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The size-weight illusion in visual form agnosic patient DF

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Disclosure of interest

The authors report no conflict of interest

Data availability statement

Data, scripts and analysis outputs are available at

https://osf.io/3s2fp/?view_only=50c8af0b39ee436b85d292b0a701cc3b

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The size-weight illusion is a perceptual illusion in which smaller objects are judged as heavier than larger objects of equal weight. A previous informal report suggests that patient DF, who has visual form agnosia, does not experience the size-weight illusion when vision is the only available cue to object size. We tested this experimentally by comparing the magnitudes of DF’s visual, kinaesthetic and visual-kinaesthetic size-weight illusions to those of 28 similarly-aged controls. A modified t-test found that DF’s visual size-weight illusion was significantly smaller than that of controls ($z_{cc} = -1.7$). A test of simple dissociation based on the Revised Standardised Difference Test found that the discrepancy between the magnitude of DF’s visual and kinaesthetic size-weight illusions was not significantly different from that of the controls ($z_{dcc} = -1.054$), thereby failing to establish a dissociation between the visual and kinaesthetic conditions. These results are consistent with previous suggestions that visual form agnosia, following ventral visual stream damage, is associated with an abnormally reduced size-weight illusion. The results, however, do not confirm that this reduction is specific to the use of visual size cues to predict object weight, rather than reflecting more general changes in the processing of object size cues or the use of predictive strategies for lifting.

Keywords: size-weight illusion; visual agnosia; multisensory integration; ageing; perception

Introduction

When planning interactions with objects, we visually assess their properties to pre-calibrate our grasping and lifting actions. The size, shape and orientation of a grasp are informed quite directly by visual cues, but the appropriate fingertip forces for lifting depend upon object weight, which cannot be assessed so directly. Object weight can only be inferred indirectly from visual cues, either by recognising the specific object, or by assessing its size and material, and accessing stored knowledge to make predictions about its likely weight.

Prior knowledge about object weight also appears to affect perceptions of heaviness, such as in the size-weight illusion, where smaller objects are judged as heavier than larger objects of equal weight (Charpentier, 1891). The size-weight illusion was once considered to be the product of a sensorimotor mismatch (Davis & Roberts, 1976). A motor plan is generated, used to predict sensory feedback, and then compared to the actual sensory feedback, resulting in objects that are lighter-than-expected being judged as relatively light, and those that are heavier-than-expected being judged relatively heavy (Buckingham, 2014). This explanation was supported by the finding that participants scale their grip and load forces according to the size of identically-weighted objects, whilst also experiencing the size-weight illusion. A subsequent investigation by Flanagan & Beltzner (2000), however, found that force scaling to size (and thus sensorimotor mismatch) occurs only for the first few lifts. In their study, fingertip forces quickly adapted to the true weight of objects but the size-weight illusion persisted. Thus, the size-weight illusion persists even when there is no longer a sensorimotor mismatch.

Flanagan & Beltzner (2000) interpreted the dissociation between force scaling and sensorimotor prediction in terms of the division between dorsal and ventral visual streams, serving spatial guidance of action and perceptual awareness respectively (Milner & Goodale, 1995). They suggested that ventral stream analyses of an object’s material and size allow access to stored knowledge, supporting cognitive predictions about its weight. These predictions usually influence the forces used for lifting, but the sensorimotor system can disregard them if they lead to inaccurate behaviour, perhaps instead applying whatever forces were appropriate for the immediately preceding lift (the default strategy used in the absence of any perceptual information about the object to be lifted; Johansson & Westling, 1988). The perceptual system might nonetheless continue to generate cognitive predictions, and the mismatch with the sensory feedback would continue to induce illusory misperceptions of weight. This interpretation is similar to the sensory mismatch hypothesis, except that the mismatched prediction is located at a cognitive, rather than a sensorimotor level, and depends upon visual analyses of size and material in the ventral stream.

Although classically the dorsal stream is proposed to use size cues received directly from the retinal array to guide certain action parameters (Milner & Goodale, 1995), recent work has highlighted the apparent role of the ventral stream in processing object features such as size, and associating these features with weight (Gallivan, Cant, Goodale, & Flanagan, 2014; Saccone & Chouinard, 2018). The precise role of the dorsal and ventral streams in weight perception, however, remains unclear. The functional utility of these pathways can be tested by studying the consequences of neurological impairment. Patient DF has severe visual form agnosia following bilateral lesions to the lateral occipital complex: a critical node for processing within the ventral stream (Goodale, Milner, Jakobson, & Carey, 1991; James, Culham, Humphrey, Milner, & Goodale, 2003; Milner et al., 1991). DF experiences impaired visual perception of object form, including basic properties such as object size (Ganel & Goodale, 2019). The damage sustained by DF has, however, left her dorsal stream relatively unaffected, and so she is still able to use vision to guide interactions with objects (Ganel & Goodale, 2019; Whitwell, Milner, & Goodale, 2014), and to recognise objects by touch (Milner et al., 1991). If a ventral visual stream analysis of object size is needed to generate sensorimotor predictions of weight, then DF’s ventral stream damage should result in a reduced or absent visual size-weight illusion. However, her ability to generate weight predictions should be normal when she is able to assess object size using non-visual cues, such as kinaesthetic cues from holding the object.

