Equal-magnitude size-weight illusions experienced within and between object categories

Gavin Buckingham[1], Melvyn A. Goodale[2], Justin A. White[3], & David A. Westwood[3]

1. Department of Psychology, School of Life Sciences, Heriot-Watt University, UK

2. The Brain and Mind Institute, Department of Psychology, The University of Western Ontario, Canada

3. Division of Kinesiology, Dalhousie University, Canada

Corresponding Author:

Gavin Buckingham

Heriot-Watt University

Edinburgh, UK

EH14 4AS

Email: g.buckingham@hw.ac.uk

Phone: +441314513643

In the size-weight illusion, small objects feel heavier than larger objects of the same mass. This effect is typically thought to be a consequence of the lifter's expectation that the large object will outweigh the small object, because objects of the same type typically get heavier as they get larger. Here, we show that this perceptual effect can occur across object category, where there are no strong expectations about the correspondence between size and mass. One group of participants lifted same-coloured large and small cubes with the same mass as one another, while another group lifted differently-coloured large and small cubes with the same mass as one another. The group who lifted the same-coloured cubes experienced a robust SWI and initially lifted the large object with more force than the small object. By contrast, the group who lifted the different-coloured objects did so with equal initial forces on the first trial, but experienced just as strong an illusion as those who lifted the same-coloured objects. These results demonstrate that colour cues can selectively influence the application of fingertip force rates while not impacting at all upon the lifter's perception of object weight, highlighting a stark dissociation in how prior information affects perception and action.

Keywords: Object lifting, colour, prior information

The perception of object weight has a long history of study (Weber, Ross, & Murray, 1996). In the past century, however, it has been established that one's experience of how heavy something feels is far from veridical. For example, individuals will consistently have their perception of object weight biased by irrelevant properties, such as object size. This effect is known as the 'size-weight illusion' (SWI), and manifests as the consistent percept that large objects feel lighter than smaller objects of the same mass (Charpentier, 1891). Although the full-strength SWI requires haptic feedback of object size, a robust illusion can be experienced with visual cues alone (Ellis & Lederman, 1993). This effect has been demonstrated in a diverse range of individuals, from those with brain injury (Buckingham, Bieńkiewicz, Rohrbach, & Hermsdörfer, in press; Li, Randerath, Goldenberg, & Hermsdörfer, 2011) to individuals with sensory deficits (Buckingham, Milne, Byrne, & Goodale, 2015; Ellis & Lederman, 1993) to young children (Pick & Pick, 1967).

Because the SWI is so powerful and ubiquitous, numerous studies over the past century have attempted to shed light on the evolutionary underpinnings and the physiological mechanisms behind this effect. Initially, it was presumed that the illusion has a sensorimotor origin, with the perception of object weight reflecting a mismatch between the expected and actual force requirements of lifting the differently-sized objects (Davis & Roberts, 1976). However, a landmark study by Flanagan & Beltzner (2000) rendered this explanation untenable. When examining fingertip force rates applied to SWI-inducing objects on a trial-by-trial basis, they noted that, although participants did grip and lift the large objects with a higher rate of force than they used with the small object on the first trial, these expectation-driven 'errors' were rapidly corrected. Yet, in spite of the rapid adaptation of the fingertip forces, the magnitude of the perceptual illusion remained unchanged, suggesting that SWI must be independent from sensorimotor prediction. This finding led the authors to suggest that, in contrast to the rapidly-adapting 'expectations' which underpin sensorimotor prediction, the SWI must reflect stable and long lasting cognitive/perceptual expectations. Although both sensorimotor and cognitive priors appear to be derived from the strong positive correlation between the size and volume of objects we encounter in our environment, their different rates of adaptation suggest they must be independent from one another. Perhaps the strongest support to date for the role of cognitive priors as a causal mechanism underpinning the SWI comes from a follow-up study by Flanagan et al. (2008). In their study, the authors allowed groups of individuals to interact with a range of object which had an inverted density (i.e., where the large objects were less heavy than the small objects), prior to lifting identically-weighted objects of difference sizes. Groups who received a moderate amount of experience with these inverse-density objects experienced a smaller SWI than individuals who did not experience these inverse objects. And, most tellingly, groups who experienced the inverse-density objects thousands of times over the course of multiple days experienced an inverted SWI – reporting that the small object felt less heavy than the large, identically-weighted object.

