Contrasting shared- and specific-mechanism accounts of developmental prosopagnosia: A new approach

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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Abstract

The understanding of developmental prosopagnosia (DP) is dominated by two opposing views: (i) that DP reflects malfunction of a mechanism shared by face and object recognition, but which is more critical for face than for object recognition, or (ii) that DP is due to malfunction of a mechanism specific to faces, but where object recognition deficits may co-occur due to collateral damage. Here we address some of the limitations in DP studies on this point by examining face and car recognition in a large cohort of healthy subjects selected in an unbiased manner. At the group level we find evidence of a general association between face and car recognition performance but at the individual level we also find occasional dissociations. We discuss the methodological implications of these findings for cognitive neuropsychology in general (association vs. dissociation) but also the theoretical implications for the current understanding of DP more specifically.

Keywords: Associations, developmental prosopagnosia, dissociations, face recognition, object recognition.

A recent review by Geskin and Behrmann (2018) on developmental prosopagnosia (DP) – a syndrome characterized by severely impaired face recognition in individuals who have experienced face recognition problems their whole life and where there is no (known) brain damage present (Susilo & Duchaine, 2013) – has led to considerable debate regarding how the empirical data on DP should be interpreted (Barton, 2018; Behrmann & Geskin, 2018; Campbell & Tanaka, 2018; de Gelder & Van den Stock, 2018; Eimer, 2018; Garrido, Duchaine, & DeGutis, 2018; Gerlach, Lissau, & Hildebrandt, 2018; Gray & Cook, 2018; Nestor, 2018; Ramon, 2018; Rosenthal & Avidan, 2018; Rossion, 2018; Starrfelt & Robotham, 2018; Towler & Tree, 2018). Central to this debate is the general question of how associations and dissociations should be weighed when inferences are made regarding the cognitive and neural underpinnings of the disorder and the underlying cognitive architecture. The purpose of the present paper is to discuss and clarify the implications of the extreme stances. This discussion is set in the context of the current debate regarding DP, but the implications are likely to apply to other areas of neuropsychology where inferences from associations and dissociations are used to support conceptual models.

The main finding in Geskin and Behrmann's review (2018) was that of the 238 identified cases with adequate data by their judgment, approximately 80% had evidence of both face and object recognition impairments while 20% showed only impaired face processing. According to Geskin and Behrmann this finding favored "...an interpretation of a single mechanism that might support the recognition of more than one [faces and objects] but not all visual classes [words]" (p. 23). Such a conclusion downplays the 20% of cases that showed a single dissociation and implies that most cases with DP have (presumably lighter) object recognition deficits (see figure 1a).

Figure 1. Three different models of the relationship between face and object recognition in DP. (a) A strong version of a shared-mechanism account where all cases with DP are assumed to have object recognition deficits because the mechanism impaired in DP (yellow area) is shared by faces and objects. (b) A strong version of a specific-mechanism account (the independent disorders hypothesis) where all processes let alone low-level vision are specific to faces and objects. (c) A hybrid model where DP may be caused by impairment to a mechanism (at an intermediate level) common for both face and object processing (yellow area), or by impairment to face-specific processes (in high-level vision) (red area).

Opposite to Geskin and Behrmann is the position taken by Gray and Cook (2018). According to their *Independent disorders hypothesis*, DP is caused by a defect in a selective face processing mechanism, and accompanying deficits merely reflect damage to other mechanisms that tends to co-occur with the defect causing DP (see figure 1b). As they speculated, this co-occurrence could be due to aberrations in occipitotemporal development that tend to affect not one but several areas that each support independent perceptual functions. In this view, co-occurrence of two disorders (association) need not imply a common mechanism underlying the two disorders – a problem that has long been recognized in cognitive neuropsychology (Caramazza, 1986; Shallice, 1988) – but a common pathology affecting different mechanisms. The Independent disorder hypothesis can be considered an extreme stance in that it implies that all cases of DP are pure face recognition disorders, but that their purity is masked by other developmental disorders that happen to co-occur. Thereby any theoretical implications of the 80% of DP cases that show an association between face and object recognition (Geskin &

Behrmann, 2018) is downplayed: Object recognition deficits are reduced to collateral maldevelopment, i.e., a concurrent developmental object agnosia (DOA) that affects objects but, on its own, not faces.