Consistent with this, a prior anecdotal report suggests that DF does not experience the size-weight illusion when vision provides the only cue to object size, but does experience the size-weight illusion when a kinaesthetic size cue is provided (Dijkerman, Lê, Démonet, & Milner, 2004). However, no data were presented, and no formal assessment of DF’s perceptual experience of the size-weight illusion under visually- and kinaesthetically-cued conditions has subsequently been reported to support the claim. Further investigation of the size-weight illusion in patient DF is necessary to move towards resolving the conflicting findings of prior research. Dijkerman et al. (2004) found that patient SB, who has visual agnosia as a consequence of damage sustained at 3 years old, experiences no visual size-weight illusion but does experience a kinaesthetic size-weight illusion. In contrast, Buckingham, Holler, Michelakakis, & Snow (2018) found that patient MC - who also sustained damage to the visual ventral stream - experiences a visual size-weight illusion that is statistically indistinguishable from that of controls. Patient MC’s size-weight illusion was, however, smaller than that of 10/12 of Buckingham, Holler, Michelakakis, & Snow's (2018) controls. This reduced size-weight illusion magnitude may represent a modest deficit in MC, which Buckingham, Holler, Michelakakis, & Snow (2018) may have been unable to detect due to low statistical power (Figure 2a). Additionally, the previous investigations by Dijkerman et al. (2004) and Buckingham, Holler, Michelakakis, & Snow (2018) do not give conclusive evidence regarding the nature of any potential dissociation between the visual and kinaesthetic size-weight illusions. The question of whether these different patients do or do not show a critical dissociation can provide a valuable insight into the function of the ventral stream.

We recently used data already available from six control participants of a comparable age to DF (Buckingham, Michelakakis, & Cole, 2016) to revisit Dijkerman et al.'s (2004) claims. We tested DF in the same visual size-weight illusion task used by Buckingham, Michelakakis, et al. (2016), with the addition of kinaesthetic and visual-kinaesthetic conditions. Comparison of the magnitude of DF's visual size-weight illusion against Buckingham, Michelakakis, et al.'s (2016) control data (n=6) suggested that the effect size of DF's visual size-weight illusion deficit, expressed as a z-score, is 3.4 (McIntosh et al., 2016) (Figure 1). DF's performance was also consistent with the expectation that, for DF, the size-weight illusion is not induced by a visual cue, but is induced by a kinaesthetic cue.

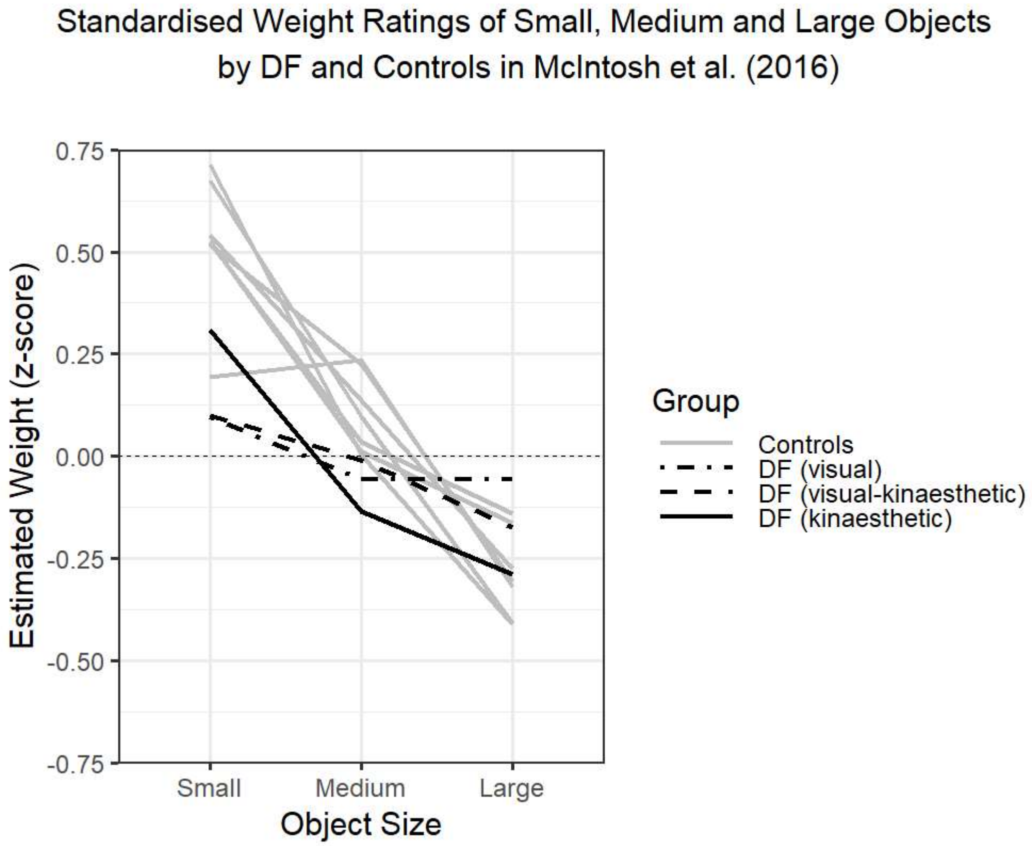

Figure 1. Standardised Weight Ratings of Small, Medium and Large Objects by DF and Controls in the preliminary experiment reported by McIntosh et al. (2016).

Whilst this data sheds some light on DF’s visual size-weight illusion, it lacked an assessment of the kinaesthetic size-weight illusion in controls, and so the critical dissociation between modalities could not be tested. The experimental procedure also did not tightly control kinaesthetic cues which may have allowed for participants to gain additional information about object properties through information such as object rotation during lifting (Amazeen & Turvey, 1996).

