findings support the notion of impaired global shape based top-down processing in DP.

Keywords: face recognition, global precedence, global shape, object recognition, top-down processing.
Developmental prosopagnosia (DP) is a disorder characterized by profound and lifelong difficulties with face recognition in the absence of any sensory or intellectual deficits or known brain injury (Duchaine, 2011). The first report of DP was made by McConachie in 1976, and several hundred cases have been reported since (Geskin & Behrmann, 2018). Despite this, the disorder is not well understood. In particular it is debated whether the deficit in DP is confined to faces or whether processing of other classes of stimuli are also affected (Geskin & Behrmann, 2018; see also a range of commentaries in the same issue).

We have recently proposed that many individuals with DP are impaired in recognizing objects in addition to faces, but that this only becomes evident when the demand on perceptual differentiation is high and stimuli are impoverished (Gerlach, Klargaard, & Starrfelt, 2016). Hence, the DPs we have studied were not significantly impaired in an object decision task when stimuli were full line drawings, but they were impaired when the stimuli were presented as silhouettes and fragmented forms. This deficit in processing of impoverished stimuli correlated with the DPs’ face recognition performance on the Cambridge Face Memory Test (CFMT) (Duchaine & Nakayama, 2006); $r = .87$ (95% CI [.55, 1]) and $r = .78$ (95% CI [.26, .98]) for silhouettes and fragmented forms respectively. Given that processing of impoverished stimuli is likely to place particular demands on global shape information (Gerlach, 2009; Gerlach & Toft, 2011), and given that global shape information has also been suggested to play a pivotal role in face recognition (Goffaux, Hault, Michel, Vuong, & Rossion, 2005; Goffaux et al., 2011), we suggested that these deficits pointed towards an underlying global shape processing deficit in DP (Gerlach et al., 2016).

A final finding which corroborates the picture of a deficit in global shape processing in this group of DPs comes from Navon’s paradigm (Navon, 1977, 2003), which uses compound letters [large letters (global level) composed of smaller letters (local level) where the global and the local letters may be the same (consistent) or different (inconsistent)]. In this paradigm three effects are typically found in normal subjects: (i) a *global precedence effect* with faster judgements of the identity of the global shape (large
letter) compared with the local elements (small letters), (ii) an interference effect with slower responses to inconsistent than consistent stimuli, and (iii) an inter-level interference effect with greater interference effects on local compared with global identity trials. These effects were also found in our control group. The DPs, however, differed from the controls in two respects: (i) They exhibited a significantly reduced global precedence effect, and (ii) their local-to-global and global-to-local interference effects were of similar magnitudes (Gerlach, Klargaard, Petersen, & Starrfelt, 2017). The DPs could perceive the global shape (the large letters), however. In fact, they did not make more errors than controls, and like controls they also exhibited a global-to-local interference effect, just of a somewhat smaller magnitude. This demonstrates that they are sensitive to global shape information. Consequently, we argued that the deficit in the DPs reflected a delay in processing of global relative to local shape information. We were further able to show that individual differences in global precedence effects for the DPs correlated significantly with both their face recognition performance on the CFMT ($r = .63$, one-tailed lower bound 95% CI = -.06), and their discrimination sensitivity with real objects and nonobjects in the object decision tasks with silhouettes ($r = .72$, one-tailed lower bound 95% CI = .13) and fragmented forms ($r = .72$, one-tailed lower bound 95% CI = .28). Other studies have also found an association between performance in Navon’s paradigm and face recognition impairments in DP (Avidan, Tanzer, & Behrmann, 2011; Bentin, Degutis, D’Esposito, & Robertson, 2007; Duchaine, Yovel, & Nakayama, 2007), although contradicting evidence has been reported (Duchaine, Germain, & Nakayama, 2007; Schmalzl, Palermo, & Coltheart, 2008).