However, the available evidence suggests that DP occurs much more frequently with than without DOA (Geskin & Behrmann, 2018). This is at odds with a proposal that DP and DOA are independent disorders and that the object recognition deficits in DP reflect concurrent DOA. A particular problem is that there are very few subjects reported with ‘pure DOA’, i.e. with intact face recognition. If pure DOA is rare – and it has, to our knowledge, only been described in one case (Germine, Cashdollar, Duzel, & Duchaine, 2011) – but DOA with DP is common, then it seems improbable that DOA is an independent disorder. Importantly, this is only the case if the available evidence is unbiased, which may not be the case. As argued by Gray and Cook (2018), cases with pure DOA may be less likely to approach researchers if object recognition difficulties are less socially debilitating than face recognition deficits. DOA might also be underreported simply because more researchers are aware of DP than of DOA. Consequently, the present literature may indeed underestimate the occurrence of DOA.

If two such divergent points of view can be derived from the same set of observations, is there any way we can pit them against each other or even falsify them? Before we offer our take on this, we need to clarify one aspect of the Independent disorder hypothesis (Gray & Cook, 2018).

What does it mean for two disorders to be independent?

Two disorders, in this case DP and DOA, are (stochastically) independent if the frequency of their co-occurrence ($DP \cap DOA$) equals the product of the frequency of the disorders in isolation [$p(DP \cap DOA) = p(DP)p(DOA)$]. Let us assume that we have data where such frequencies can be derived in an unbiased manner, and that it is found that the disorders are non-independent [$p(DP \cap DOA) > p(DP)p(DOA)$]. Would that mean that DP and DOA reflect the same cognitive mechanism(s)? As argued above the answer is “no” because co-occurrence may be caused by pathology that affects two different neural mechanisms that each support a different function, i.e. object and face recognition. In this case, we have a ‘separable disorders hypothesis’ rather than an independent disorders hypothesis. But what if the results do show stochastic independence? Would that imply

that independent neural or cognitive mechanisms underly the disorders? The answer is “yes”. If disorders are stochastically independent, they share nothing, neither neurally nor cognitively.

Of course, at early levels of processing (low-level vision), object and face recognition do depend on common forms of processing. The functions of striate cortex are required for both face and object recognition, but we would consider subjects with loss of striate function as being blind rather than having a DP/DOA overlap syndrome. While this is an obvious example, object and face recognition also involve many low-level and intermediate cognitive operations (e.g., figure ground segregation) beyond striate cortex, and these too are almost certain to be shared. Hence the question of independence really should only apply to higher levels of processing, where there is the hypothetical chance of divergence into selective processing streams for faces and objects (see figure 1c). If cases with failures of low-level or intermediate visual processing are not identified, this will lead to an overestimation of cases with co-occurring DP and DOA. Indeed, one can ask whether this may be partly responsible for the observation that 80% of DP show object recognition deficits (Geskin & Behrmann, 2018). This then could be a second reason why associations between face and object recognition deficits are frequent, without necessarily invoking a common vulnerability to pathology of selective face and object recognition processes.

Given that it may be difficult to identify all intermediate-level problems that could impair both face and object recognition, it seems unlikely that the data will support independence of DP and DOA. Rather, the better question may be whether we can find evidence that DP and DOA are *separable* disorders. That is, instead of trying to show that $p(\text{DP} \cap \text{DOA}) = p(\text{DP})p(\text{DOA})$, we might show that $p(\text{DP}/\text{nonDOA}) > 0$ and $p(\text{nonDP}/\text{DOA}) > 0$ – that is, that the disorders are double dissociable. This is a more modest starting point than the one implied by the independent disorders hypothesis because it also allows for the possibility that DP may reflect maldevelopment of both face-specific mechanisms and mechanisms common to face and object recognition; a point we will explain below.

Does DP reflect a face-specific mechanism, or a mechanism shared by face and object recognition?