To provide a critical test of the dissociation between modalities in DF and controls, we conducted the current study in a much larger sample of 28 healthy older adults, encompassing DF’s age. The experimental procedure allowed a tighter control of the kinaesthetic cues available, with the object lift constrained to prevent the objects tilting, which might provide additional cues to size. Participants completed three cue conditions: visual, kinaesthetic, and visual-kinaesthetic combined. These data provide a basis for a more definitive quantification of DF's experience of the size-weight illusion under different sensory conditions.

Our first hypothesis was that DF would show a significantly smaller visual size-weight illusion than healthy controls. Our second hypothesis was that DF would show a significant dissociation between the visual size-weight illusion and kinaesthetic size-weight illusion.

Methods

Participants

Patient DF, 65 years old at the time of testing, has bilateral lesions to the lateral occipital complex sustained as a consequence of carbon monoxide poisoning when she was 34 years old (Ganel & Goodale, 2019; Goodale et al., 1991; Whitwell et al., 2014). The visual ventral stream damage that DF sustained has resulted in visual form agnosia, leaving her unable to perceive the form of objects. However, she retains the ability to make broad distinctions between objects of different sizes (McIntosh et al., 2016), and is able to use object form information to guide her actions due to her comparatively spared dorsal stream (Ganel & Goodale, 2019; Milner & Goodale, 1995).

We recruited 30 adults, with one participant removed due to them withdrawing their consent. Another participant showed a highly unusual negative size-weight illusion in the kinaesthetic and visual-kinaesthetic conditions. Given that the size-weight illusion is such a robust phenomenon (Buckingham, 2014), this finding was assumed to be due to erroneous reporting by the participant and so their data were removed. For transparency, analyses with this participant included are available in the Appendix (see also Discussion). The control sample therefore consisted of 28 adults (18 female, 10 male) with a mean age of 66.2 ± 4.7 years (range 56.3-73.3). All control participants reported no knowledge of any cognitive, physical or uncorrected visual impairments which would interfere with task performance. This study was approved by The University of Edinburgh Philosophy, Psychology and Language Sciences Ethics Committee (ref: 270 1718/5).

Power Considerations

The control sample size provides close to the maximum power for case-control tests of deficit. This is illustrated in Figure 2a, which shows how the power to detect a deficit changes with control sample size for different sizes of deficit (expressed as standard deviations of the control mean, i.e. a z-score). Our sample size of n = 28 is indicated by the vertical dashed line. Figure 2b shows how the power to detect a dissociation between tasks changes with the strength of inter-task correlation. Our observed correlation between visual size-weight illusion and kinaesthetic size-weight illusion in the control group is r = .62, indicated by the vertical dotted line.

Our prior estimate of DF's size of deficit for the visual size-weight illusion, based upon our preliminary testing, was $z_{cc} = 3.4$ (where z_{cc} is DF's size-weight illusion estimate expressed as a z-score of the six controls' scores) (Crawford, Garthwaite, & Porter, 2010). This is an approximate estimate, and it may be an over-estimate. However, even if we assume a smaller deficit size, of 3, Figures 2a and 2b suggest that we should have power at around 90% to test hypotheses 1 and 2. This would be extremely high power for a single case study design.

