The influence of size in weight illusions is unique relative to other object features

Elizabeth J. Saccone
Philippe A. Chouinard

School of Psychology and Public Health
La Trobe University
Melbourne, Victoria, Australia

10030 words

Correspondence should be sent to:
Dr Elizabeth J. Saccone
School of Psychology and Public Health
La Trobe University
Edwards Road, Flora Hill
Victoria 3552 Australia
Ph: +61 (0) 3 5444 7489
Email: e.saccone@latrobe.edu.au
Abstract
Research into weight illusions provide valuable insight into the functioning of the human perceptual system. Associations between the weight of an object and its other features, such as size, material, density, conceptual information or identity, influence our expectations and perception of weight. Earlier accounts of weight illusions underscore the importance of previous interactions with objects in the formation of these associations. In this review, we propose a theory that the influence of size on weight perception could be driven by innate and phylogenetically older mechanisms and is therefore more deep-seated than other features that influence our perception of an object’s weight. To do so, we first consider the different associations that exist between the weight of an object and its other features and discuss how different object features influence weight perception in different weight illusions. After, we consider the cognitive, neurological, and developmental evidence highlighting the uniqueness of size-weight associations and how they might be reinforced rather than driven by experience alone. In the process, we propose a novel neuroanatomical account of how size might influence weight perception differently than other object features.
Evidence from weight illusions demonstrates that our conscious experience of an object’s weight is variable according to its other features. The influence of size in particular has been well-studied since the size-weight illusion (SWI; Fig. 1a) was first documented over a century ago (Charpentier, 1886, 1891). The tendency of the smaller of two objects of equal mass to feel heavier has been reported many times as researchers have attempted to understand the mechanisms accounting for this compelling illusion (see Buckingham, 2014 for a review). Both visual and somatosensory information about object size have been implicated in the SWI (Buckingham & Goodale, 2010b; Plaisier & Smeets, 2015) and the perceptual experience of the illusion persists in spite of a) the knowledge that the objects have the same mass and b) having learned to apply the correct fingertip forces to match the objects’ veridical weight during lifting (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). Although much remains to be understood about the SWI, and our conscious experience of weight more generally, research in the field has provided valuable insight.

Our review consists of two parts. In the first part, we consider the different associations that exist between an object’s weight and its other features. Research into weight illusions demonstrates that these associations not only underlie expectations of weight but also influence how we perceive weight. We discuss object features that are both associated with weight and implicated in weight illusions, such as size, material, density, concept, and identity. We also review the evidence for current theories explaining weight illusions, including those based on Bayesian frameworks. After reviewing how different object features influence weight perception, and the more current prominent theories, we then proceed to the second part. In this section, we propose a different theory. Namely, we argue that size is more deep-seated to influence weight perception than the other object features reviewed earlier. In the process, we
evaluate the evidence from cognitive, neurophysiological, and developmental research demonstrating how size processing is not entirely mediated by experience-based mechanisms. A novel neuroanatomical account of how size might influence weight perception differently than other object features is proposed.

Fig. 1 The top two panels of the figure show photographs depicting the size-weight (A) and material-weight (B) illusions. In the size-weight illusion, participants lift two objects that differ in size but have the same weight. The smaller one typically feels heavier. In the material-weight illusion, participants lift two objects that differ in apparent material, such as cardboard and brass as shown in the second photograph. The material known to
be less dense, in this case cardboard, typically feels heavier. In some studies, force transducers are used to measure the forces applied during lifting. The bottom panel shows examples of horizontal (grip) and vertical (load) forces applied during lifting in Newtons (N) as a function of time in seconds (s) (C). Experiments measuring both perceived weight and fingertip forces typically demonstrate that the former continues to be different throughout the experiment while the latter becomes more similar after only a couple of trials.

1. **How do we predict and perceive an object’s weight based on their other features?**

Weight illusion research highlights people’s ability to form associations and make use of them. Currently, there is a growing trend to apply Bayesian frameworks to understand a wide array of mental processes (e.g., Geisler & Kersten, 2002; Wolpert, Ghahramani, & Jordan, 1995). Under these frameworks, a prior refers to the outcome of a previous experience, which is then considered in the perceptual analysis of a stimulus or the preparation of an action towards it. To explain, in a given situation, the brain receives sensory information about a stimulus, information that would differ if that stimulus were presented in a different time or place. For example, viewing conditions can vary in terms of lighting as well as orientation and positioning of the stimulus relative to the observer’s eyes. Sensory information will also be processed by the brain in a different manner according to the observer’s intentions, levels of arousal, volition, and the context under which the stimulus is viewed. Thus, the brain rarely, if ever, processes a given stimulus twice in the exact same manner. As such, the brain needs to consider the currently available information by weighing its probability against that which has occurred in previous situations. What is ultimately perceived or carried out in terms of an action,
then, will not reflect a perfect match with the incoming sensory information, but instead will reflect what the brain considers to be the best fit, in line with established associations. With respect to lifting an object, then, we can anticipate its weight based on previous interactions with those or similar objects under similar conditions (Gordon, Westling, Cole, & Johansson, 1993).