If, as in the independent or separable disorders hypotheses, DP can reflect impairment of a face-specific mechanism – which we will refer to as a *specific-mechanism* account as opposed to a *shared mechanism* account

– it should be possible to find evidence of a (double) dissociation between DP and DOA. On this question we believe that there is agreement in principle, even if there is disagreement as to whether convincing dissociations have yet been reported (Gerlach, Klargaard, & Starrfelt, 2016; Gerlach et al., 2018). However, it is less clear what sort of evidence could falsify specific-mechanism accounts. In a related manner, it is also not clear what empirical evidence would support *shared-mechanism* accounts, given that one can always claim that a concurrent object recognition impairment reflects an associated defect in a separable mechanism and not the workings of a shared mechanism. This argument is in principle a light version of Gary and Cook's (2018) Independent disorder hypothesis, and can also be found elsewhere (Garrido et al., 2018). These are important conceptual points, because the inability to support its position and falsify a competing hypothesis places the shared mechanism account at a disadvantage.

Finally, there are questions of what counts as a dissociation, and what kind of dissociations are found. A classical dissociation implies that one performs normally on one task but abnormally on another, and as a further requirement that the difference in performance between the tasks differs significantly from the difference seen in healthy populations (Crawford, Garthwaite, & Gray, 2003). However, there can also be strong dissociations, in which the subject is impaired on both tasks, but much worse on one. There are likely to be many possible reasons why maldevelopment of mechanisms that are common to face and object recognition may lead to greater difficulties with face than with object recognition, thus giving rise to strong dissociations. As an example, some of the present authors have suggested that DP in some cases may reflect delayed processing of global shape information (Gerlach, Klargaard, Petersen, & Starrfelt, 2017; Gerlach & Starrfelt, 2018a). On this account fast derivation of global shape information is important for efficient recognition of most visual stimuli, including faces and objects, but critical when stimuli are highly visually similar and must be classified at a subordinate level, as with faces. Consequently, maldevelopment that affects fast global shape processing will lead to a disproportional recognition impairment for faces relative to objects, i.e. DP characterized by strong rather than classical dissociations.

If the frequent associations observed between face and object recognition impairments in DP are accepted, which they appear to be as nobody have contested the associations as such, is it possible to make a prediction

from a shared-mechanism account – such as the delayed shape processing hypothesis – that cannot readily be explained by specific-mechanisms accounts by means of a collateral-disturbance argument? We believe it is; at least in principle.

A procedure for contrasting shared- and specific-mechanism accounts

If DP can reflect maldevelopment of mechanisms shared by both face and object recognition, but which are more important for face than for object recognition, individuals with DP should have subtle object recognition deficits. Hence, the shared-mechanism account predicts that DPs on average have worse object recognition than neurotypical controls. A specific-mechanism account does not make this prediction but can accommodate such an outcome by claiming that the DP group includes a subset of comorbid cases (DP+DOA) who lower the group mean for object recognition. However, if such comorbid cases are removed (DP+DOA), the specific-mechanism account predicts no difference in object processing performance between the ‘pure’ DP group and controls. In contrast, a shared-mechanism account still predicts worse object processing in the remaining DPs than in controls even when cases showing significant deficits in object processing (DOA cases) are removed, although the difference would likely be diminished because cases with very poor object processing performance have been removed. Accordingly, the following two hypotheses regarding face and object recognition in DP can be derived, and the outcome of the second of these hypotheses has the potential to differentiate between shared- and specific-mechanism accounts:

- ***Hypothesis A (common to both shared- and specific mechanism accounts):*** Object recognition performance will be reduced in DP groups compared with control groups.
- ***Hypothesis B (shared-mechanism accounts only):*** Reduced object recognition performance will be present in DP groups even when cases of combined DP and DOA are removed.

In the following experiment, we will test these hypotheses in a preliminary fashion in a large sample of psychology students who have performed two tests that are commonly used in studies of DP: The Cambridge

Face Memory Test (CFMT) (Duchaine & Nakayama, 2006) and the Cambridge Car Memory Test (CCMT) (Dennett et al., 2012). If a given student scores significantly below a normal sample on the CFMT we will consider that person to be a DP suspect (DP+). If a given student scores significantly below the normal sample on the CCMT we will consider that person to be a DOA suspect (DOA+).