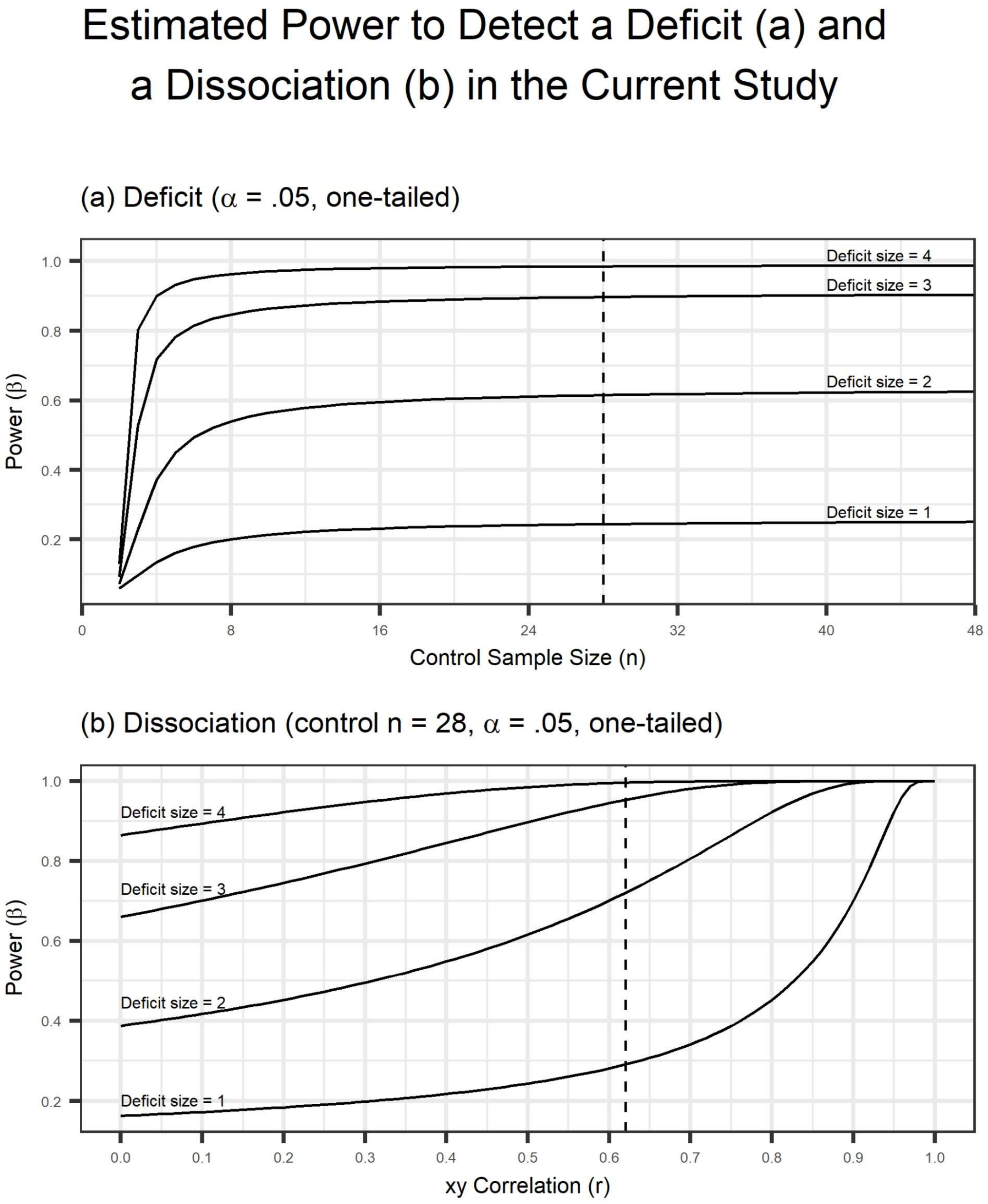

Figure 2. Estimated power to Detect a Deficit (a) and a Dissociation (b) in the Current Study. Dashed line in (a) indicates the control sample size of n = 28 used in the current study. Dashed line in (b) represents the observed correlation of r = .62 between the between the visual (x) and kinaesthetic (y) modalities in the control sample.

Procedure

Nine cylinders differing only in size (diameter) and weight were used (see Figure 3a). Each object was 3D printed in black plastic in order to avoid providing a material cue to object weight (Buckingham, Goodale, White, & Westwood, 2016). Each object contained small lead balls in order to achieve the desired weight as well as foam to prevent rattling. There were three different weight groups (200g, 325g, 450g) with each group consisting of three different sizes (5cm diameter, 7.5cm diameter, 10cm diameter). All of the objects were the same height, 7.5cm, with a 3cm tall, 3cm wide handle attached to the lid. Each cylinder had a 1.5cm diameter hole running through the centre of its long axis, which allowed them to fit onto a metal retort stand, thus minimising lateral movement during lifting. The pole was wrapped in tape to reduce noise, and pushed through a piece of foam, which acted as a platform and dampened the sound of the cylinders being put down.

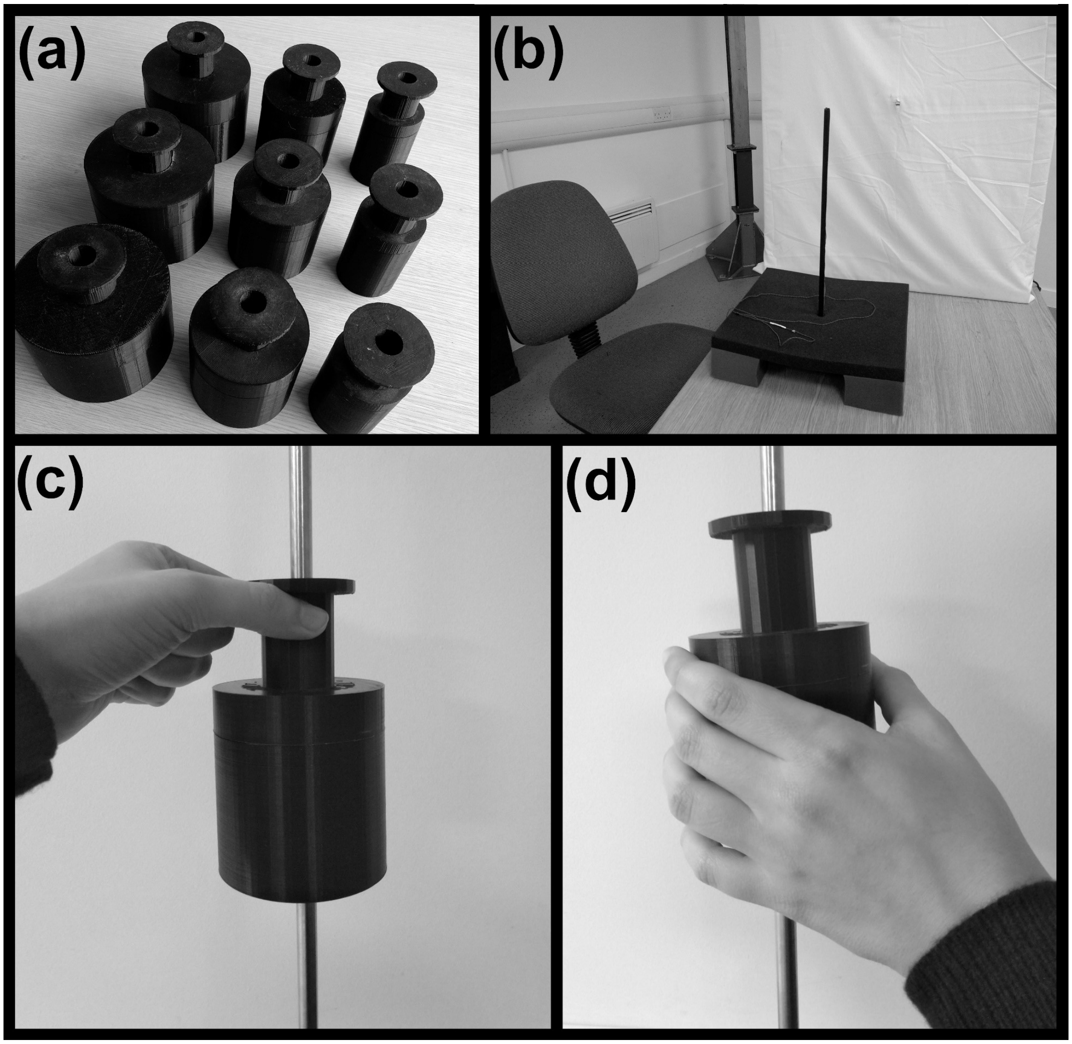

Figure 3. Objects (a), Experimental Setup (b), Visual Grasp (c), and Kinaesthetic Grasp (d) used in the Current Study.