**Weight associations and the SWI**

The size of an object is one feature that typically informs the brain about its weight (Buckingham & MacDonald, 2016; Flanagan, Bittner, & Johansson, 2008; Plaisier & Smeets, 2015). Larger objects are often heavier and this is especially true of objects comprising the same material. This expectation is inherently violated in the SWI in that the objects vary in volume but not mass. Expectations based on this typical size-weight association are particularly evident in experiments that record fingertip forces applied during object lifting in the unusual context of the SWI (Buckingham, Ranger, & Goodale, 2011; Chouinard, Large, Chang, & Goodale, 2009; Flanagan & Beltzner, 2000; Flanagan et al., 2008; Grandy & Westwood, 2006) (Fig. 1c). To overcome forces of gravity and lift an object, sufficient force must be applied by the fingers for grasping and by the muscles of the arm for lifting (Johansson & Westling, 1984). Given that an object’s true weight can only be determined after physical displacement, feedforward mechanisms are required to lift objects ballistically, which must rely on known associations between object weight and its other features (Johansson & Westling, 1984). Associations between size and weight are thought to be reinforced during our lifetime given that size often serves as a reliable cue about an object’s weight.

Apparent size is an important driver for the SWI (Buckingham & Goodale, 2013; Buckingham & MacDonald, 2016). To illustrate, in their experiment, Buckingham and
Goodale (2010b) asked participants to lift one object per trial. Before each trial, participants were presented with a small, medium, or large cube. Participants then had their vision occluded and were asked to lift the cube using a handle attached to the object. Rather than the cube they had just viewed, participants unknowingly lifted the medium cube on every trial. They reported the typical SWI perceptual experience as though they had lifted the previewed small or large cube. In other words, it was the apparent size, based on the cube they had seen prior to lifting, rather than the actual size of the cube, that produced the SWI. This finding is particularly remarkable in that the participants conceivably received kinaesthetic information about the cubes' true size from the torques applied during lifting. Nonetheless, their expectations of weight, based on the size of the previewed stimuli, seemed to override the kinaesthetic input from influencing perceived weight.

SWI stimuli differ not only in size but also in density. By definition, the smaller of two objects of equal mass also has a higher density. Accordingly, researchers have considered the role of density in the SWI (Chouinard et al., 2009; Harshfield & DeHardt, 1970; Peters, Ma, & Shams, 2016; Ross & Gregory, 1970; Wolf, Bergmann Tiest, & Drewing, 2018). For example, Chouinard et al. (2009) demonstrated with functional magnetic resonance imaging (fMRI) that brain areas implicated in processing an object's density are also implicated in the SWI. However, the precise way in which density contributes to the SWI remains unclear. We offer two possible explanations that are not necessarily mutually exclusive. For the first one, it is important to note that density differences between two stimuli in a typical SWI experiment are not expected before lifting but rather inferred after lift-off. Hence, it is reasonable to expect that two objects that look identical except for their size would have the same density. Consequently, the unexpectedness of this unusual scenario that the participant only begins realising during
the lift might cause them to perceive the smaller one as heavier and the larger one as lighter. Alternatively, the association between density and weight is such that lifting a denser object will cause one to perceive that object as heavy because denser objects are typically heavier.

Examples of weight associations from other weight illusions

Aside from the SWI, evidence from other weight illusions demonstrate that conceptual features can also be associated with object weight, which in turn can influence weight perception. Ellis and Lederman (1998) demonstrated this effect by having experienced golfers and non-golfers judge the weight of real and practice golf balls. The critical point here is that practice golf balls are lighter than real ones, despite their near-identical appearance – a fact known by experienced golfers but not non-golfers. In this experiment, the two groups of participants judged the weight of balls that appeared to be either practice or real golf balls, although in reality the two sets of balls had the same mass. The experienced golfers, who expected the practice balls to be lighter, perceived them as heavier. However, the non-golfers, who did not expect a weight difference between the two sets of golf balls, did not perceive a difference in weight.

Another example of how conceptual knowledge can influence weight expectations is provided by the material-weight illusion (MWI; Fig. 1b) (Buckingham, Cant, & Goodale, 2009; Ellis & Lederman, 1999; Seashore, 1899; Wolfe, 1898). In the MWI, people lift two objects of the same mass and volume that appear to be made from different materials, such as styrofoam and brass. As the objects are the same size, there is an expectation that the brass object will be heavier than the styrofoam one, based on a conceptual understanding of the density of these materials. Instead, the styrofoam object is typically reported as being the heavier of the two (Baugh, Kao, Johansson, & Flanagan, 2012;
The evidence reviewed above demonstrates that associations between weight and other stimulus properties can influence both expected and perceived weight. However, the
precise mechanisms by which these expectations produce illusory weight experiences remains unknown. A number of detailed theories have been proposed with little resolution of this issue (for reviews, see Buckingham, 2014; Dijker, 2014). Some of these theories will be reviewed below.