We proposed (Gerlach et al., 2017) that the pattern of deficits exhibited by the DPs can be accounted for within the PACE (Pre-semantic Account of Category-effects) model of visual object processing (Gerlach, 2009, 2017b). In this model, visual object processing includes two operations: shape configuration and selection. Shape configuration refers to the binding of visual elements into elaborate shape descriptions in which relationships between the parts are specified, whereas selection refers to the matching of visual impressions to representations stored in visual long-term memory (VLTM). The matching process is thought
of as a race among VLTM representations that compete for selection, and the VLTM representation that matches the configured representation the best according to a given criterion will win the competition; hence be selected. The race is initiated by matching the outline (gestalt) of the stimulus to VLTM representations. This first-pass access to VLTM yields initial hypotheses regarding the likely identity of the stimulus. These hypotheses are then used in a top-down manner to augment the buildup of a more detailed description of the visual impression of the stimulus (i.e. shape configuration), which again serves as input for a more specific match with VLTM representations. The greater the demand placed on perceptual differentiation, the more loops comprising VLTM access and shape configuration are required to reach a successful match between the visual input and VLTM representations (i.e. recognition). It is clear that within this model, fast derivation of global shape information is important in the recognition process because it: (i) facilitates the matching process by narrowing down the scope of likely VLTM candidates, and (ii) provides the initial frame in which local details can later be embedded, i.e. shape configuration. Hence, when interpreted within the PACE framework it makes good sense that delayed derivation of global shape may not only slow down performance, but also lead to recognition problems. In particular, we have previously made the case that derivation of global shape is especially important for recognizing objects characterized by a high degree of visual similarity when the demand for perceptual differentiation is high (Gerlach, 2009; Gerlach & Toft, 2011). Face recognition seems to be characterized by both aspects: Faces are highly visually similar and they are typically recognized at a subordinate level which requires more perceptual differentiation than basic level recognition.

The PACE model bears clear resemblance to the face recognition account developed by Rossion and colleagues (Rossion, 2014; Rossion, Dricot, Goebel, & Busigny, 2011). Their account also entails a coarse-to-fine temporal dynamic in face recognition and the notion of recurrent processing when fine-grained discriminations are required. What differs is that the PACE model is not specific to faces, and that it seeks to explain category-effects in terms of underlying differences between object classes in visual similarity
(Gerlach, 2017a), visual complexity (Gerlach & Marques, 2014), and how these differences interact with task demands (Gerlach, 2017b).

In our account of DP outline above, delayed processing of global shape is central in explaining the pattern of deficits observed in both the DPs’ face and object recognition deficits. More specifically we argue that delayed derivation of global relative to local shape information gives rise to altered top-down effects in visual object processing: Only if global shape is derived prior to local shape information will the first-pass access to VLTM representations based on outline shape be effective in augmenting the recognition process.

A well-known example of an augmenting role of top-down processing is the so-called object superiority effect where object features are processed more efficiently when part of a configuration than when presented in isolation (Davidoff & Donnelly, 1990). A similar effect, the “real object superiority effect”, has been described by Starrfelt, Habekost, and Gerlach (2010), and refers to faster processing of real (familiar) objects compared with (unfamiliar) nonobjects. This effect, henceforth referred to as ROSE (Real Object Superiority Effect) to distinguish it from the (part/whole) object superiority effect, may be reduced or eliminated following brain injury (Starrfelt et al., 2010). In comparison, normal subjects process real objects considerably faster than nonobjects because only familiar objects, as opposed to nonobjects, are associated with stored object representations which can successfully aid the recognition process. In fact, if the nonobjects consist of parts of real objects, as chimeric nonobjects do, they may lead the object recognition process astray, exacerbating the ROSE.

The relevance of the ROSE in the present context is straightforward: If the delay in global shape processing that we have observed in DP leads to altered top-down processing, we should expect the DPs to show a reduced or abolished ROSE in comparison with control subjects when discriminating real objects and nonobjects because DPs cannot benefit from the global shape based first-pass accesses to VLTM representations for real objects. Thus, a reduced difference between objects and non-objects should be observed in all conditions where global shape information is important, and the more important global
shape information is relative to local shape information (features), the larger the reduction is likely to be. We test the hypothesis regarding a general reduction in global shape based top-down effects by comparing reaction times (RTs) to real objects and nonobjects in the three object decision tasks with full line drawings, silhouettes, and fragmented forms originally reported by Gerlach et al. (2016). We note that this aspect of object decision was not examined by Gerlach et al. (2016) as we at that time had not established that the global shape deficit of the DPs was likely to reflect a delay in processing. However, we consider it an important test of the idea that the delay in global processing causes altered top-down processing.

**Method**

**Participants**

Background information on the group of individuals with DP ($N = 10$) can be found in Gerlach et al. (2016). Individually, they all performed significantly outside the normal range on the CFMT and the first part of the Faces and Emotion Questionnaire (29-items) (Freeman, Palermo, & Brock, 2015) compared with a matched control sample (Crawford, Garthwaite, & Porter, 2010) (see also Table 2).

All participants provided written informed consent according to the Helsinki declaration. The Regional Committee for Health Research Ethics of Southern Denmark has assessed the project, and ruled that it did not need formal registration.

