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

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Abstract

Research into weight illusions has provided valuable insight into the functioning of the human perceptual system. Associations between the weight of an object and its other features, such as its size, material, density, conceptual information, or identity, influence our expectations and perceptions of weight. Earlier accounts of weight illusions underscored 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 that it is therefore more deep-seated than the effects of 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 this, 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 do.

Keywords Visual perception · Motor planning/programming · Weight perception · Weight illusions

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, more than 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) participants' 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 about our conscious experience of weight more generally, research in the field has provided valuable insight.

The present review consists of two parts. In the first we consider the different associations that exist between an object's weight and its other features. Research into weight illusions has demonstrated that these associations not only underlie expectations of weight but also influence how we perceive weight. We discuss the 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. Then we proceed to the second part, where we propose a new theory: Namely, we argue that size is a more deep-seated influence on weight perception than are the other object features reviewed earlier. In the process, we evaluate the evidence from cognitive, neurophysiological, and developmental research demonstrating that size processing is not entirely mediated by experience-based mechanisms. A novel neuroanatomical account is then proposed of how size might influence weight perception differently than other object features do.

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How do we predict and perceive an object's weight on the basis of other features?

Weight illusion research has highlighted people's ability to form associations and make use of them. Currently, there is a growing trend to apply Bayesian frameworks in order 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 toward 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 in the 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 and 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 in terms of what 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, we can anticipate its weight on the basis of 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 that comprise 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 the 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 the 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 in order

to lift objects ballistically, and these forces must rely on the known associations between an object's weight and its other features (Johansson & Westling, 1984). The 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.

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 the cardboard and brass 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 the 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, whereas the latter become more similar after only a couple of trials.

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 kinesthetic information about the cube's 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 kinesthetic input from influencing the 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; H. E. Ross & Gregory, 1970; Wolf, Bergmann Tiest, & Drewing, 2018). For example, Chouinard et al. demonstrated with functional magnetic resonance imaging (fMRI) that the 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 the density differences between two stimuli in a typical SWI experiment are not expected before lifting, but rather are inferred after liftoff. 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, which the participant only begins realizing during the lift, might cause participants to perceive the smaller object as being heavier and the larger one as being lighter. Alternatively, the association between density and weight may be such that lifting a denser object will cause one to perceive that object as being heavy, because denser objects are typically heavier.

Examples of weight associations from other weight illusions

Aside from the SWI, evidence from other weight illusions has demonstrated 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 nongolfers judge the weights 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 nongolfers. In this experiment, the two groups of participants judged the weights 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 nongolfers, 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. Because 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 densities of these materials. Instead, the styrofoam object is typically reported as being the heavier of the two (Baugh, Kao, Johansson, & Flanagan, 2012; Buckingham et al., 2009; Ellis & Lederman, 1999). The MWI is consistent with the SWI, in the sense that the object that is expected to be lighter is ultimately perceived as heavier. Unlike the SWI, in which differences in density are inferred only after liftoff, the MWI appears to implicate density expectations prior to lifting based on knowledge of the different materials.

Contextual weight associations

Aside from the stable, well-established associations that exist between an object's features and its weight, there is also evidence to suggest that newly learned contextual associations can influence weight perception. Studies have demonstrated modulation, or even reversal, of the SWI through mass practice of either associating different colors with different levels of heaviness (Trewartha & Flanagan, 2017) or lifting small objects that are heavy and large objects that are light (Flanagan et al., 2008). However, the acquisition of these newly learned artificial associations does not completely override the effects of well-established associations that are reinforced over the course of a lifetime (Buckingham et al., 2009). For example, in Flanagan et al.'s study, the artificially induced reverse-SWI was considerably weaker than the standard SWI, regardless of how much practice was carried out. It is also unknown how long this reversal is retained and whether or not it generalizes to other untrained families of objects or contexts. Nonetheless, these studies have demonstrated that learned contextual weight-related associations can affect the perceived weights of objects.