This ‘cognitive/perceptual expectation’ explanation for the SWI has been challenged by scientists who have proposed instead that the illusion reflects the detection of a more ecologically relevant property than mass such as density (Grandy & Westwood, 2006; Ross & Di Lollo, 1970), inertia tensor (Amazeen & Turvey, 1996; Oberle & Amazeen, 2003; Wagman, Zimmerman, & Sorric, 2007), or throwability (Zhu & Bingham, 2011; Zhu, Shockley, Riley, Tolston, & Bingham, 2013). Nevertheless, a growing body of work suggests that prior expectations must influence weight perception to some degree. Strong evidence for the role of cognitive/perceptual expectations in weight perception comes from a range of other weight illusions which are induced without variations in object size. The most famous of these is the ‘material-weight illusion’, where objects which appear to be made from a low-density material (e.g., polystyrene) feel heavier than identically-weighted objects which appear to be made from metal or other high-density materials (Buckingham, Cant, & Goodale, 2009; Buckingham, Ranger, & Goodale, 2011; Ellis & Lederman, 1999; Seashore, 1899). Perhaps the clearest demonstration of a top-down weight illusion comes from Ellis and Lederman (1998), who had expert golfers and non-golfers compare the weight of practice and real golf balls which had been adjusted to weigh the same amount as one another. The expert golfers, who had clear prior expectations that the practice golf ball should be lighter than the real golf ball, experienced that the practice ball felt heavier than the real ball. By contrast, the non-golfer group, who had no prior expectations relating to the practice and real golf balls, experienced no weight illusion whatsoever, reporting that the balls felt the same weight as one another. Direct support for the role of prior expectations in the SWI comes from a study showing that the SWI can be induced in a single object. Buckingham and Goodale (2010a) had blindfolded participants lift and judge the weight of a single, unchanging, object over multiple trials, while varying the size of the object they saw in a brief preview period before each lift. When participants saw a large object, they reported that the lifted object felt lighter than it did when they saw a small object prior to the lift – experiencing a robust SWI in a situation where only their expectations were manipulated from trial to trial.

Although it seems reasonably uncontentious that long-held prior expectations can influence weight perception in the context of the MWI, it is far from clear what body of information the SWI-inducing prior is drawn from. For one, given that the objects lifted in typical SWI paradigms often are made from materials which do not give a clear indication of their density (e.g., plastic), one tacit assumption is that the SWI stems from recent experiences with the other stimuli in the set. For example, the smallest object of a set will feel comparatively heavy because of participants’ experiences with the larger object lifted on earlier trials. By contrast, in the MWI and other such paradigms, participants are unlikely to be experiencing a comparison to earlier lifts, but to their long-held ideas of how much a particular material should weigh. Of course, in the real world, both of these types of prior expectations are likely to both play a role in how heavy an object feels, as an object's density will govern how its mass relates to size. Given that it takes a substantial amount of perceptual learning to alter the magnitude of the SWI, Flanagan et al. (2008) suggest that the perceptual effect reflects slowly-adapting priors which are based on entire families of objects (e.g., all objects of a particular type, which are likely to have approximately the same density, such as all types of books). In other words, the SWI may reflect the way in which our perceptual system flags objects which have a particularly high or low density for their type. This suggestion is appealing on several grounds, not least that such a mechanism would have a clear ecological purpose such as signalling that a particular fruit might not yet be ripe or that a wooden log might be too wet to use as firewood. However, recent findings have questioned this hypothesis.

Buckingham and Goodale (2013) had participants lift and judge the weight of large and small cubes which appeared to be made from different materials (metal and polystyrene), but which had all been adjusted to weigh the same amount as one another. The prediction was that, if the SWI reflected deviations from the usual size-weight mappings of different families of objects, the more dense-looking stimuli should induce a stronger SWI because participants would expect the large metal cube object to far outweigh the small metal cube. By contrast, the objects which appeared to be made from a low-density material should induce a far smaller illusion, because participants would expect the large polystyrene cube to outweigh its small counterpart by only a few grams. Surprisingly, however, participants' expectations of heaviness for the small and large exemplars of each material were unrelated to their subsequent perceptions of heaviness; both the metal and the polystyrene cubes induced robust weight illusions in both conditions, which were of equal magnitude to one another. In other words, the SWI experienced for one type of object was invariant, and not specific to that category of object, suggesting that the illusion reflected a contrast with a more general, broader, prior expectation. The Buckingham and Goodale (2013) study, however, cannot offer a complete rejection of the proposal that the SWI reflects a contrast to the lifter's prior expectations. For one thing, even though participants had clear prior expectations about how heavy each object would be, it is not clear whether the prior expectations for each material were of equal reliability (if, for example, one type of material is assumed to be hollow more often than the other). Furthermore, all the participants lifted each type of object multiple times in the same session, which may have biased the perceptual ratings given on each trial toward the mean.