For a time, one of the leading theories was the sensorimotor-mismatch theory (Davis & Roberts, 1976; Gregory, 1968; Müller & Schumann, 1889; for a review see Buckingham, 2014). It was typically used to explain the SWI but similar logic could apply to all other weight illusions in which there is an expectation for one stimulus to be heavier than the other. To explain, when lifting two SWI objects, people apply more force for the larger one than they would for the smaller one, resulting in too great a force for the former and too little for the latter. It was thought that the sensation of applying too much or too little force caused the objects to feel lighter or heavier, respectively.

However, more recent experiments have demonstrated that although forces are misapplied in the initial trials, the motor system quickly learns to apply more accurate forces for each object after only a few trials while the perceptual experience of the SWI endures (Buckingham & Goodale, 2010b; Buckingham et al., 2011; Chouinard et al., 2009; Flanagan & Beltzner, 2000; Flanagan et al., 2008; Grandy & Westwood, 2006). For example, in the first paper to demonstrate this motor adaptation, Flanagan and Beltzner (2000) compared maximum rates of grip (horizontal) and load (vertical) force, and lift-off times for the small and large objects. They divided the 20 lifting trials into 4 blocks of 5 lifts for the purpose of analysis. In the first block, participants exhibited greater maximum rate of grip and load force application for the large object compared to the small one. Lift-off times were also shorter for the large one. By the second block, the maximum grip force rate was still greater for the large object but the maximum load force rates and lift-off times were not statistically different between the two objects. For the
third and fourth blocks, there were no statistical differences between the two objects for these three variables yet differences in perceived weight remained as strong as in the initial lifts. These findings demonstrate the co-existence of a) a more veridical understanding of weight by the motor system and b) the perceptual experience of a weight difference that remains consistent. These findings create a problem for the sensorimotor-mismatch theory, which proposes that the misapplication of forces during lifting drives the change in weight perception. If this were true then people should no longer experience the illusion when they apply lifting forces that match their true weight – which the aforementioned studies demonstrate is not the case.

However, we think the sensorimotor mismatch theory may still have some merit despite the above studies suggesting otherwise. Even though the motor system becomes more veridical in applying appropriate forces, it is still possible that there remains tiny misapplications of forces that are too subtle to measure but can still influence weight perception. As Dijker (2014) points out, measuring the forces applied during lifting typically includes several dependent variables (e.g., maximum grip and load forces, the maximum rate of grip and load forces, lift-off time). In some cases, not all of them show the same degree of change in adaptation over time. For example, Buckingham and Goodale (2010a) reported the typical pattern of sensorimotor adaptation over the course of their SWI experiment with respect to maximum grip force, grip force rates and load force rates. However, participants consistently applied a greater maximum load force for the large object compared to the small one for the majority of trials while the other measurements adapted more quickly. Thus, on balance, the sensorimotor mismatch theory should not be dismissed outright but nor should it be construed as the sole explanation for the SWI given that substantial motor adaptation does occur. Other factors must contribute to the perceptual illusion.
A more recent consideration is whether or not the SWI and other weight illusions fit into a Bayesian framework. This consideration appears to be mixed for the SWI and not applicable for other weight illusions. Some authors describe the SWI as anti-Bayesian (Brayanov & Smith, 2010; Ernst, 2009) according to the following logic. Smaller objects have a higher probability to weigh less than larger ones in the real world. It then follows under a Bayesian framework that the smaller of two objects that have the same mass should be perceived as lighter – which is the opposite to what people experience in the SWI. On the other hand, the SWI can be explained well within a Bayesian framework if one considers density instead of size as the determinant (Chouinard et al., 2009; Harshfield & DeHardt, 1970; Peters et al., 2016; Ross & Gregory, 1970). As denser objects are typically heavier in the real world, and the smaller object in the SWI inherently has a higher density, a Bayesian framework predicts that the smaller object should be perceived as heavier – which is precisely what people experience in the SWI.

However, Bayesian frameworks do not seem to explain other weight illusions at all. That is, regardless of which object feature that is varied within the illusion (e.g., material, concept, identity), perceived weight is typically the opposite of what is expected based on the relevant feature-weight association. For example, brass is heavier than styrofoam in the real world. Yet, in the context of the MWI, people typically perceive the former as lighter. Therefore, the MWI is arguably anti-Bayesian. The same can likewise be said for Ellis and Lederman's (1998) golf ball illusion. Practice golf balls are typically lighter than real ones yet the former are perceived as heavier when both are adjusted to have the same mass. Taken together, Bayesian frameworks do not seem to explain the SWI and other weight illusions to the same extent as other perceptual phenomena (Friston, 2005; Gregory, 1980; Helmholtz, 1867).
Other alternative accounts of the SWI are based on the influence of third party processing. To explain, these accounts posit that the processing of some other feature is translated perceptually as weight (Amazeen & Turvey, 1996; Ross & Di Lollo, 1970; Stevens & Rubin, 1970). Some of these accounts draw from Gibson's (1979) ecological view that we perceive object attributes in terms of their action-relevance (affordances) rather than their physical properties such as mass.