Because two of the DPs did not contribute to the analysis based on object decision with silhouettes (PP16 did not perform the task and PP04’s data could not be interpreted due to chance level performance with extreme hit and false alarm rates, see Gerlach et al. (2016)), we only report results from eight of the DPs and their 16 age, gender and educationally matched controls. The mean age of the DP group was 36.6 (SD = 11.7) and 37 (SD = 11.5) for the controls. The mean educational level (years of education) of the DP group was 15.4 (SD = 2.3) and 15.1 (SD = 2) for the controls.
Tasks

In each of the tasks, the participants were instructed to press '1', on a serial response box, if the picture represented a real object and '2', if it represented a nonobject. Participants were encouraged to respond as fast and as accurately as possible. Prior to each of the three tasks, the participants performed a practice version of the upcoming task. Stimuli used in these practice versions were not used in the actual experimental conditions. The three tasks were performed in separate blocks with the same order for the DPs and the controls (fragmented, full, and silhouettes).

Stimuli

160 pictures were presented in each task: 80 real objects and 80 chimeric nonobjects. The full drawings of real objects were taken from the set of Snodgrass and Vanderwart (1980). The 80 chimeric drawings of nonobjects were selected mainly from the set made by Lloyd-Jones and Humphreys (1997). These nonobjects are line-drawings of closed figures constructed by exchanging single parts belonging to objects from the same category. The fragmented stimuli were made by imposing a mask, consisting of blobs of different sizes and shapes, as a semi-transparent layer on the regular line drawings (see Fig 1). The same mask was used for the generation of all fragmented stimuli. The silhouette drawings were made by replacing the colour of each pixel within the interiors of the regular line drawings with the colour black (see Fig 1). The order of pictures was randomized within each task.
Fig 1. Examples of the stimuli used in the Object Decision Tasks. Upper panel: three versions (full drawing, silhouette, and fragmented) of a real object. Middle and lower panel: three versions of a chimeric nonobject.

Statistical analyses

To examine ROSE we calculated the standardized mean difference between RTs to nonobjects and real objects for each subject for each of the three conditions. Hence, positive ROSE scores reflect that RTs are higher for nonobjects than real objects whereas negative scores reflect the reverse. Calculating ROSE scores this way has the advantage that it expresses ROSE as an effect size (Cohen’s $d$), and that potential differences between subjects in absolute RTs do not affect this measure because it is the relative difference between nonobjects and real objects for the individual subject that is computed. Consequently, group differences in ROSE scores cannot reflect that DPs are generally slower than controls as this would affect RTs to real objects and nonobjects alike and thus cancel each other out. Another advantage of using standardized scores in the present analyses, rather than the absolute RT data, is that many of the absolute
RT variables (7/12) departed from normality (Shapiro-Wilk, $p < .05$), whereas none of the variables with standardized scores did (Shapiro-Wilk, all $p$’s > .13).

Prior to calculating ROSE scores, the data were trimmed excluding trials from a particular participant if the RT of that trial fell +/- 2.5 SD from the mean of the participant’s RT. This was done separately for real objects and nonobjects and only trials with correct responses were used.

To examine possible trade-offs between speed and accuracy we looked for negative correlations between absolute RTs and error rates across subjects. This was done separately for each group for each of the six conditions. Two out of 12 correlations were negative but non-significant: full drawings of real objects ($r = -.2$, $p = .47$, 95% CI [-.63, .33]) and of nonobjects ($r = -.43$, $p = .09$, 95% CI [-.77, .08]) in the control group.

**Results**

Looking at the mean ROSE scores for each group across the three conditions (Table 1), it is clear that real objects were generally associated with faster RTs than nonobjects (positive ROSE scores). However, for the DPs the mean ROSE score was not reliable for silhouettes (as the 95% CI included 0), and it was considerably lower than that of the controls for fragmented forms (for individual scores for the DPs see Table 2).
### Table 1