Overview of theories of the SWI and other weight illusions

The evidence reviewed above demonstrated 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 remain unknown. A number of detailed theories have been proposed, with little resolution of this issue (for reviews, see Buckingham, 2014; Dijk, 2014). Some of these theories are 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 logics could apply to all other weight illusions in which one stimulus is expected to be heavier than the other. To explain, when lifting two SWI objects, people apply more force for the larger than 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 the 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, but that 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 article to demonstrate such motor adaptation, Flanagan and Beltzner compared the maximum rates of grip (horizontal) and load (vertical) forces and the liftoff times for small and large objects. They divided 20 lifting trials into four blocks of five lifts for the purpose of analysis. In the first block, participants exhibited a greater maximum rate of grip and load force application for the large than for the small object. Liftoff 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 liftoff times were not statistically different between the two objects. For the third and fourth blocks, there were no statistical differences between the two objects in these three variables, yet the differences in perceived weight remained as strong as in the initial lifts. These findings demonstrate the coexistence 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 applied lifting forces that matched the true weight—which the aforementioned studies demonstrated is not the case.

However, we think the sensorimotor-mismatch theory may still have some merit, despite the studies above suggesting otherwise. Even though the motor system becomes more veridical in applying appropriate forces, it is still possible that

tiny misapplications of force remain that are too subtle to measure but that can still influence weight perception. As Dijk (2014) has pointed 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, and liftoff time). In some cases, not all of these variables 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 than for the small object on the majority of trials, whereas the other measurements adapted more quickly. Thus, on balance, the sensorimotor-mismatch theory should not be dismissed outright, but also it should not 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 in a Bayesian framework. This consideration appears to be mixed for the SWI and not to be applicable for other weight illusions. Some authors have described 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 do 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 of 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; H. E. Ross & Gregory, 1970). Because 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 is varied within the illusion (e.g., material, concept, or identity), the perceived weight is typically opposite what would be expected on the basis of 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 being 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 being heavier when both types of balls 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 that they do 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; J. 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 of 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, as the mass distribution varied, the rotational inertia of the rods also varied as the rods 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 was mass per se. Amazeen and Turvey argued that when their rods were wielded, the critical, action-relevant variable influencing weight perception was rotational inertia, rather than mass (see Plaisier & Smeets, 2015, and Zhu, Shockley, Riley, Tolston, & 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 perception of the throwability of hand-held objects. From these results, the authors speculated that weight perception was ultimately a byproduct of an innate mechanism that was necessary in order for our prehistoric ancestors to quickly select rocks and sticks as weapons to attack and defend themselves.

Size as a unique, weight-associated object feature

Much of the research reviewed above centered 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 its receiving so much attention is that it seems to be an especially strong and reliable illusion; the illusory experience of weight 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 than do 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 developmental research on the SWI in young

children, which, when considered thoroughly, sheds light on 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 influences of other object features. Plaisier and Smeets (2015) investigated the SWI using two objects that differed in overall size but that 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 the material was divided into two halves and attached to either end of a cylindrical bar. The overall size of the divided object was thus greater than that of 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 being heavier, in line with the SWI. One consideration here is that perhaps we are less skilled at making weight judgments of unusual or more complex objects, such as in the case of the divided object in this experiment. Regardless, though, Plaisier and Smeets's finding demonstrates that size cues can overwrite other information that can and should inform as to an object's weight, such as volume.

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 from aluminum. 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 aluminum cubes than for the polystyrene set, presumably owing to the known densities of these materials. Despite these expectations, and the relevant material–weight associations, participants reported SWIs of remarkable consistency for both sets of stimuli. Accordingly, Buckingham and Goodale

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.

(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 color rather than material (Buckingham, Goodale, et al., 2016). Here they used color to denote object families and had participants lift two SWI objects that were either of the same or of different colors. The authors predicted a stronger SWI for objects of the same color, for which the participants should expect, first, that both would have the same density and, second, 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 reflect a violation of the expectation that larger objects are heavier, Buckingham and MacDonald demonstrated that size cues can elicit an 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 that were similar in mass. As is depicted in Fig. 3, these included a golf ball (45 g), a toy soccer ball (52 g), and a beach ball (52 g). Before lifting, participants reported expecting the golf ball to be heaviest, followed by the soccer ball and then the beach ball. After lifting, the participants' heaviness ratings were consistent with their expectations, reporting the golf ball to be the heaviest and the beach ball 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