To illustrate the influence of affordances on weight perception, Amazeen and Turvey (1996) had participants rate the heaviness of long rods that had weights attached at different locations. Thus, a set of stimuli was consistent in both mass and overall volume but the distribution of mass varied across the objects. Critically, in varying the mass distribution, the rotational inertia of the rods also varied as they were held and manipulated by the participants. The results demonstrated that the distribution of mass within an object was a stronger predictor of perceived weight than mass per se. Amazeen and Turvey (1996) argued that when their rods were wielded, the critical, action-relevant variable influencing weight perception was rotational inertia, rather than mass (see Plaisier and Smeets (2015) and Zhu, Shockley, Riley, Tolston, and Bingham (2013) for results that are inconsistent with this proposal). In a similar manner, Zhu and Bingham (2011) demonstrated a tight coupling between the SWI and the perception of throwability of hand-held objects. From these results, the authors speculated that weight perception was ultimately a by-product of an innate mechanism that was necessary for our pre-historic ancestors to quickly select rocks and sticks as weapons to attack and defend themselves.
2. **Size as a unique, weight-associated object feature**

Much of the research reviewed above centres on the SWI. After all, the SWI was the first documented weight illusion and has been the most studied of all the weight illusions. One potential reason for it receiving so much attention is that it seems to be an especially strong and reliable illusion – the illusory weight experience persists even in spite of knowledge that the test objects have the same mass (Flanagan & Beltzner, 2000). In the following section, we evaluate the evidence that size exerts a particularly strong influence on weight perception. We also introduce a novel neuroanatomical account of how size could have a stronger propensity to influence weight perception over other object features because of its dependence on neural pathways that are phylogenetically older. To further support our theory, we provide a detailed review of the developmental research of the SWI in young children, which, when considered thoroughly, sheds light into the innate versus acquired nature of the SWI.

*Size exerts a strong influence on weight expectations and perception*

There is evidence to suggest that size is especially powerful and dominant in predicting perceived weight and that its influence can even override the influence of other object features. Plaisier and Smeets (2015) investigated the SWI using two objects that differed in overall size but appeared to contain the same volume of material (Fig. 2). One stimulus appeared to be a solid rectangular prism whereas the other comprised the same amount of material except that it was divided into two halves and attached to either end of a cylindrical bar. The overall size of the divided object was greater than the solid one. Although participants could see that the two objects contained the same volume of material, they perceived the smaller, solid looking one as heavier, in line with the SWI.
One consideration here is that perhaps we are less skilled at making a weight judgement of unusual or more complex objects, such as in the case of the divided object in this experiment. Regardless, though, Plaisier and Smeets’ finding demonstrates that size cues can overwrite other information that can and should inform on object’s weight, such as volume.

![Figure 2](image)

**Fig. 2** Depiction of the stimuli employed in Plaisier and Smeets (2015). Although their participants could see that the two objects contained the same volume of material, they perceived the smaller, solid looking object as heavier than the larger, spacer object, which is in line with the SWI.

Buckingham and colleagues (Buckingham & Goodale, 2013; Buckingham, Goodale, White, & Westwood, 2016) have also produced findings consistent with this idea. Buckingham and Goodale (2013) had participants lift two sets of SWI stimuli (i.e., small and large cubes of equal mass) that were identical except that one set appeared to be made from polystyrene and the other aluminium. Before lifting, participants reported the expectation that both of the large cubes would be heavier than their small counterparts. They also expected a larger difference between the small and large aluminium cubes than the polystyrene set, presumably owing to the known density of these materials. Despite these expectations, and the relevant material-weight associations, participants reported a SWI of remarkable consistency for both sets of stimuli. Accordingly, Buckingham and Goodale (2013) argued that size cues must be particularly influential or dominant in their
effect on weight perception. These authors documented a similar finding with different
sets of SWI stimuli that varied in colour rather than material (Buckingham, Goodale, et
al., 2016). Here they used colour to denote object families and had participants lift two
SWI objects that were either the same or different colours. The authors predicted a
stronger SWI for objects of the same colour for which there should be an expectation by
the participants that both would have the same density and that the larger should be
heavier. However, the SWI was once again remarkably consistent, regardless of whether
participants lifted stimuli within or across object families.