Participants were seated at a table with the pole and platform in front of them and a screen to their left concealing the objects from view (see Figure 3b). They placed their dominant hand on the near ipsilateral corner of the platform with their eyes closed. The experimenter said "2, 1, go". On "go", participants opened their eyes, lifted the object to a prescribed height around 85% of the height of the pole, rated the weight of the object verbally, put the object down, put their hand back on the corner of the platform and closed their eyes. The weight of the object was rated according to absolute magnitude estimation (Zwislocki & Goodman, 1980), where larger numbers represent heavier weights and smaller numbers represent lighter weights with the scale itself being of the participants' own choosing. Participants were instructed to be as consistent as possible in their ratings. This procedure was practised five times with the medium weight, medium size (325g, 7.5cm diameter) object prior to the beginning of the experimental trials

The experimental trials were arranged as three blocks of 54 trials, with short breaks between blocks. In each block, participants lifted each object six times in a pseudorandom order. This order ensured that within every nine trials all nine objects were lifted, and no object could be presented more than twice in a row. Each block of 54 trials was conducted in one modality condition. In the visual condition, participants were able to see the object and grasped the handle with a pinch grip in order to lift it (Figure 3c). In the kinaesthetic condition, participants' sight was occluded using a blindfold, and they grasped around the body of the object with the whole hand during lifting (Figure 3d). In the visual-kinaesthetic condition, participants were able to see the object and also grasped around its body.

Each control participant completed the task in one of six different counterbalanced block orders. DF completed the trial blocks in the order: visual, kinaesthetic, visual-kinaesthetic. Examination of the control data does not suggest that the trial order has any influence on the pattern of differential responding between visual and kinaesthetic conditions.

Analyses

Dependent Variable

The raw data are the weight ratings given per trial. We regressed object weight (in grams) on these ratings, and similarly regressed object volume (in cm^3) on the ratings, extracting the beta (slope) coefficient for each relationship. This provides the basis for a scaled measure of the size-weight illusion, expressed as the number of grams weight difference perceived per cubic cm of volume change, with the sign flipped so that a larger illusion is more positive.

Operationally, we calculate:

$$\text{Size-Weight Illusion} = -(1/bW * bV)$$

where bW is the beta for Weight and bV is the beta for Volume.

This scaled measure of the size-weight illusion more accurately detects changes in the size-weight illusion than a simple difference score and allows for comparison between individuals, whilst still accounting for individual differences in real weight perception.

Hypotheses Tests

The critical analyses are based upon case-control comparisons, which statistically compare DF's size-weight illusion measures against the range of those in controls.

Hypothesis 1 was tested using a test of deficit based upon Crawford & Howell's (1998) modified t-test, using an alpha of .05 (one-tailed). Effect sizes are reported using $z_{cc,}$ an analogue of Cohen's d which expresses the single-case difference score as a z-score of the control sample (Crawford et al., 2010).

Hypothesis 2 was tested using a test of simple dissociation (McIntosh, 2018), based upon the Revised Standardised Difference Test of Crawford & Garthwaite (2005), using an alpha of .05 (one-tailed). Effect sizes are reported using z_{cc} (Crawford et al., 2010).

Preliminary analysis indicates that the correlations by sex and age with the visual size-weight illusion and kinaesthetic size-weight illusion were all lower than the .3 level recommended for inclusion as a covariate in the above tests (maximum observed r = .20, between age and visual size-weight illusion; see Crawford, Garthwaite, & Ryan, 2011). No covariates will therefore be included in these analyses. The analyses for both hypotheses one and two were conducted using custom programs (Crawford et al., 2010).