Fig. 3 Depiction of Buckingham and MacDonald's (2016) stimuli: a golf ball (weight 45 g, diameter 4.3 cm), toy soccer ball (weight 52 g, diameter 8.6 cm), and beach ball (weight 52 g, diameter 27.5 cm). 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 either of other balls.

directly resulted in an especially strong influence of somato-sensory size cues on perception, given that past research had suggested that haptic feedback of size has a strong influence on the illusion (Ellis & Lederman, 1993; but see also the results from Buckingham & Goodale, 2010b, which contradict this view). Regardless, Buckingham and MacDonald's study demonstrated the dominant influence that size can have on weight perception.

Another clue that something is 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 aluminum. Testing the effects of both size and material properties on heaviness ratings revealed that size ($\eta_p^2 = .98$) had a much stronger effect size than material ($\eta_p^2 = .42$). A similar difference in illusion strength was reported in a neuropsychological study by Buckingham, Bienkiewicz, Rohrbach, and Hermsdörfer (2015), which included a small control sample that was tested on both illusions. The control group reported an SWI on 95.8% of trials, whereas they reported an MWI on only 35.1% of trials. These studies indicate a difference in the effect magnitudes of the two illusions. A more systematic meta-analysis in a larger number studies is warranted, to confirm whether a substantial difference really exists between the size–weight and material–weight illusions.

To provide further evidence that something is 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 participants had practiced 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 the SWI was much weaker than the standard SWI. Furthermore, the reverse-SWI had the same strength on Day 11 as 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 both 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, as

compared to other object features that have associations with weight, such as material, concept, or identity. To explain, consider the division of labor 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 sizes and shapes of objects. It does not process color, nor is it concerned with scrutinizing 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 prioritizing information that needs to be analyzed with greater scrutiny by the slower, parvocellular system (Laycock et al., 2008; Laycock & Crewther, 2008).

Magnetoencephalography (MEG) studies have demonstrated that the low spatial frequencies of objects, providing size and shape information, are 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. demonstrated activation in the orbitofrontal cortex that occurred approximately 50 ms before activity in the ventral stream, which is 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 recognized the masked, briefly presented objects, as

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 composed of high-spatial-frequency information. Other MEG studies have since replicated the findings by Bar et al. and further determined that the conscious perceptual awareness of a stimulus is time-locked to 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 than is information related to other properties, such as material or identity. This is because these studies have demonstrated that information about size and shape can undergo substantially more processing before the emergence of a perceptual experience, given that they are processed much more rapidly.

It is relevant that a neuroimaging study by Gallivan, Cant, Goodale, and Flanagan (2014) has implicated ventral-stream areas of 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 multivoxel 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, during the planning stage of a lift, activation in the medial areas of the ventral stream that are important for processing color and texture (Cant & Goodale, 2007) could be decoded in the same manner as activation in the motor cortex during the lift, but only after participants had learned to associate a particular material with a particular

Fig. 4 Model of Bar et al. (2006) for the top-down facilitation of object recognition. Low-spatial-frequency (SF) retinal information is transmitted quickly from early visual areas (A) to the orbitofrontal cortex (B), then to temporal areas of the ventral visual processing stream (C), which are implicated and necessary for object recognition. This fast pathway is

represented by the long cool 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 short wavy arrow.