To examine how prior information influences weight perception in a more controlled manner, and to gain insight into exactly what visual cues are diagnostic of objects being within the same category or family as one another, we tested separate groups of participants on a SWI task. One group performed a traditional SWI task – lifting and judging the weight of large and small cubes with identical mass which were the same colour as one another. Participants in this group would presumably expect the objects to be from the same family (i.e., have the same density) and, after lifting the small cube should form strong expectations that the large cube will be heavier. A second group also lifted similar identical-mass cubes, but here the large cube was a different colour from the small cube. If simple colour cues are sufficient to distinguish one object as being categorically different from another object, it is likely that individuals in this latter group would have no reason to expect the objects to have the same density as one another and should have no reason to assume that the large cube will be heavier than the recently-lifted small cube (at least, not to the same degree as individuals lifting objects of the same colour). Thus, if short-term expectations which are specific to a particular type of object do play a causal role in the SWI, people lifting objects which differ in size and colour should experience a smaller SWI and show less-robust sensorimotor prediction than when lifting objects which vary only in their size. If, however, differences in colour between differently-sized, otherwise similar-looking objects are not cues utilized by the perceptual or sensorimotor systems to distinguish between object categories, then we would expect both groups to show similar weight illusions and fingertip force scaling.

Method

Participants

We recruited a total of 72 participants (23 male, 49 female; mean age = 19.9 years +/- 1.9) for the experiment, and randomly assigned 36 to a Same-Colour stimulus group (hereafter 'Same') and 36 to a Different-Colour group (hereafter 'Different'). Most participants were self-reported right handers (64 versus 8), and all were screened against a history of neurological or motor disturbances. Participants all had normal or corrected-to-normal vision. All participants gave informed consent to participate in the study, and all procedures were approved by the Dalhousie University Research Ethics Board.

Materials

Four wooden cubes were created for this experiment, two large (9.3 cm x 9.3 cm x 9.3 cm) and two small (7.4 cm x 7.4 cm x 7.4 cm), all having a mass of 400g (Figure 1A). Densities were 0.5 g/cm^3 for the large cube and 1.0 g/cm^3 for the small cube. One cube of each size was painted red and one cube of each size was painted yellow. A force-torque transducer (Nano 17, ATI Industrial Automation) with a moveable harness was mounted to the top of each object (Figure 1B), and participants used their preferred hand to lift the objects with a precision grip.

Figure 1 (A) The identically-weighted large and small cubes lifted in this study. Participants in the Same group lifted large and small cubes of the same colour, whereas participants in the Different group lifted large and small cubes which had different colours from one another. (B)

Procedure

For individuals in the Same group, the large and small test cubes were the same colour. For half of the individuals, both objects were yellow, whereas for the other half of the individuals, both objects were red. Individuals in the Different group lifted objects which were different colours. For half of the individuals in this group, the small object was yellow and the large one was red, whereas for the other half, the small object was red and the large one was yellow. With their preferred hand, participants lifted the small object followed by the large object, repeating the alternating sequence for a total of 30 lifts. The participants were instructed to use a quick ‘hefting’ motion to lift the objects rather than a slow and careful lifting action, to ensure that the measured lifting forces accurately reflected their expectations about object mass. After each lift participants were asked to rate the perceived heaviness of the object using a ten point rating scale where 1 was a very light object and 10 was a very heavy object.