<table>
<thead>
<tr>
<th>Developmental prosopagnosics (n = 8)</th>
<th>Mean (SD)</th>
<th>95% CI</th>
<th>Control Subjects (n = 16)</th>
<th>Mean (SD)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real object superiority score: Full drawings</td>
<td>0.70 (.46)</td>
<td>0.42, 1.01</td>
<td></td>
<td>0.77 (.37)</td>
<td>0.58, 0.94</td>
</tr>
<tr>
<td>Real object superiority score: Silhouettes</td>
<td>0.32 (.59)</td>
<td>-0.04, 0.69</td>
<td></td>
<td>0.70 (.33)</td>
<td>0.57, 0.84</td>
</tr>
<tr>
<td>Real object superiority score: Fragmented forms</td>
<td>0.64 (.70)</td>
<td>0.09, 1.11</td>
<td></td>
<td>1.26 (.41)</td>
<td>1.06, 1.48</td>
</tr>
<tr>
<td>RT Full drawings: Real objects</td>
<td>945 (461)</td>
<td>728, 1253</td>
<td></td>
<td>766 (229)</td>
<td>683, 866</td>
</tr>
<tr>
<td>RT Full drawings: Nonobjects</td>
<td>1319 (518)</td>
<td>1005, 1677</td>
<td></td>
<td>978 (291)</td>
<td>867, 1100</td>
</tr>
<tr>
<td>RT Silhouettes: Real objects</td>
<td>1219 (491)</td>
<td>951, 1526</td>
<td></td>
<td>898 (184)</td>
<td>817, 982</td>
</tr>
<tr>
<td>RT Silhouettes: Nonobjects</td>
<td>1362 (620)</td>
<td>1062, 1736</td>
<td></td>
<td>1208 (275)</td>
<td>1078, 1327</td>
</tr>
<tr>
<td>RT Fragmented forms: Real objects</td>
<td>1227 (545)</td>
<td>968, 1569</td>
<td></td>
<td>931 (245)</td>
<td>838, 1045</td>
</tr>
<tr>
<td>RT Fragmented forms: Nonobjects</td>
<td>1642 (413)</td>
<td>1371, 1922</td>
<td></td>
<td>1607 (465)</td>
<td>1368, 1839</td>
</tr>
</tbody>
</table>

Table 1. The mean real object superiority scores [the standardized mean difference between RTs to Nonobjects – Real objects] for object decision with full line drawings, silhouettes, and fragmented forms, and the mean correct RTs to real objects and nonobjects for full drawings, silhouettes, and fragmented forms (SDs in brackets). 95% confidence intervals (CIs) are based on bias corrected and accelerated bootstrap estimates (1000 samples).

### Table 2

<table>
<thead>
<tr>
<th>Cambridge Face Memory Test</th>
<th>Face and Emotion Questionnaire: First part</th>
<th>Real object superiority score: Full drawings</th>
<th>Real object superiority score: Silhouette drawings</th>
<th>Real object superiority score: Fragmented drawings</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP07</td>
<td>41 (-2.5)</td>
<td>1.60 (2.2)</td>
<td>-0.34 (-3.2)</td>
<td>1.56 (0.7)</td>
</tr>
<tr>
<td>PP09</td>
<td>43 (-2.3)</td>
<td>0.76 (0.0)</td>
<td>-0.15 (-1.7)</td>
<td>0.9 (-0.9)</td>
</tr>
<tr>
<td>PP10</td>
<td>33 (-3.6)</td>
<td>0.38 (-1.1)</td>
<td>0.09 (0.9)</td>
<td>0.63 (-1.5)</td>
</tr>
<tr>
<td>PP13</td>
<td>35 (-3.3)</td>
<td>0.27 (-1.4)</td>
<td>-0.41 (-3.4)</td>
<td>0.39 (-2.1)</td>
</tr>
<tr>
<td>PP17</td>
<td>35 (-3.3)</td>
<td>1.09 (0.9)</td>
<td>0.92 (0.7)</td>
<td>0.25 (-2.5)</td>
</tr>
<tr>
<td>PP18</td>
<td>30 (-4.0)</td>
<td>0.38 (-1.1)</td>
<td>0.47 (-0.7)</td>
<td>-0.74 (-4.9)</td>
</tr>
<tr>
<td>PP19</td>
<td>33 (-3.6)</td>
<td>0.33 (-1.2)</td>
<td>-0.14 (-2.5)</td>
<td>1.1 (-0.4)</td>
</tr>
<tr>
<td>PP27</td>
<td>42 (-2.4)</td>
<td>0.79 (0.1)</td>
<td>0.71 (0.0)</td>
<td>1.06 (-0.5)</td>
</tr>
</tbody>
</table>

| Control Mean | 60.6 | 21.6 | 0.77 | 0.7 | 1.26 |
| Control SD   | 7.7  | 11.4 | 0.37 | 0.33 | 0.41 |