We acknowledge from the outset that we do not have enough information to conclude whether the DP+ and DOA+ individuals do in fact have DP or DOA. This would ideally require the absence of lesions on brain imaging, exclusion of psychiatric issues such as autism, a history of long-life face and/or object recognition difficulties, and problems on additional objective tests of face and object recognition (Barton & Corrow, 2016). Having said that we note: (i) that this uncertainty is similar for DP+ and DOA+ subjects, and (ii) no agreement exists so far on diagnostic criteria for DP and certainly not DOA. Hence, while the dataset is intended to serve as a ‘proof of procedure’, we do believe that it amounts to more than just a simulation and that the results are likely to be indicative of what would be found in a representative sample of the population using more stringent criteria.

Method

Tasks

In addition to the CFMT and the CCMT we also had data on all participants on the Cambridge Face Perception Test (CFPT) (Duchaine, Yovel, & Nakayama, 2007). While not of main interest here, we include results from the CFPT because it provides a second measure of face processing performance: If participants score poorly on the CFMT due to face processing problems we would expect them to perform poorly on the CFPT also; at least if the deficit reflects a perceptual rather than a memorial impairment.

In the CFMT and the CCMT the participant is introduced to six target stimuli, and then tested with forced choice items consisting of three stimuli, one of which is the target. The tests comprise a total of 72 trials each distributed over 3 phases: (a) an intro-phase with 18 trials where the study stimulus and the target

stimulus are identical, (b) a novel-phase with 30 trials where the target differs from the study stimulus in pose and/or lighting, and (c) a novel+noise phase with 24 trials where the target differs from the study stimulus in pose and/or lighting and where Gaussian noise is added to the target. The depended measure is number of correct trials. The maximum score is thus 72; chance-level is 24.

In CFPT the participant must arrange six facial images according to their similarity to a target face. The images were created by morphing six different individuals with the target face. The proportion of the morph coming from the target face is varied in each image (88%, 76%, 64%, 52%, 40%, and 28%). The test comprises 16 trials, half with upright and half with inverted faces. Scores for each item are computed by summing the deviations from the correct position for each face. Scores for the 8 trials are then added to determine the total number of respectively upright and inverted errors. Hence, the depended measure is a deviation-score; the higher the score the poorer the performance, with chance-level at each orientation being a deviation-score of 93.3. We only use data from the upright trails here.

Participants

Test sample: 343 first-year psychology students (255 females; mean age = 23.2 years, SD = 5.2 years) who were naïve to our hypotheses took part in the study as part of their course in cognitive psychology. The course is approved by the study board at the Department of Psychology, University of Southern Denmark, and the experiments conducted do not require formal ethical approval/registration according to Danish Law and the institutional requirements. Prior to participation, the students were informed that data collected in the experiments might be used in an anonymous form in future publications. Participants were free to opt-out if they wished, and participation in the experiments was taken as consent. Hence the sample size was determined by the number of students who took the course in the years 2014-2018 and provided data for all three tasks (CFMT, CCMT and CFPT). No participants were excluded from the analyses reported below. Task order was counterbalanced for the CFMT and the CCMT. Except for one year, the CFPT was always performed

a week prior to the CFMT and the CCMT, which were performed on the same day. The individual data for each of the 343 participants are given in the accompanying file: 'Supplementary Data'.

Even though the test sample is clearly not representative of the normal population, it is unbiased in the sense that the participants were *not* recruited because they were likely to have either face or object recognition difficulties. Such bias is prevalent in many studies where object recognition is examined in participants who are selected because of their face recognition problems, and this bias is likely to inflate the difference observed between face and object recognition performance (Klargaard, Starrfelt, & Gerlach, 2018).

Reference sample: Any individual in the test sample who scored significantly below the mean of an *independent* reference sample on the CFMT or CCMT was classified as DP+ or DOA+ respectively. The use of an independent reference sample is important because using the mean and standard deviation (SD) of the test sample would yield biased estimates; by definition any normally distributed sample will have 2.5% of its subjects scoring 2 SD below the mean – a proportion that is conspicuously similar to the 2-3% prevalence suggested for DP (Bowles et al., 2009; Kennerknecht et al., 2006).