Data reduction and analysis

Grip forces (the forces normal to the surface of the handle) and load forces (the forces tangential to the surface of the handle) were recorded at 200 Hz and analysed offline using custom software. These force traces were filtered using a second-order, dual-pass Butterworth filter with a low-pass cut-off of 14 Hz differentiated with a 5-point central difference equation to yield grip force rate (GFR) and load force rate (LFR). As fingertip force rates have been shown to rapidly adapt over repeated trials, the peak values of the grip and load force rates on the first lift of each cube were taken as an index of sensorimotor prediction (Buckingham & Goodale, 2013). First, separate 2 × 2 mixed-design ANOVAs (within-subject factor: size, between-subject factor: group) were conducted to examine the effect of object size on fingertip forces and perceptions of heaviness. Then, to compare these respective effects across groups, the difference between the initial force rate used to lift the large and small cubes (hereafter referred to as 'sensorimotor prediction') was compared between the Same and Different groups with an independent samples t-test. By contrast, as the perceptual SWI is stable and unchanging, we compared the average ratings given to each cube as an index of the SWI. As with the grip force rates, the small-large cube difference score was compared across the Same and Different groups with an independent samples t-test.

Results

A preliminary examination of the grip and load force rates for the lifts of both objects across trials showed that, in terms of GFR, the Same group (Figure 2A) showed the 'classic' pattern of data, with divergent force rates used to grip the large and small objects on early trials, followed by a rapid period of adaptation over the course of several trials (Buckingham & Goodale, 2010b; Flanagan & Beltzner, 2000). By contrast, participants in the Different group appeared to be unaffected by size cues on early trials, or across the entire experiment (Figure 2B). Neither group showed an effect of object size in terms of their LFRs (Figures 2C & 2D). Prior to the statistical analysis, we removed four participants as outliers for having GFR difference scores which were greater than two standard deviations above or below the mean. Thus, the final analyses were performed on 68 participants (34 in the Same group, 34 in the Different group).