Buckingham and MacDonald (2016) have provided further evidence that size is
uniquely placed to influence the perceptual experience of weight. Although the SWI is
thought to somehow reflect a violation of the expectation that larger objects are heavier,
Buckingham and MacDonald demonstrated that size cues can elicit a SWI even when
there is reason to expect the smaller object to be heavier. Participants were asked to lift
and rate the heaviness of familiar objects that varied in volume but were similar in mass.
As depicted in Fig. 3, these included a golf ball (45g), a toy soccer ball (52g), and a beach
ball (52g). Before lifting, they reported expecting the golf ball to be the heaviest, followed
by the soccer ball, and then the beach ball. After lifting, their heaviness ratings were
consistent with their expectations, reporting the golf ball as the heaviest and the beach
ball as the lightest. Their perception of weight reflected a typical SWI, even though
participants had reported expectations that were inconsistent with the typical size-
weight association. One consideration with respect to this experiment is that participants
received direct haptic feedback of the objects’ size from lifting them without the use of
handles. It is possible that hefting the objects directly resulted in an especially strong
influence of somatosensory size cues on perception given that past research suggests that
haptic feedback of size has a strong influence on the illusion (Ellis & Lederman, 1993);
but also see results from Buckingham and Goodale (2010b) which contradict this view). Regardless, Buckingham and MacDonald's (2016) study demonstrates the dominant influence that size can have on weight perception.

![Fig. 3 Depiction of Buckingham and MacDonald's (2016) stimuli: a golf ball (weight 45g, diameter 4.3cm), toy soccer ball (weight 52gm, diameter 8.6cm) and beach ball (weight 52g, diameter 27.5cm). Participants reported expecting the golf ball to be the heaviest, followed by the soccer ball, and then the beach ball before lifting the objects. After lifting, their heaviness ratings were consistent with their expectations, reporting the golf ball as the heaviest and the beach ball as the lightest. However, the true weight of the golf ball was in fact lighter than the beach ball.](image)

Another clue that there is something particularly unique about size is the strength of the SWI relative to other weight illusions. For example, in considering the SWI alongside the MWI, which is the next most studied weight illusion, evidence suggests that the SWI is considerably stronger (Buckingham & Goodale, 2013; Buckingham, Michelakakis, & Cole, 2016). In the Buckingham and Goodale's (2013) study mentioned earlier, participants were tested on both illusions, in that they lifted two sets of large and small stimuli, one apparently made from polystyrene and one from aluminium. Testing the effects of both size and material properties on heaviness ratings revealed that size
(\eta^2_p = .98) had a much stronger effect size than material (\eta^2_p = .42). A similar difference in illusion strength was reported in a neuropsychological study by Buckingham, Bieńskiewicz, Rohrbach, and Hermsdörfer (2015), which included a small control sample that was tested on both illusions. The control group reported a SWI on 95.8% of trials, whereas they reported a MWI on only 35.1% of trials. These studies indicate a difference in effect magnitudes for the two illusions. A more systematic meta-analysis in a larger number of studies is warranted to confirm if there really exists a substantial difference between the size-weight and material-weight illusions.

To provide further evidence that there is something particularly strong about the influence of size on weight perception, consider the Flanagan et al. (2008) study described earlier. The authors demonstrated that the illusion could be reversed after having participants practice lifting small, heavy objects and large, light objects for approximately 30 days. Participants were assessed on day 11 and reported the reverse-SWI; however, the resulting reversal in SWI was much weaker than the standard SWI. Furthermore, the reverse-SWI was the same strength on day 11 as it was on day 30, despite continued training. This finding demonstrates that normal size-weight associations are deep-seated and that their influence still remains even after intensive training aimed to abolish their influence. On balance, this research suggests that the stimulus property of size has a particularly strong association with expected and perceived heaviness.

Why is size special?

Why might the stimulus property of size be unique in its ability to influence weight perception? The answer could be found in the way that size is processed visually by the brain compared to other object features that have an association with weight, such as
material, concept, or identity. To explain, consider the division of labour between the magnocellular and parvocellular visual systems (Laycock, Crewther, & Crewther, 2008; Livingstone & Hubel, 1988). In short, both systems originate from the retina and remain largely segregated as information is processed by the cortex. The magnocellular system transmits signals quickly, processing motion and crude, low-spatial frequency information, including the size and shape of objects. It does not process colour nor is it concerned with scrutinising details such as material properties. In contrast, the parvocellular system transmits signals more slowly and processes some chromatic information as well as high-spatial frequency information, such as surface texture. Differences in processing speeds between the two systems are believed to be important for perception. That is, some authors have argued that the magnocellular system, which is the faster system, plays an important role in driving attention and prioritising information that needs to be analysed with greater scrutiny by the slower parvocellular system (Laycock et al., 2008; Laycock & Crewther, 2008).