The reference sample consisted of 61 individuals for whom we have data on several tests, including the CFMT and CCMT (40 females; mean age = 36.7 years, SD = 9.8 years). The CFMT was always performed before the CCMT. This group fulfilled the following inclusion criteria: Performance on the CFPT and the CFMT were within the normal range according to the sex and age corrected norms of Bowles et al. (2009), no indication of autism spectrum disorder as assessed by the Autism-Spectrum Quotient questionnaire (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), and no history of serious psychiatric illness, neurological or developmental disorders. While this procedure is commendable in some respects, it does introduce a potential bias in the present context because no inclusion criterion was applied for CCMT performance. The reason is that there are no suitable normative data, since those reported by Dennett et al. (2012) only cover the age range of 18-32 years.

Even though the reference sample is on average older than the test sample we found no age effect in the reference sample on the CFMT ($r = -.05$, $p = .68$) or the CCMT ($r = -.09$, $p = .48$) which is similar to what has been reported by Bowles et al. (2009) for the CFMT on age groups below 50 years. However, on the CFPT we found a positive correlation with age ($r = .34$, $p = .008$) suggesting that performance decreased with age (low scores on the CFPT signify good performance). The correlation between the CFMT and the CCMT in the reference sample was $r = .07$ ($p = .57$). The mean score for the reference sample was 59.02 (SD = 7.17) on the CFMT, 52.05 (SD = 9.16) on the CCMT, and 39.08 (SD = 13.11) on the CFPT. The individual data for each of the 61 control participants are given in the accompanying file: 'Supplementary Data'

Alternative reference sample: To evaluate the generalizability of the results obtained we had originally planned to use an additional reference sample comprising a large group ($N = 261$) of university students from New Zealand with approximately the same age ($M = 19$, $SD = 3$) and gender composition (71% females) as the test sample. We decided to abandon this otherwise important check, however, because it turned out that the New Zealandic sample performed significantly below the Danish test sample on the CFMT ($M_{\text{difference}} = 3.5$, 95% CI [2.2, 4.8], $t_{602} = 5.18$, $p < .0001$); a problem not present with the Danish reference sample which did not differ systematically from the test sample ($M_{\text{difference}} = -1.1$, 95% CI [-3.1, .9] $t_{402} = -1.1$, $p = .28$). Hence, had the New Zealandic sample been used instead of the Danish reference sample the number of DP+ cases would have dropped from the 8.7% reported below to 1.2% and the number of DOA+ cases from 5.2% to 1.5% (the New Zealandic sample also scored below the Danish test sample on the CCMT albeit not significantly so ($M_{\text{difference}} = .93$, 95% CI [-.4, 2.3], $t_{602} = 1.34$, $p = .18$)). Use of the New Zealandic sample would thus also have made the group-based analyses, to be presented below, impossible due to too few observations. The individual data for each of the 261 participants in the alternative reference sample are given in the accompanying file: 'Supplementary Data'

Even though we consider it correct not to use the New Zealandic sample to evaluate the generalizability of the present results, it clearly highlights that the outcome of the present procedure depends heavily on the reference sample used as cut-off scores can differ from sample to sample (Albonico, Malaspina, & Daini, 2017; Bowles et al., 2009). While this is true of all approaches that uses reference samples to classify abnormality it is

nevertheless an aspect that requires careful attention if the procedure we suggest here should be tried out for real.

Statistical procedures

We used Crawford and colleagues' procedure for classifying abnormal performance for each individual on the CFMT and CCMT (Bayesian one-sided point estimate: Less than 5% of the population with a score more deviant than the one observed) (Crawford, Garthwaite, & Porter, 2010). For the CFPT we used the procedure developed by Crawford, Garthwaite, and Ryan (2011) which allows for controlling of covariates; in this case age which correlated with task performance in the reference sample.

Having identified the individuals who scored significantly below the mean of the reference sample on the CFMT (DP+) and the CCMT (DOA+) we made the following two group-based comparisons. First, we compared the mean CCMT score of the DP+ individuals vs. the mean score of the remaining subjects (nonDP), who had scored in the normal range on the CFMT. This addressed hypothesis A. Second, we eliminated those DP+ subjects who had also scored poorly on the CCMT, and then compared the mean CCMT score of the remaining members of the DP+ group with the nonDP group. This addressed hypothesis B. These analyses were performed by independent samples *t*-tests with bias corrected and accelerated bootstrapping (1000 samples). We computed the 90% CI for the mean differences and considered a difference reliable if its associated lower-level CI was not 0 or negative (corresponding to a one-tailed test).