Results

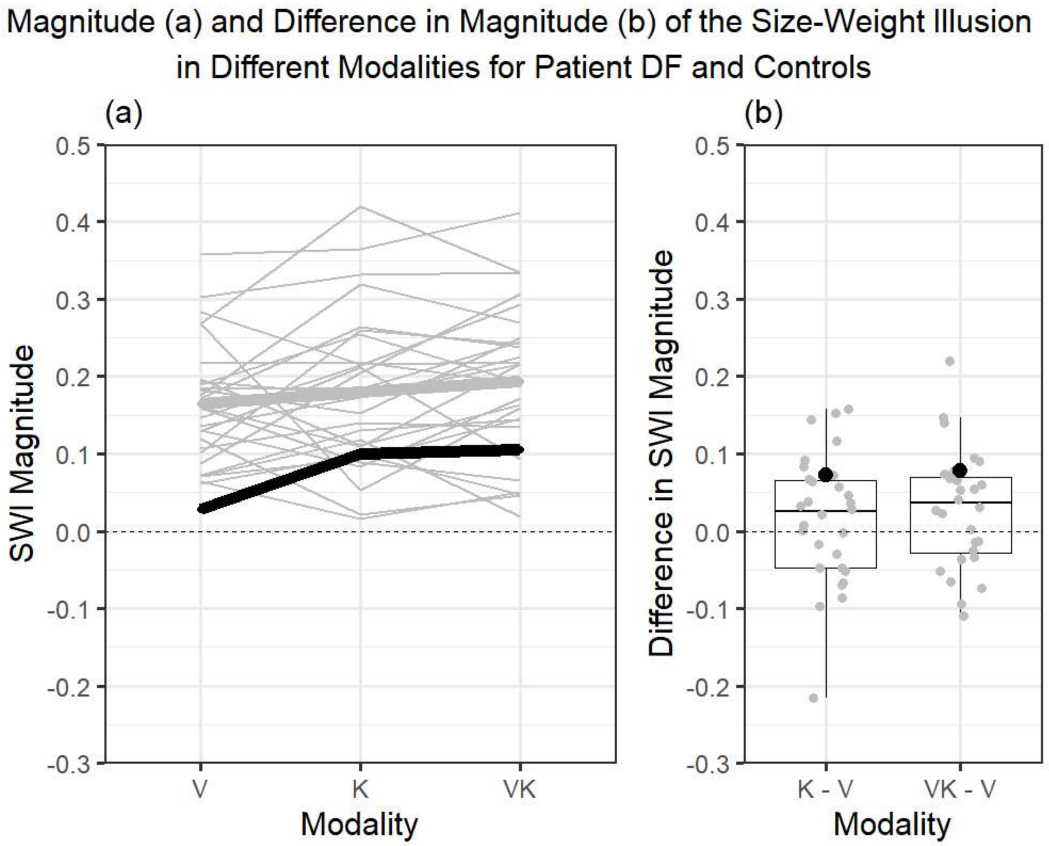

Figure 4. Magnitude (a) and Difference in Magnitude (b) of the Size-Weight Illusion in Different Modalities for Patient DF and Controls. V = Visual, K = Kinaesthetic, VK = Visual-Kinaesthetic. In (a), values above the dashed line indicate participants experiencing a size-weight illusion, with larger values indicating a higher magnitude size-weight illusion. Each individuals' size-weight illusion is represented by thin grey lines, with the thick grey line representing the mean in the controls. DF's size-weight illusion data is represented by the thick black line. In (b), values above the line indicate that the size-weight illusion was smaller in the

visual modality, with values below the line indicating the size-weight illusion was larger in the visual modality. Box plots represent the control data: upper and lower whiskers (vertical lines) extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with median shown as the middle line. Grey circles show the size-weight illusion for each control participant, with the larger black circle showing DF's size-weight illusion.

Hypothesis 1: patient DF will show a significantly smaller visual size-weight illusion than healthy controls

We tested this hypothesis using a one-tailed Crawford and Howell's (1998) modified t-test. This found a significant difference in the visual size-weight illusion between patient DF and controls, t (28) = -1.726, p = .048, z_{cc} = -1.76 [95% CI: -2.345, -1.155], estimated percentage of control population falling below case's scores = 4.79% [0.95%, 12.41%]. Patient DF's visual size-weight illusion was significantly smaller than that of healthy controls (see Figure 4a).

Hypothesis 2: DF will show a significant dissociation between the visual size-weight illusion and the kinaesthetic size-weight illusion in comparison with controls

We tested this hypothesis using a using a test of simple dissociation (McIntosh, 2018), based upon the one-tailed Revised Standardised Difference Test of Crawford and Garthwaite (2005). This analysis found no significant difference between patient DF and controls, t (27) = 1.005, p = .162, z_{dcc} = -1.054 [95% BCI: -1.701, -0.448], estimated percentage of control population with a more extreme difference between modalities than the case = 16.2%. Patient DF did not show a significant dissociation between the visual size-weight illusion and kinaesthetic size-weight illusion in comparison with controls (see Figure 4b). Visual inspection of these data also reveals that, in addition to having no dissociation between her visual and kinaesthetic size-weight illusion, DF's kinaesthetic and visual-kinaesthetic size-weight illusion were almost identical.

Exploratory Analyses

Visual inspection of the data revealed that DF appears to have a generally reduced size-weight illusion. To investigate this further, we compared the magnitude of DF's size-weight illusion with that of controls in two one-tailed Crawford and Howell's (1998) modified t-tests.

In the kinaesthetic condition, the estimated percentage of the control population falling below the case's scores was 22.4% [11.45%, 36.19%], t (28) = -0.770, p = .224, z_{cc} = -0.78 [95% CI: -1.203, -0.353]. Patient DF's kinaesthetic size-weight illusion was smaller than that of an estimated 77.6% of the control population.

In the visual-kinaesthetic condition, the estimated percentage of the control population falling below the case's scores was 19.24% [9.11%, 32.54%], t (28) = -0.883, p = .192, z_{cc} = -0.90 [95% CI: -1.334, -0.453]. Patient DF's visual-kinaesthetic size-weight illusion was smaller than that of an estimated 80.76% of the control population.

Discussion

Our first hypothesis was supported, with DF showing a visual size-weight illusion which was significantly different from that of similarly aged controls. This is consistent with the idea that ventral visual stream analysis of object size is necessary to generate predictions about object weight, and that ventral stream damage affects this (Dijkerman et al., 2004; Flanagan & Beltzner, 2000). Notably, however, we excluded one participant due to their highly unusual negative kinaesthetic and visual-kinaesthetic size-weight illusion. An analysis with this participant included (see Appendix) would have found that DF did *not* have a significantly different visual size-weight illusion from controls (p = .055, z_{cc} = -1.68). Taken together, these results are potentially ambiguous. However, it is reasonable to believe that DF does indeed have an abnormal visual size-weight illusion and that our removal of this participant is valid. First, previous investigations support the finding that DF has an absent visual size-weight illusion (Dijkerman et al., 2004; McIntosh et al., 2016). Second, the participant who was excluded is unique in their pattern of responses, indicating that they are at best very unusual. We therefore conclude that DF does have an impaired visual size-weight illusion, though the difference between DF and other adults of a similar age is less dramatic than may have been previously thought ($z_{cc} = -1.76$ in the current study vs 3.4 in McIntosh et al., 2016).