Magnetoencephalography (MEG) studies have demonstrated how the low-spatial frequencies of objects, providing size and shape information, is processed by the frontal lobes preconsciously before the high-spatial frequencies of the same objects are processed consciously by the ventral stream in the inferior temporal cortex (Bar et al., 2006; Noguchi, Yokoyama, Suzuki, Kita, & Kakigi, 2012; see Fig. 4). A seminal study reported by Bar et al. (2006) demonstrated activation in the orbitofrontal cortex that occurred approximately 50 ms before activity in the ventral stream that are known to play a critical role in the perceptual recognition of objects (Farah, 2004; Goodale & Milner, 1992). Importantly, this early orbitofrontal activity was specific to trials in which participants successfully recognised the masked, briefly-presented objects, compared to trials in which objects were not identified. Another key finding from this study was that
this differential activity in the orbitofrontal cortex was found for object images that had been filtered to contain predominantly low-spatial frequency information, but not for images that were primarily comprised of high-spatial frequency information. Other MEG studies have since replicated the findings by Bar et al. (2006) and further determined that the conscious perceptual awareness of a stimulus is time-locked at the precise moment that the ventral stream areas become activated (e.g., Noguchi et al., 2012). These MEG studies are important in demonstrating how size and shape information might be better placed for providing context that can influence the perceptual analysis of objects compared to other properties such as material or identity. This is because they demonstrate that information about size and shape can undergo substantially more processing before the emergence of a perceptual experience given they are processed much more rapidly.

![Fig. 4 Model of Bar et al. (2006) on top-down facilitation of object recognition. Low SF (spatial frequency) retinal information is transmitted quickly from early visual areas (A) to the orbitofrontal cortex (B), then to the temporal areas of the ventral visual processing stream (C), which are implicated and necessary for object recognition. This fast pathway](image)
is represented by the blue arrows. High SF retinal information is transmitted more slowly from the primary occipital cortex to the temporal lobe (C) along the ventral visual pathway, represented by the red arrow.

It is relevant that a neuroimaging study by Gallivan, Cant, Goodale, and Flanagan (2014) has implicated ventral stream areas in the inferior temporal cortex in the processing of object weight associated with another object feature. Specifically, participants were shown objects made from different materials, which they lifted after several seconds of viewing exposure time. Using multi-voxel pattern analysis, which is a “brain reading” technique used to determine specific mental states akin to those used in machine learning (Diedrichsen, Yokoi, & Arbuckle, 2017; Haxby et al., 2001), the authors demonstrated that activation in the medial areas of the ventral stream, which are important for processing colour and texture (Cant & Goodale, 2007), during the planning stages of the lift could be decoded in the same manner as activation in the motor cortex during the lifts but only after participants learned to associate a particular material with a particular weight. Based on these findings, the authors conclude that ventral stream areas are important for associating weight with another object feature – at least for the purposes of lifting objects. However, it is unclear from their results as to whether or not this activation might also reflect perceived weight. Perhaps it does if one considers that the agnosia literature implicates a critical role of these areas in the perceptual awareness of objects (Farah, 2004; Goodale & Milner, 1992).

Although our proposals have thus far focused on visual processing, the somatosensory system is likewise designed to transmit and process different types of information at different speeds. Proprioception is faster than touch, which is faster than
either pain or temperature (McGlone & Reilly, 2010; Rowe, 2002). Amazeen and colleagues have demonstrated on multiple occasions the strong influence of size information obtained kinaesthetically on the SWI (Amazeen, 1999; Amazeen & Turvey, 1996; Kloos & Amazeen, 2002; Oberle & Amazeen, 2003). This information is processed by the fast proprioceptive channel, which could perhaps fulfil a role similar to the magnocellular pathway in providing context that will influence perception. This notion, if it is correct, could help explain why information about material obtained haptically does not elicit a MWI, as demonstrated by Harshfield and DeHardt (1970). This tactile information is not processed by the proprioceptive channel but rather by a slower touch channel, which may not be able to process contextual information fast enough to exert an influence on perceived weight.

Studies on size constancy in infants indicate that the mechanisms underlying size processing have an important innate component to them. Size constancy is the ability to perceive objects as having the same size regardless of viewing distance (Sperandio & Chouinard, 2015). Adults perform this function effortlessly and several studies indicate that infants, including newborns, also have this ability (Bower, 1966; Day & McKenzie, 1981; Granrud, 2006; Slater, Mattock, & Brown, 1990). As size processing is a prerequisite for size constancy, it follows that infants who demonstrate size constancy must be able to process size information. Slater et al. (1990) investigated size constancy in newborns with a mean age of 2 days. The first phase of the experiment was a familiarisation stage, in which the infants were shown a single object at various viewing distances. In the second phase, this same object was presented alongside a new object that was a different physical size. The two objects were placed at different distances, such that the two objects cast the same retinal image size. On average, the newborns looked at the new object for 84% of the viewing time, indicating the original object was indeed
familiar, despite its unfamiliar retinal size. Granrud (2006) employed a similar and more modern version of this design with 4-month old infants and reported similar results.

A relevant consideration is if infants can process other object properties known to influence weight perception. Our arguments regarding the uniqueness of size would be weakened if this were the case. It is particularly relevant to consider density. Piaget (1941) reasoned that a child cannot understand density until an understanding of size and weight was achieved. To add to that, it would seem strange to us that an infant who has not reached the stages of being able to manipulate objects manually would be able to process their density given the lack of priors. Indeed, these notions are supported by a comprehensive developmental study by Smith, Carey, and Wiser (1985). They examined children’s understanding of size, weight, and density between the ages of 3 and 9 years. They used a variety of tasks, including those that rely on a cognate understanding of these concepts and their verbal labels (e.g., “Which object is larger?”) and tasks that did not (e.g., “Will this block fit inside this cube and touch the penny at the bottom?”). Overall, their results were in line with Piaget (1941). Namely, the authors demonstrated that children aged 3-4 years had a distinct understanding of size and weight but not density. Children aged 5-7 years displayed some understanding of density, although often this was not clearly differentiated from weight. In contrast, children aged 8-9 years demonstrated understanding of density that was distinct from weight.