In the last group-based analyses, we compared: (i) the mean CFPT score of the DP+ group with the mean CFPT score of the nonDP group, and (ii) the mean CFPT score of the DOA+ group with the mean CFPT score of the nonDOA group. This was also performed by means of bias corrected and accelerated bootstrapping estimating the upper level 90% CI (corresponding to a one-tailed test). The use of one-tailed tests is justified because we have no reason to expect the DP+ individuals to perform better on the CCMT and the CFPT than the nonDP individuals. As mentioned above, this was done simply to check whether the DP+ group showed difficulties with faces on tests other than the CFMT.

In addition to the group-based analyses we performed dissociation analyses at the individual level to see if any of the individuals exhibited a dissociation in performance on the CFMT and the CCMT. We did this by applying the criteria suggested by Crawford et al. (2003) and implemented in the software program DissocsBayes_ES.exe (Crawford et al., 2010). To count as a dissociation two criteria must be fulfilled: (i) the person's performance on task *X* must differ significantly from that of the normal population (estimated based on our reference sample), and (ii) the *difference* in performance of that person on tasks *X* and *Y* must differ significantly from the difference-scores of the normal population on tasks *X* and *Y*. If a dissociation is detected, it may be either a strong or a classical dissociation (Shallice, 1988). A strong dissociation refers to a pattern in which an individual's scores deviate significantly from the reference sample on *both* tasks *X* and *Y*, *and* where the individual's difference between tasks *X* and *Y* exceeds that expected in the normal population. In comparison, a (putative) classical dissociation refers to a performance pattern where an individual's scores deviate significantly from the reference sample on one of the tasks but is within the normal range on the other, *and* where the individual's performance difference between tasks *X* and *Y* exceeds what can be expected in the normal population. The reason why the classical dissociation is termed 'putative' is that failure to reject the null-hypothesis for one of the tasks does not really constitute evidence of normal performance on that task (Crawford et al., 2003).

Results

The data for each individual in the test sample on the CFMT, the CCMT and the CFPT are given in supplementary Table 1. Thirty (8.7%) individuals (DP+) scored at or below the CFMT cutoff of 46, and 18 (5.2%) individuals (DOA+) did so on the CCMT (cutoff ≤ 36). Four individuals (1.2%) performed poorly on both the CFMT and the CCMT (DP+/DOA+). If DP and DOA are independent disorders the frequency of those performing poorly on both tests should equal the product of the frequency of those performing abnormally on either test, which would be 1.57 subjects (0.46%). Hence there are 2.7 times more subjects with +DP/+DOA than predicted by independence.

The mean difference between the CCMT score of the nonDP group ($n = 313$) and the DP+ group ($n = 30$) was 4.5 (lower 90% CI = 2.2), $d = .56$. In comparison, the mean difference between the CCMT score of the nonDP group ($n = 313$) and the DP+/nonDOA group ($n = 26$) was 2.8 (lower 90% CI = 0.5), $d = .36$.

Dissociation analyses revealed a total of six putatively classical dissociations (1.7%). Four individuals exhibited impaired face recognition but normal car recognition, while two individuals showed impaired car recognition but normal face recognition. Together these observations form a double dissociation between face and object (car) performance.

The mean difference between the CFPT score of the nonDP group ($n = 313$) and the DP+ group ($n = 30$) was -10.6 (upper 90% CI = -5.6), $d = .76$. In comparison, the mean difference between the CFPT score of the nonDOA group ($n = 325$) and the DOA+ group ($n = 18$) was -5.8 (upper 90% CI = .38), $d = .43$, which is not significant. At a single-subject level, 7 of the 30 DP+ individuals performed abnormally on the CFPT (23%). This included two subjects who also performed poorly on the CCMT (i.e. DP+/DOA+). In contrast, none of the individuals who performed abnormally on the CCMT alone (DOA+; $n = 14$) performed abnormally on the CFPT.