We further predicted that DF's ventral stream damage would leave her kinaesthetic size-weight illusion relatively unaffected by comparison with the visual size-weight illusion. To test this prediction, we examined the dissociation between DF's size-weight illusion magnitude in the visual and kinaesthetic modalities. We found no evidence in support of this second hypothesis. Whilst DF did show a kinaesthetic size-weight illusion well within the range of those of controls, it was nonetheless much smaller than average, and was not statistically dissociable from her impaired visual size-weight illusion.

It is possible of course that DF does have a truly selective impairment of the visual size-weight illusion, but that our experiment was not able to detect this true dissociation. Our power calculation was based on a preliminary finding that DF's visual deficit was around $z_{cc} = 3.4$, but the current findings reveal a more modest deficit of only $z_{cc} = -1.76$. Our power to detect a dissociation between the magnitude of the size-weight illusion in the visual and kinaesthetic conditions was therefore below 60%, as opposed to the 90% originally estimated. DF may therefore experience a true dissociation which we are not able to detect in the current study. Alternatively, DF may truly have no dissociation between modalities, instead perhaps showing more general abnormalities in the way that she generates and uses predictions of object weight for lifting. DF shows a generally reduced size-weight illusion, with magnitudes below the 5th, 22nd and 20th percentile of the control sample in the visual, kinaesthetic and visual-kinaesthetic conditions respectively. As a consequence of having visual agnosia, DF presumably experiences an increased amount of uncertainty when interacting with her environment. We can speculate that DF's generally reduced size-weight illusion reflects a modality-general adaptive strategy which involves interacting with the environment in a way that reduces uncertainty by relying less on prediction and more on sensory feedback. Previous analysis of older adults' grip forces during object lifting has revealed that older adults do not apply force in accordance with their predictions about object weight, but instead seem to rely more on sensory feedback during object lifting to guide their force application (Buckingham, Reid, & Potter, 2018). An analysis of the forces DF applies to objects during lifting would reveal whether she engages in similar behaviour, and whether this behaviour is consistent across all modalities or specific only to the visual modality. Alternatively, DF's behaviour may be a consequence of her more widespread brain damage. The lesions that DF sustained are not limited to the ventrolateral cortex and recent evidence has indicated that her dorsal stream visual processing may not be as unimpaired as previously thought (Whitwell et al., 2014; see Ganel & Goodale (2019) for a review and discussion of this evidence). DF's brain damage may have had a more general effect on her ability to generate, or perhaps to use, predictions about object weight. Her kinaesthetic- and visual-kinaesthetic size-weight illusion may have somehow been affected by this more diffuse damage, though this possibility cannot be tested given the current evidence. The current lack of evidence for a dissociation in DF contrasts with previous findings in another ventral stream patient, SB (Dijkerman et al., 2004). Patient SB has damage in ventral stream areas very similar to those of DF, and experiences no visual size-weight illusion but a robust kinaesthetic size-weight illusion. DF was also informally reported to show a similar pattern of responses, consistent with a dissociation. Dijkerman et al. (2004) concluded that this evidence provides support for the role of the ventral stream in visual processing of size. The current evidence fails to confirm this, and brings to question the nature of the apparent dissociation in patient SB. The evidence for a dissociation in SB is based on whether his responses were significantly difference from chance. His responses were no different from chance when visual size cues were available, and significantly above chance when kinaesthetic size cues were available. This pattern of responses was not, however, compared to the performance of healthy controls, and no direct test of dissociation was conducted. The selective impairment of the visual size-weight illusion is therefore yet to be definitively demonstrated in any patient with ventral stream damage.

In any study examining neuropsychological patients, the performance of the control group requires careful consideration. The older adults' size-weight illusion magnitudes were overall relatively small. Whilst the older controls can perceive size cues, some of them may not form strong predictions based on these cues. Older adults have been found to use more effortful but more cautious feedback-based approaches to interacting with objects in their environment as opposed to more efficient but riskier prediction-based approaches (Buckingham, Reid, et al., 2018). This may be due to a reduction in sensory acuity (Ranganathan, Siemionow, Sahgal, & Yue, 2001) and reduced hand functionality (Cicerale, Ambron, Lingnau, & Rumiati, 2014; Cole, Rotella, & Harper, 1999; Kinoshita & Francis, 1996) which increases uncertainty regarding perceptual judgements of object size. Making weaker predictions would reduce the perceived mismatch between predicted and experienced weight and subsequently reduce the magnitude of the size-weight illusion. Individual differences in the ways that older adults generate and use their predictions might also account for the variability in the differences found between the controls' responses in different modalities (Figure 4b). In the same way that older adults' responses are variable across modalities, their responses may change over time. This may have contributed to differences between the magnitude of DF's visual-kinaesthetic size-weight illusion in our earlier examination of her performance (McIntosh et al., 2016), and our current findings. Given that DF's visual agnosia may result in her experiencing additional uncertainty, we could expect that the differences in DF's performance over time would be more extreme than those found in other older adults. Whether performance variability would be apparent in DF only in more recent years or throughout her lifetime is unclear. Nonetheless, this finding raises an interesting question about how information from different modalities is used across the lifespan, and how this might change as a consequence of ageing.