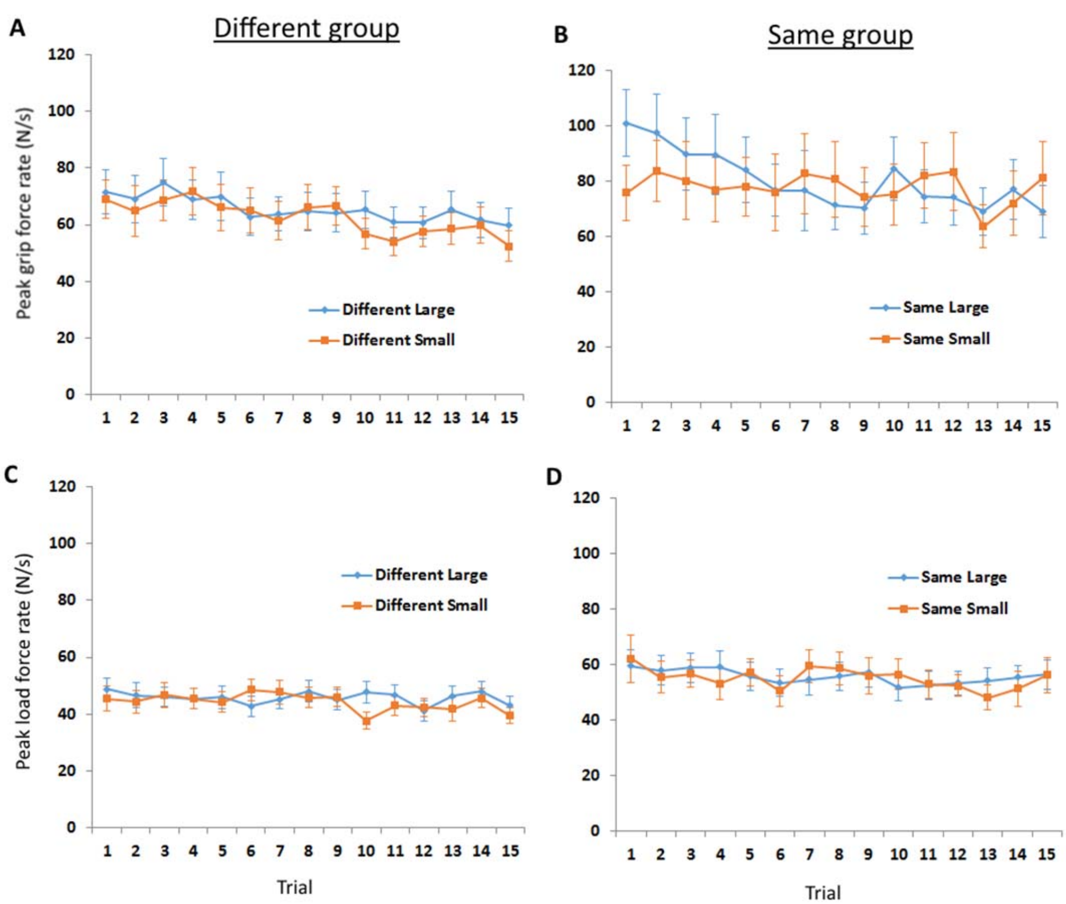

Figure 2. Grip force rates for the same (A) and different (B) groups, and load force rates for the Same (C) and different (D) groups plotted across all trials. Error bars indicate standard error of the mean.

Due to a range of studies showing that colour and luminance can influence how heavy an object feels (Alexander & Shansky, 1976; Walker, Francis, & Walker, 2010; Warden & Flynn, 1926), we first examined our implicit assumption that the colour of the object being lifted (i.e., independent from group) did not influence individuals' perceptions of heaviness. Indeed, when averaging across the Same and Different groups and comparing the different colours with independent samples t tests, we found no influence of colour on the perceived heaviness of the small objects ($t(64) = 0.39$, $p=.83$) or the large objects ($t(64) = 0.75$, $p=.46$). For the rest of the analysis we collapse across the colour groupings.

The omnibus analysis examining the effects of group and object size on the perceptual ratings of heaviness highlighted a main effect of size ($F(1,64) = 145.95$, $p<.001$). Post hoc analyses showed that subjects in the Same group reported that the small object felt heavier than the large object ($t(32) = 8.7$, $p<.001$). Interestingly, subjects in the Different group also reported that the small object felt heavier than the large object ($t(32) = 8.4$, $p<.001$). No interaction was observed between size and group ($F(1,64) = 0.01$, $p=.91$), suggesting that individuals in the Same and Different group experienced weight illusions of similar magnitudes (Figure 3A & 3B).

With the omnibus analysis for the first-trial GFR, we observed a main effect of size ($F(1,64) = 12.6$, $p<.005$). Post hoc analyses showed that subjects in the Same group applied significantly more force to the large objects than the small objects ($t(32) = 3.9$, $p<.001$), whereas subjects in the Different group applied similar force to the large and small objects ($t(32) = 0.59$, $p=.56$). Critically, a significant interaction between size and group was observed ($F(1,64) = 8.2$, $p<.01$), indicating that participants in the Same group had their GFRs influenced by object size to a greater degree than participants in the Different group (Figure 3C & 3D).

In terms of first-trial LFR, we observed no main effect of object size ($F(1,64) = 0.05$, $p=.95$), indicating that, on average, size did not influence how individuals lifted the objects (Figure 3E & 3F). This indication was confirmed by the lack of an interaction between size and group ($F(1,64) = 1.3$, $p=.25$).