Discussion

Compatible with both specific- and the shared-mechanism accounts we find that object recognition (indexed by CCMT performance) is impaired in DP+ individuals at a group level. This confirms hypothesis A. Importantly, this is still the case when individuals who perform abnormally on both the CFMT (DP+) and the CCMT (DOA+) are removed from the group analysis. Consequently, the poorer object recognition performance of the DP+ group cannot be explained by comorbidity alone (DOA+). This suggests that object recognition performance is affected in the subset of individuals with DP+ who do not meet the criterion for DOA+ ($n = 24$). This finding confirms hypothesis B, and therefore is consistent with what would be expected in a shared-mechanism account but does not follow readily from a specific-mechanisms account.

On the other hand, the single-subject analysis provides some support for the specific-mechanisms account, in that, using the same tasks, the same reference sample and strict classification criteria, we find evidence of a double dissociation in performance on the CCMT and the CFMT for some individuals.

Considered together these findings suggest that both shared and specific mechanisms are involved in face and object recognition, both of which could be impaired in DP. To the degree that the DP+ individuals really have DP, a point we return to below, this implies that two types of DP exist: (i) one reflecting maldevelopment of a mechanism(s) specific to faces (Duchaine, Yovel, Butterworth, & Nakayama, 2006), and (ii) one reflecting maldevelopment of a mechanism(s) common to face and object recognition but more critical for faces (Gerlach et al., 2016).

With respect to the frequency of deficits at a single-subject level, 30 out of 343 (8.7%) exhibited abnormal face recognition performance. Of these 30 DP+ subjects, only four (i.e., 13% of the 30) could be considered as showing good evidence – i.e., a putative classical dissociation – for a selective face recognition deficit (DP+/nonDOA). On the other hand, 4 of the 30 (13%) performed abnormally with both faces and objects (DP+/DOA+), leaving 22 DP+ subjects with indeterminate evidence for either involvement or sparing of object recognition. Conversely, 2 of 18 DOA+ subjects had a putative classical dissociation supporting normal face recognition (nonDP/DOA+), versus 4 of 18 with an impairment in both (DP+/DOA+), and 12 subjects with indeterminate evidence. Although the numbers are small, this would suggest that the frequency of associated deficits (DP+/DOA+) is equal to or exceeds that of either selective deficit (+DP/nonDOA or nonDP/DOA+). This would not be compatible with DP and DOA being stochastically independent. This is reflected in the fact that there are 2.7 times more DP+/DOA+ subjects than predicted by independence of DP+ and DOA+.

If face-selectivity in DP+ subjects is defined by a putative classical dissociation, then 13% of the DP+ cases exhibited a face-selective impairment, a figure similar to the 20% estimate made by Geskin and Behrmann (2018) in their review of DP. Our estimate of selectivity may be somewhat lower because the criteria for a putative classical dissociation is more conservative (Gerlach et al., 2018).

What do these findings mean for the competing hypotheses about the nature of DP and the selectivity or non-selectivity of the underlying perceptual mechanisms? Logically it would be incorrect to infer that all cases of

DP are pure because some cases are (Gray & Cook, 2018), but it would be similarly incorrect to infer that all cases of DP are caused by a deficit in a shared mechanism because most DPs have some impairment in object recognition (Geskin & Behrmann, 2018). Although these two points may be considered trivial, they deserve emphasis because without it, we will probably never get around to the critical question: What sort of pathologic and/or functional mechanisms can explain both the existence of cases with selective impairments AND the frequent association between face and object recognition deficits (Towler & Tree, 2018)?

Limitations

Even if we are certain that face and object recognition do rely on shared mechanisms to a large degree, we must exercise caution when interpreting the specific performance pattern of our test sample described above because the datasets on which it is based are subject to limitations.

As mentioned in the section on Method, there may be a potential bias in the reference sample we used which may have influenced the proportion of individuals classified as DP+ and DOA+. As noted, the reference sample was unlikely to include individuals with DP but may have included individuals with DOA. If so this could increase the average CFMT score relative to the average CCMT score in the reference sample, making it more likely for individuals in the test sample to be classified as DP+ than DOA+. On the other hand, all individuals in the reference sample performed the CFMT before the CCMT, whereas individuals in the test sample were randomized so that half performed the CFMT first and half the CCMT. If experience with the format of the Cambridge tests makes the task easier, this should have favored CCMT performance for the reference sample. This in turn should make it more likely for an individual in the test sample to obtain a DOA+ score. Hence, there may be two potential but opposing biases that may have affected our estimate of the frequency of DP+ and DOA+. To this we can add the general problem – discussed above – that the results obtained will always depend, at least to some extent, on the particular reference sample used for classifying abnormality (Gerlach et al., 2016).