Table 2. Individual scores for the DPs on the Cambridge Face Memory test, the Faces and Emotion Questionnaire (first part), and the three real object superiority measures for full drawings, silhouette drawings and fragmented drawings. The difference between the individual DP compared with the control sample (z-score) are given in brackets. Values written in boldface indicate a score that departs significantly (p < .05) from the control sample according to a Bayesian one-sided point estimate (Crawford, Garthwaite, and & Porter, 2010). Also shown are the means/SDs for the control sample.
We analysed these differences in ROSE scores more directly in a mixed ANOVA with Stimulus Type (full drawings, silhouettes, fragmented forms) as a within-subject factor, and Group (DPs, Controls) as a between-subjects factor. This analysis revealed a main effect of Stimulus Type ($F(2,44) = 6.16$, $MSe = 1.06$, partial $\eta^2 = .22$, $p < .01$), and a main effect of Group ($F(1,22) = 7.46$, $MSe = 2.06$, partial $\eta^2 = .25$, $p < .05$), with ROSE scores being higher for controls than for DPs. The interaction between Stimulus Type and Group was not significant ($p = .11$).

**Discussion**

Based on previous results from the present group of developmental prosopagnosics (DPs) we have argued that a central part of their deficit concerns delayed processing of global relative to local shape information. This proposition is based on the following main findings: (i) The DPs are impaired at recognizing objects when presented as silhouettes and fragmented forms (Gerlach et al., 2016); stimuli which place particular demands on global shape processing (Gerlach, 2009; Gerlach & Toft, 2011), (ii) their impairments with silhouettes and fragmented forms are highly correlated with their face recognition performance (Gerlach et al., 2016), (iii) they show a reduced global precedence effect compared with controls in Navon’s paradigm (Gerlach et al., 2017), and (iv) the magnitude of their global precedence effect correlates with both their face recognition performance and their object recognition performance with silhouettes and fragmented forms (Gerlach et al., 2017).

According to the PACE model of visual object processing (Gerlach, 2009, 2017b) this pattern of deficits can be accounted for by assuming that the DPs cannot effectively use the global shape based first-pass access to visual long-term memory (VLTM) representations. In the PACE model, this initial sweep of processing is important for efficient recognition because it: (i) facilitates the matching process by narrowing down the scope of likely VLTM candidates, and (ii) provides the initial frame in which local details can later
be embedded. Interpreted this way, much of the recognition difficulty exhibited by the DPs can be understood as a deficit in using top-down information to augment the recognition process. To test this hypothesis we here examined whether the DPs exhibited normal real object superiority effects (ROSE), that is faster processing of real objects compared with nonobjects. This effect is consistently found in normal subjects (Gerlach, 2001; Gerlach & Toft, 2011; Starrfelt et al., 2010), and is likely to reflect the influence of top-down processing (Starrfelt et al., 2010).

Consistent with altered top-down processing we find that the DPs as a group exhibit reduced ROSE scores; reductions that were numerically larger with silhouettes and fragmented forms than with full drawings. Indeed, the mean ROSE score was not reliable for silhouettes in the DP group and approximately half the size of that of controls with fragmented forms. Accordingly, the present findings support the idea that delayed derivation of global relative to local shape information in DP leads to weakened top-down influences on the recognition process making it less efficient. We stress “weakened” here because we are not suggesting that top-down effects are completely abolished in DP. Indeed, the DPs examined here do exhibit global-to-local interference effects in Navon’s paradigm, albeit somewhat reduced compared with controls (Gerlach et al., 2017), and they also exhibit a normal word superiority effect in reading (Starrfelt, Klargaard, Petersen, & Gerlach, 2018). Hence, it may only be in conditions where processing of global shape characteristics are of outmost importance for successful performance – that is when fine-grained discriminations of impoverished objects (Gerlach, 2009; Gerlach & Toft, 2011) or face individuation is required (Goffaux et al., 2005; Goffaux et al., 2011; Rossion, 2014) – that the deficit is most apparent. Even though we did not find a significant interaction between Group and Stimulus Type in the present experiments there is such a tendency in the data as the group differences in ROSE scores were numerically larger for impoverished stimuli (silhouettes and fragmented forms) than for full drawings. Consequently, had we had more observations (statistical power) both a main effect of Group and an interaction between Group and Stimulus Type (impoverished vs. full drawings) might have been revealed.
In closing, we also note that while a reduction in ROSE scores was apparent at the group level, this reduction was not evident for all of the DPs examined. In particular, one DP (PP07) performed quite well in this respect across all conditions. Consequently, impaired top-down processing may not be characteristic for all cases of DP, just as delayed derivation of global shape may not (Gerlach et al., 2017), but it seems to be a central part of the deficit seen in many DPs.
References