weight. On the basis of these findings, the authors concluded 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 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 kinesthetically 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 fulfill 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 an MWI, as was demonstrated by Harshfield and DeHardt (1970). This would be because 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 have indicated 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 have indicated that infants, including newborns, also have this ability (Bower, 1966; Day & McKenzie, 1981; Granrud, 2006; Slater, Mattock, & Brown, 1990). Because 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. investigated size constancy in newborns with a mean age of 2 days. The first phase of the experiment was a familiarization 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 produced the same retinal image size. On average, the newborns looked at the new object for 84% of the viewing time, indicating that 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 whether 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 understanding of size and weight has been achieved. To add to that, it would seem strange to us if an infant who had not reached the stage of being able to manipulate objects manually were able to process the objects' 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. The study was based on a variety of tasks, including both tasks that rely on a cognate understanding of these concepts and their verbal labels (e.g., "Which object is larger?") and tasks that do not (e.g., "Will this block fit inside this cube and touch the penny at the bottom?"). Overall, the results were in line with Piaget's (1941) reasoning. Namely, the authors demonstrated that children 3–4 years of age had a distinct understanding of size and weight but not of density. Children 5–7 years of age displayed some understanding of density, although this was often not clearly differentiated from weight. In contrast, children 8–9 years of age demonstrated an 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. These 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 h. The authors examined the Müller-Lyer (1889) and Ponzo (1910) illusions, both of which involve comparing the sizes of a pair of two-dimensional visual stimuli. For both illusions, viewers judge the relative lengths of two identical lines, which are accompanied by contextual information that is thought to provide distance cues in a manner typical for two-dimensional images that depict three-dimensional scenes (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), whereas the stimuli in the Müller-Lyer illusion are similar to the corners of buildings and corridors (Fig. 5B). As such, accounts of both illusions are sometimes experience-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 having no experience with processing either two- or three-dimensional visual scenes. These results

Fig. 5 The Ponzo (A) and Müller-Lyer (B) illusions. In panel A, participants judge the relative sizes of two identical horizontal lines and typically report that the one on top is longer. In panel B, the two vertical lines are identical, but the one in the stimulus on the right 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

demonstrate instead that an innate visual processing mechanism can produce these illusory size experiences in the absence of learned associations.

Overall, it would seem that size is uniquely placed to influence perception more than other kinds of object 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 color and high-spatial-frequency information (Laycock et al., 2008; Livingstone & Hubel, 1988). In terms of somatosensation, 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 the 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

below. The influences 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 had recently gained sight for the first time following cataract removal. These findings suggest that an important innate component of size perception is independent of experience.

(Slater et al., 1990) as well as 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 of when the SWI might manifest in childhood. If the size–weight association is the result of reinforcement of an innate predisposition, then it follows that the SWI should be exhibited at an early age. Aside from the age of onset, the developmental trajectory of the strength of the illusion could also inform as to 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 that show decreases in strength with increasing age are more likely to be driven by innate mechanisms that become attenuated as certain abilities in cognition are acquired. Both also reasoned that illusions that show

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 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 children aged. This trajectory has since been replicated many times (Brosvic, Dihoff, & Fama, 2002; Hanley & Zerbolo, 1964; Pollack, 1970; Porac & Coren, 1981), but not always (Hartmann, Gelfand, Courtney, & 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 to it among newly sighted children and adolescents, as discussed above (Gandhi et al., 2015).

With respect to the SWI, then, the 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 (1895) 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 grew older. According to both Binet's and Piaget's (1969) reasoning, these findings would indicate that an acquired mechanism underlies the SWI, which contrasts with our present proposal. However, a young child might still perceptually experience the SWI but be unable to report it, because of a lack of cognitive understanding of size and weight. In line with this idea, two studies have employed alternative techniques of investigating the SWI in children, in an attempt to increase the validity of heaviness reporting. These alternative methods produced results that contrast with 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 thus not be able to report differences in perceived heaviness even when they experienced them. Accordingly, he administered an intensive reinforcement-training phase before testing children for 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 participants received a treat following each correct identification of the heavier object and were explicitly told that they were incorrect when they chose 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 than in 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 (1964), these authors were concerned about children's ability to report perceived weight, so they devised a clever way to keep the children engaged and provide a report that would accurately reflect their perception of weight, without requiring either 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 that 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 side of 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 weights of the objects, which were consistent with a typical SWI. Thus, similar to Robinson's findings, Kloos and Amazeen demonstrated that the SWI is present in young children who have an alternative means to report perceived weight, rather than conventional methods that require a cognate understanding of weight. These findings provide further support that an innate component may underlie or influence 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 toward an unfamiliar object, previous interactions with objects with similar features help us anticipate its weight—features that include those reviewed in this article, such as size, density, material, concept, and identity. It is clear that these features and their associations with weight influence our expectations, and even our subjective experiences, of object weight. However, in this article we have argued that something is unique about the size feature and how it is processed in the brain, which could account for this feature's especially strong association with weight, an association that may be simply reinforced rather than entirely explained by experience.