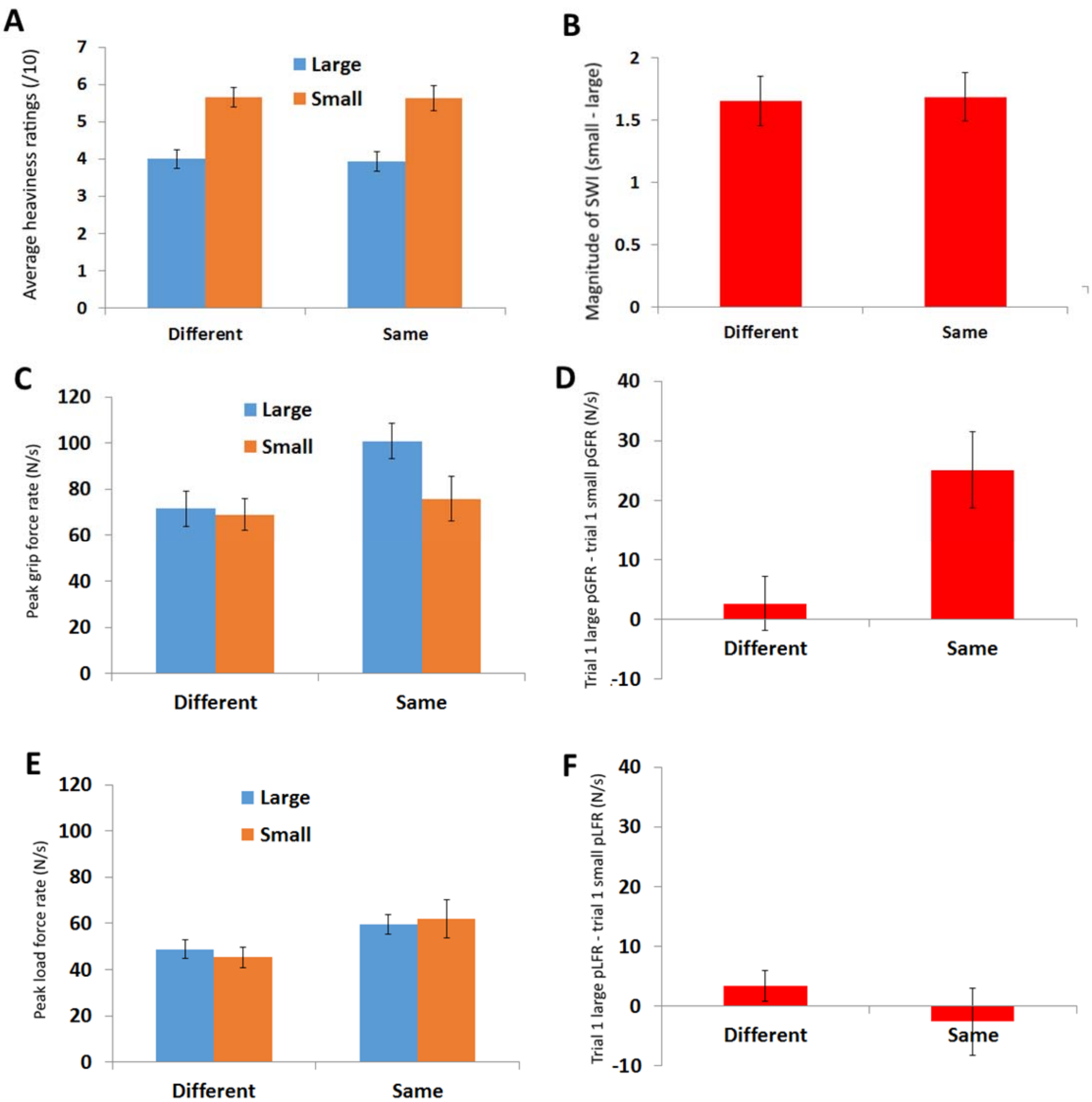

Figure 3 (A) the average rating of heaviness given by subjects in each group for each object and (B) the difference between the ratings given to the large and small objects (i.e., the magnitude of the perceptual illusion) compared across the groups. (C) the peak GFR and (E) the peak LFR applied by subjects in each group on their first lift of each object and (D) the difference between GFR and (F) LFR applied to the large and small objects (i.e., the magnitude of the effect of object size on sensorimotor prediction) compared across the groups. Error bars indicate standard error of the mean.

Discussion

In the SWI, people judge small objects as feeling heavier than large objects. This effect is thought to come about because participants expect the large objects to outweigh the small objects, due to the positive correlation between size and volume in objects outside of the lab. Of course, this correlation between object volume and object mass is strongest within objects of the same category (e.g., which appear to be made from the same material as one another). Thus, large and small objects which have similar visual features as one another should invoke stronger expectations of heaviness, and thus elicit a far more robust weight illusion than large and small objects which look dissimilar. To test this hypothesis, we examined perceptions of heaviness and sensorimotor prediction in two groups of individuals. One group lifted identically-weighted large and small cubes which were the same colour (i.e., objects from the same category), whereas the other group lifted identically-weighted large and small cubes which differed in colour from one another (i.e., appeared to be from different families of objects). Subjects lifting the same-coloured objects showed a clear influences of object size of sensorimotor prediction (i.e., lifted the large object at higher rate of force than the small object) and perception of heaviness (i.e., experienced a robust SWI). By contrast, subjects who lifted the different-coloured objects showed a different pattern of behaviour. Because they had no reason to assume the large object would outweigh the small object, they initially lifted the objects with similar rates of force, presumably reflecting the tendency to apply forces in line with previous lifts when no salient cues to object weight are available (Chouinard, Leonard, & Paus, 2005; Loh, Kirsch, Rothwell, Lemon, & Davare, 2010). Interestingly, in spite of their failure to integrate size cues into their initial grip and lift behaviour, this group also experienced a robust SWI. Indeed, the magnitude of the SWI when lifting across category was almost identical to the SWI experienced when lifting within category.