Gandhi, Kalia, Ganesh, and Sinha (2015) have provided further support for the innate nature of size processing. The authors reported striking findings of susceptibility to two visual illusions in children and adolescents who were congenitally blind but who had gained sight for the first time following cataract removal in the previous 48 hours. The authors examined the Ponzo (Ponzo, 1910) and Müller-Lyer (Müller-Lyer, 1889)
illusions, both of which involve comparing the size of a pair of two-dimensional visual stimuli. For both illusions, viewers judge the relative lengths of two identical lines, lines which are accompanied by contextual information that are thought to provide distance cues in a manner that is typical for a two-dimensional image that depicts a three-dimensional scene (Gregory, 1963; Sperandio & Chouinard, 2015). Namely, the converging lines in the Ponzo illusion are similar to linear perspective cues that we encounter in the real world (Fig. 5a) while the stimuli in the Muller-Lyer illusion are similar to the corners of buildings and corridors (Fig. 5b). As such, accounts for both illusions are sometimes experienced-based, in that we have learned how a three-dimensional image is represented in a two-dimensional format (see Gregory, 1963; Sperandio & Chouinard, 2015 for relevant discussions). Gandhi et al.’s findings are inconsistent with pure experience-based accounts, in that newly-sighted individuals were susceptible to these illusions despite no experience processing either two- or three-dimensional visual scenes. These results demonstrate instead that an innate visual processing mechanism can produce these illusory size experiences in the absence of learned associations.
Fig. 5 The Ponzo (A) and Müller-Lyer (B) illusions. For A, participants judge the relative size of two identical horizontal lines and typically report the one on top to be longer. For B, the two vertical lines are identical but the rightward stimulus typically appears longer. Some theories propose that the perceptual rescaling that takes place is driven by contextual cues on the illusory background that simulate depth cues, as indicated in the photographs below. The influence of these cues are thought to be reinforced through experience. In opposition to this notion, Gandhi et al. (2015) reported immediate susceptibility to these illusions in children and adolescents who recently gained sight for the first following cataract removal. These findings suggest an important innate component to size perception that is independent from experience.

Taken together, it would seem that size is uniquely placed to influence perception over other kinds of objects features. In terms of vision, the magnocellular pathway
processes low-spatial frequency information, such as size, before conscious awareness for the purposes of providing context, directing attention, and influencing perception (Laycock et al., 2008; Livingstone & Hubel, 1988; Noguchi et al., 2012). Other object features, such as texture, are processed later by the parvocellular pathway, which is more concerned with colour and high-spatial frequency information (Laycock et al., 2008; Livingstone & Hubel, 1988). In terms of somatosensory perception, proprioception is transmitted and processed more quickly than other forms of somatosensory information, which could similarly explain the strong influence of size information obtained kinesthetically on the SWI (Amazeen, 1999; Amazeen & Turvey, 1996; Kloos & Amazeen, 2002; Oberle & Amazeen, 2003). It is tempting to speculate, as others have before us, that faster processing channels in the brain are phylogenetically older than slower ones (e.g., Méndez-Bértolo et al., 2016; Milner & Goodale, 2006). This notion could explain why size perception is evident in newborns (Slater et al., 1990) and in children and adolescents experiencing sight for the first time after cataract removal (Gandhi et al., 2015).

**Developmental research and the SWI**

In light of our proposal that the strength of the SWI might reflect a deep-seated mechanism underlying the processing of object size, this line of thinking invites the question when the SWI manifests in childhood. If the size-weight association is the result of a reinforcement of an innate predisposition then it follows that the SWI should be exhibited at an early age. Aside from age of onset, the developmental trajectory of the strength of the illusion could also inform on the nature of the underlying perceptual mechanism. Thus, in the following section, we consider the evidence thoroughly to assess the innate versus acquired nature of the SWI.
Both Binet (1895), and later Piaget (1969), proposed that the study of illusions offers opportunities to understand typical cognitive development and to tease apart perceptual mechanisms that are innate from those that are acquired. Both reasoned that illusions showing decreases in strength with increasing age are more likely driven by innate mechanisms that become attenuated as certain abilities in cognition are acquired. Both also reasoned that illusions showing increases in strength with age are more likely driven by acquired mechanisms that are obtained during the course of typical cognitive development. In this vein, Binet (1895) carried out an early investigation of the developmental trajectory of the Müller-Lyer illusion in primary school children. He demonstrated that the strength of the illusion was strongest in the youngest children and that the illusion decreased in strength as the children aged. This trajectory has since been replicated many times (Brosvic, Dihoff, & Fama, 2002; Hanley & Zerbolio, 1964; Pollack, 1970; Porac & Coren, 1981) but not always (Hartmann, Gelfand, Courtney Jr, & Malouf, 1972; Rival, Olivier, Ceyte, & Ferrel, 2003). Of note, the idea that innate perceptual mechanisms underlie this illusion fits nicely with the evidence of immediate susceptibility in newly sighted children and adolescents, as discussed above (Gandhi et al., 2015).