To conclude, the current study confirms previous anecdotal reports that DF experiences a smaller visual size-weight illusion than controls. However, we could not confirm that this was in the context of a relative preservation of the size-weight illusion when kinaesthetic cues are available. It is possible that instead of having a specific visual deficit, DF has a generally reduced size-weight illusion, which may reflect a tendency to rely less on predictive strategies when interacting with objects in her environment.

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Appendix: Analyses without exclusion of participant with negative kinaesthetic and visual-kinaesthetic size-weight illusion

One control participant (E12) provided weight reports which indicated that they experience a negative kinaesthetic and visual-kinaesthetic size-weight illusion. This is highly unusual given that the size-weight illusion is a robust phenomenon (Buckingham, 2014), and so this participant was removed. In the interests of transparency, the analyses shown here are the same as those in results, but were conducted with participant E12 included.

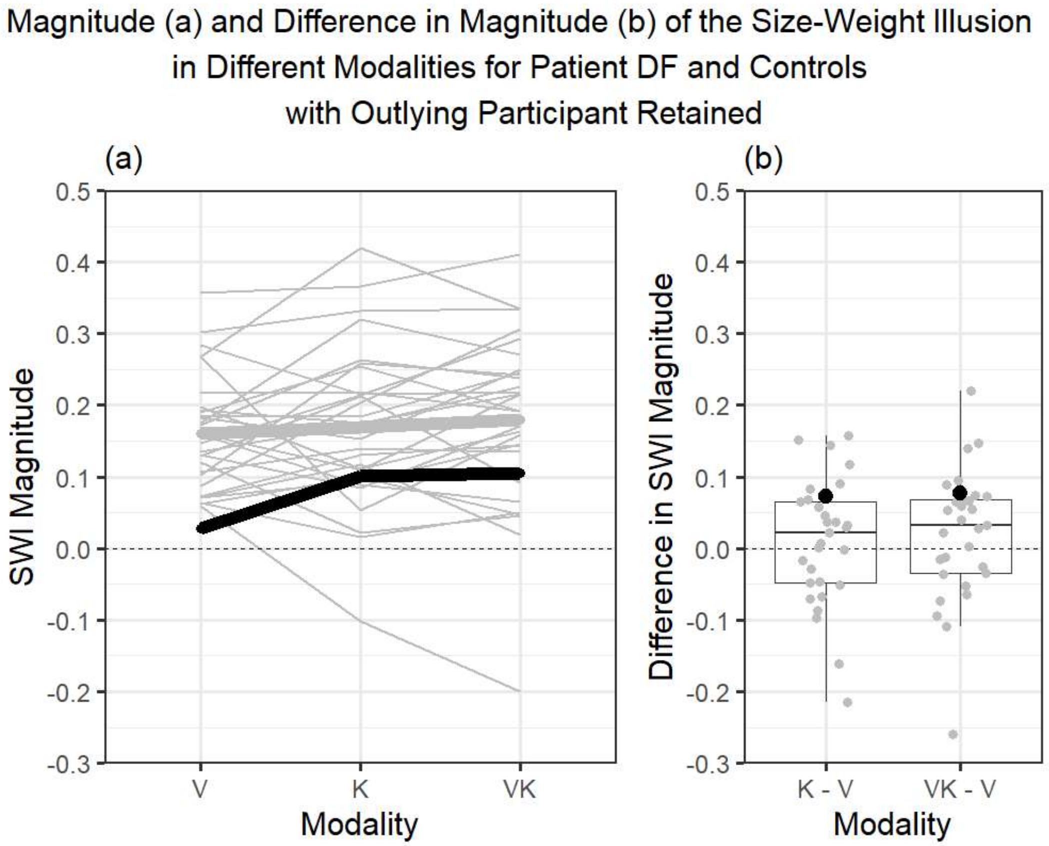

Figure 5. Magnitude (a) and Difference in Magnitude (b) of the size-weight illusion in Different Modalities for Patient DF and Controls. V = Visual, K = Kinaesthetic, VK = Visual-Kinaesthetic. In (a), values above the dashed line indicate participants experiencing a size-weight illusion, with larger values indicating a higher magnitude size-weight illusion. Each individuals' size-weight illusion is represented by thin grey lines, with the thick grey line representing the mean in the controls. DF's size-weight illusion data is represented by the thick black line. In (b), values above the line indicate that the size-weight illusion was smaller in the visual modality, with values below the line indicating that the size-weight illusion was larger in the visual modality. Box plots represent the control data: upper and lower whiskers (vertical lines) extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with median shown as the middle line. Black circles show the size-weight illusion for each control participant, with the larger blue circle showing DF's size-weight illusion.

Hypothesis 1 was tested using a one-tailed Crawford and Howell's (1998) modified t-test. This found no significant difference in the visual size-weight illusion between patient DF and controls, t (29) = -1.65, p = .055, z_{cc} = -1.68 [95% CI: -2.247, -1.107], estimated percentage of control population falling below case's scores = 5.45% [1.23%, 13.41%]. Patient DF's visual size-weight illusion was not significantly smaller than that of healthy controls.

Hypothesis 2 was tested using a using a test of simple dissociation (McIntosh, 2018), based upon the Revised Standardised Difference Test of Crawford and Garthwaite (2005). This analysis found no significant difference between patient DF and controls, t (28) = 1.153, p = .13, z_{dcc} = -1.209 [95% BCI: -1.843, -0.615], estimated percentage of control population with a more extreme difference between modalities than the case = 12.94%. Patient DF did not show a significant dissociation between the visual size-weight illusion and kinaesthetic size-weight illusion in comparison with controls.