The current work provides further support for the well-established dissociation between sensorimotor prediction and perceptions of heaviness (Buckingham, 2014; Nowak, Glasauer, & Hermsdörfer, 2013). Although several studies have shown that fingertip force rates and perception of heaviness adapt at independent rates from one another (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006), it has been difficult to rule out the possibility that the sensorimotor mismatch during initial lifts could cause a long-lasting perceptual illusion. Participants in a study by Chang and colleagues did experience a robust SWI without fingertip force errors when lifting objects out of their other hand (Chang, Flanagan, & Goodale, 2008), but their task made it difficult to rule out the possibility of a sensorimotor mismatch during the initial placement of each object. Here, participants in the Different group, who lifted SWI-inducing objects which differed in colour, experienced a robust perceptual illusion without a single instance of sensorimotor mismatch, confirming that the SWI cannot be due to fingertip force application. Indeed, the initial grip force rates of the Different group highlights the stark specificity of the sensorimotor system, such that colour cues are sufficient to break this aspect of the sensorimotor system's reliance on volume cues. This surprising level of specificity mirrors findings from motor learning studies where the dynamics of a learned force field impairs the learning rate of a second force field (e.g., Cothros, Wong, & Gribble, 2008). However, these conclusions must be moderated by the failure to find any effect of volume cues on the load force rates of the initial lifts, in either the Same or Different group (Figures 2C & 2D). It is worth noting that the current work is not the first time that different effects have been found in measures related to grip force than load force (e.g., Green, Grierson, Dubrowski, & Carnahan, 2010; Quaney, Rotella, Peterson, & Cole, 2003). We suspect that, in the context of the current work, this discrepancy between grip and load force rates reflects the fact that peak grip force rate is less closely coupled to the actual mass of an object than peak load force rate, making it a less biased index of how heavy an object appears to be. Of course, many other studies do typically find sensorimotor prediction with parameters related to load force, and it is still an open question the degree to which grip and load parameters can be taken as interchangeable measures and under which (if any) circumstances they become uncoupled from one another.

The main goal of the current work was to better understand the cause of the SWI. The findings from this study are consistent with our earlier work showing that apparent material cues do not influence the magnitude of the SWI within individuals (Buckingham & Goodale, 2013). Here we extend those findings by showing directly, for the first time, a full-strength SWI can be induced across object category. The findings from the current work are difficult to reconcile with the idea that the SWI reflects a contrast with size-weight mappings for individual families of objects (Flanagan et al., 2008). Indeed, the findings from the current work offer strong support for direct perception accounts of the SWI, indicating that the identical-magnitude illusion experienced by both groups must stem from a property which is invariant across the groups (e.g., differences in density between the stimuli). However, a significant body of work does highlight an irrefutable causal role for cognitive/perpetual expectations of heaviness accounting for at least a portion of the illusory heaviness difference experienced by those lifting SWI-inducing stimuli (Buckingham & Goodale, 2010a; Flanagan et al., 2008). We suggest that our findings support the idea that the cognitive/perceptual expectations which drive the SWI are not specific to object categories, but broadly generalizable across categories of stimuli (in contrast to the specific, non-generalizable, and rapidly-adapting expectations which must drive sensorimotor prediction when lifting novel objects). Thus, our findings extend beyond the conclusions of Flanagan et al. (2008) to suggest that, rather than the SWI reflecting a deviation from the average size-weight map for a particular family of objects, it instead reflects a deviation from the size-weight map of all objects which one typically interacts with. Put another way, the SWI appears to be the way in which our perceptual system highlights objects which have an unusual density on average, rather than specific to a particular category of objects.

To conclude, the current work confirms that a full-strength SWI can be induced across object category, highlighting the powerful and distinct role that visual size cues have on the human perceptual system. These findings provide further support for the idea that, in contrast to the specificity of human sensorimotor control, human weight perception is influenced by a particularly broad range of prior knowledge.

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