With respect to the SWI, then, developmental research has been mixed with respect to the age at which it emerges and the trajectory of illusion strength with increasing age. In contrast to Binet’s findings with the Müller-Lyer illusion, early research into the SWI in children demonstrated that the illusion had the reverse developmental trajectory (Dresslar, 1894; Flournoy, 1894; Gilbert, 1894; Philippe & Clavière, 1895); namely, the SWI was absent in the youngest children and increased in strength as the children got older. According to both Binet and Piaget’s reasoning, these findings would indicate an acquired mechanism underlying the SWI, which contrasts our current
propose. However, it could be the case that a young child might still perceptually experience the SWI but is unable to report it because of a lack of a cognitive understanding of size and weight. In line with this idea, two studies have since employed alternative techniques of investigating the SWI in children in an attempt to increase the validity of heaviness reporting. These alternative methods have produced results that contrast the early findings of the SWI in children, instead demonstrating a strong illusion in young children.

In the first study, Robinson (1964) was concerned that the youngest participants might not understand the concept of weight and would not be able to report differences in perceived heaviness even when they experience it. Accordingly, he administered an intensive reinforcement training phase before testing the children on the SWI. Children between the ages of 2 and 10 years were trained to indicate the heavier of two objects that did in fact differ in mass. The participant received a treat following each correct identification of the heavier object and were explicitly told that they were incorrect when they choose the lighter object. After completing this training phase, the children were then tested on the SWI. Contrary to all earlier work, Robinson demonstrated that the SWI was stronger in the youngest compared to the older children.

The second study was conducted by Kloos and Amazeen (2002), who investigated the SWI in children between the ages of 3 and 5 years. Like Robinson, the authors were concerned about children’s ability to report perceived weight and so they devised a clever way to keep the children engaged and provide a report that could accurately reflect their perception of weight without having a complete understanding or appreciation of what weight is. The children were shown a picture of a mouse at the bottom of a steep hill and a house on top of the hill. The children held a task object in one hand and were told it was
a block of cheese that the mouse had to take home. They were also told that the mouse would have to take a break to rest somewhere along the hill. The children pointed to a position on the hill to indicate where the mouse might take a break after holding each task object. The indicated locations served as an index of the children's perceived weight of the objects, which were consistent with a typical SWI. Thus, similar to Robinson’s (1964) findings, Kloos and Amazeen (2002) demonstrated that the SWI is present in young children who have alternative means to report perceived weight rather than conventional methods requiring a cognate understanding of weight. These findings provide further support that there could be an innate component underlying or influencing the SWI.

**Conclusion**

There is no doubt that experience-based learning contributes to our near-effortless interactions with the physical environment. When preparing an action towards an unfamiliar object, previous interactions with objects with similar features help us to anticipate its weight, features including those reviewed in this paper, such as size, density, material, concept or identity. It is clear that these features, and their association with weight, influence our expectations and even subjective experience of object weight. However, in this paper we have argued that there is something unique about the feature of size, and how it is processed in the brain, that could account for its especially strong association with weight, an association that may be reinforced rather than entirely explained by experience.

**Acknowledgements**
We thank the two anonymous reviewers for their feedback on our manuscript. This work was supported by the Australian Research Council (DP170103189). We have no conflicts of interest to declare.
References


Buckingham, G., Cant, J. S., & Goodale, M. A. (2009). Living in a material world: how visual cues to material properties affect the way that we lift objects and perceive their weight. *Journal of Neurophysiology, 102*(6), 3111-3118. doi:10.1152/jn.00515.2009


Chouinard, P. A., Large, M. E., Chang, E. C., & Goodale, M. A. (2009). Dissociable neural mechanisms for determining the perceived heaviness of objects and the predicted weight of objects during lifting: An fMRI investigation of the size-


Gilbert, J. A. (1894). Researches on the mental and physical development of school-children. *Studies from the Yale Psychological Laboratory, 2*, 40-100.


doi:10.1111/j.1467-8624.1972.tb02061.x


doi:10.1007/bf00237997


doi:10.1126/science.3283936


Sensorimotor Control of Movement and Posture (pp. 47-55). Boston, MA: Springer US.


Zhu, Q., Shockley, K., Riley, M. A., Tolston, M. T., & Bingham, G. P. (2013). Felt heaviness is used to perceive the affordance for throwing but rotational inertia does not affect either. *Experimental Brain Research, 224*(2), 221-231. doi:10.1007/s00221-012-3301-7