Finally, even if our estimates of the frequencies of face and object recognition difficulties in the normal population are correct, we do not know whether the DP+ individuals actually have DP, just as we do not know whether the DOA+ individuals really suffer from DOA. However, the fact that the DP+ group also performed worse

than the nonDP group on the CFPT suggests that their impaired scores on the CFMT are not due to chance. We can offer no similar check for the DOA+ classification. We also do not know whether the impairment observed in the DOA+ group would manifest on other object categories than cars, which it should if the problem is of a general nature. Only to the degree that car recognition serves as a good index of object recognition in general - and there are some data that suggest that cars and/or vehicles may differ from other objects (Cepulic, Wilhelm, Sommer, & Hildebrandt, 2018; Gerlach & Starrfelt, 2018b; Richler, Wilmer, & Gauthier, 2017; Van Gulick, McGugin, & Gauthier, 2016) - can the present data be used to draw firm inferences regarding the relationship between face and object recognition. Consequently, future studies adopting the procedure described here should address these limitations.

Advantages

Despite its limitations, the present approach represents an advance in some methodological respects. First, the results are based on an unbiased sample, given that the test sample had not been selected on the basis of having impairments in either face or object recognition. This circumvents a problem in most of the current literature on DP, namely that individuals are selected for study because of their poor face recognition. This selection bias increases the likelihood of finding dissociations between face and object recognition (Klargaard et al., 2018). Second, in all studies of DP reviewed by Geskin and Behrmann (2018), dissociations were based on criteria that did not require the difference between face and object recognition scores to differ significantly from that seen in the normal population (Gerlach et al., 2018). Our estimates of selectivity are based on the stricter criteria for a putative classical dissociation.

Finally, we find a *double dissociation* between face and object (car) recognition performance using the same tasks and the same reference sample. To our knowledge, there has been no prior demonstration of such a conservatively derived double dissociation. At the very least this provides evidence at the single subject level, that performance on the CCMT and CFMT require at least some cognitive operations that are likely to be separable for faces and cars.

Conclusion

The understanding of DP is currently dominated by two opposing views. On the account represented by Geskin and Behrmann (2018), DP is assumed to reflect an impairment to a mechanism that is shared by face and object recognition, but perhaps more important for faces. By the independent disorders hypothesis, represented by Gray and Cook (2018), DP is thought to reflect a mechanism that is specific to faces, and associations between face and object recognition deficits are attributed to pathologic co-morbidity. In the present paper we have suggested an unbiased procedure that may contribute to the debate, and we have provided a concrete example of how the procedure can be applied to existing data. Even though our results should be interpreted with caution, given the limitations discussed above, our findings are close to the results obtained by Geskin and Behrmann (2018) in their review of DP. Notably, we find that *selective* face recognition impairments only account for 13% of all cases with abnormal face recognition. However, these 13% cannot be dismissed easily because: (i) they are identified using stringent criteria (putative classical dissociation), (ii) the same set of tasks and procedures were used to assess object and face recognition performance, and (iii) the sample was recruited in an unbiased manner. On the other hand, we also find evidence for a general reduction in object recognition in the DP+ group, and a higher frequency of subjects with both face and object recognition impairments (DP+/DOA+) than expected if the disorders were truly independent. Hence, the challenge for any coherent account of DP is to explain how both dissociations and frequent associations can occur in an unbiased sample examined with comparable tasks and identical criteria for classification of associations and dissociations across tasks. One possibility is that DP may be a heterogeneous condition that could result from damage to either selective or shared perceptual processes (see figure 1c).

Even though the method we have presented here has its limitations, it also has advantages that provide a complement to the current approaches used to study DP. Further work from other approaches would be useful in providing converging evidence in the debate on the selectivity of face and object recognition processing.

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