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References

- Amazeen, E. L. (1999). Perceptual independence of size and weight by dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 102–119. doi:<https://doi.org/10.1037/0096-1523.25.1.102>

- Amazeen, E. L., & Turvey, M. T. (1996). Weight perception and the haptic size–weight illusion are functions of the inertia tensor. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 213–232. doi:[10.1037/0096-1523.22.1.213](https://doi.org/10.1037/0096-1523.22.1.213)
- Bar, M., Kassam, K. S., Ghuman, A. S., Boshyan, J., Schmid, A. M., Dale, A. M., . . . Rosen, B. R. (2006). Top-down facilitation of visual recognition. *Proceedings of the National Academy of Sciences*, 103, 449–454. doi:<https://doi.org/10.1016/b978-012375731-9/50029-x>
- Baugh, L. A., Kao, M., Johansson, R. S., & Flanagan, J. R. (2012). Material evidence: Interaction of well-learned priors and sensorimotor memory when lifting objects. *Journal of Neurophysiology*, 108, 1262–1269. doi:<https://doi.org/10.1152/jn.00263.2012>
- Binet, A. (1895). La mesure des illusions visuelle chez les enfants. *Revue Philosophique de la France et de l'Étranger*, 40, 11–25.
- Bower, T. G. (1966). The visual world of infants. *Scientific American*, 215, 80–97. doi:<https://doi.org/10.1038/scientificamerican1266-80>
- Brayanov, J. B., & Smith, M. A. (2010). Bayesian and “Anti-Bayesian” biases in sensory integration for action and perception in the size–weight illusion. *Journal of Neurophysiology*, 103, 1518–1531. doi:<https://doi.org/10.1152/jn.00814.2009>
- Brosvic, G. M., Dihoff, R. E., & Fama, J. (2002). Age-related susceptibility to the Müller-Lyer and the horizontal–vertical illusions. *Perceptual and Motor Skills*, 94, 229–234. doi:<https://doi.org/10.2466/pms.2002.94.1.229>
- Buckingham, G. (2014). Getting a grip on heaviness perception: A review of weight illusions and their probable causes. *Experimental Brain Research*, 232, 1623–1629. doi:<https://doi.org/10.1007/s00221-014-3926-9>
- Buckingham, G., Bieńkiewicz, M., Rohrbach, N., & Hermsdörfer, J. (2015). The impact of unilateral brain damage on weight perception, sensorimotor anticipation, and fingertip force adaptation. *Vision Research*, 115, 231–237. doi:<https://doi.org/10.1016/j.visres.2015.02.005>
- 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, 3111–3118. doi:<https://doi.org/10.1152/jn.00515.2009>
- Buckingham, G., & Goodale, M. A. (2010a). The influence of competing perceptual and motor priors in the context of the size–weight illusion. *Experimental Brain Research*, 205, 283–288. doi:<https://doi.org/10.1007/s00221-010-2353-9>
- Buckingham, G., & Goodale, M. A. (2010b). Lifting without seeing: The role of vision in perceiving and acting upon the size weight Illusion. *PLoS ONE*, 5, e9709. doi:<https://doi.org/10.1371/journal.pone.0009709>
- Buckingham, G., & Goodale, M. A. (2013). Size matters: A single representation underlies our perceptions of heaviness in the size–weight illusion. *PLoS ONE*, 8, e54709. doi:<https://doi.org/10.1371/journal.pone.0054709>
- Buckingham, G., & MacDonald, A. (2016). The weight of expectation: Implicit, rather than explicit, prior expectations drive the size–weight illusion. *Quarterly Journal of Experimental Psychology*, 69, 1831–1841. doi:<https://doi.org/10.1080/17470218.2015.1100642>
- Buckingham, G., Goodale, M. A., White, J. A., & Westwood, D. A. (2016). Equal-magnitude size–weight illusions experienced within and between object categories. *Journal of Vision*, 16(3), 25:1–9. doi:<https://doi.org/10.1167/16.3.25>
- Buckingham, G., Michelakakis, E. E., & Cole, J. (2016). Perceiving and acting upon weight illusions in the absence of somatosensory information. *Journal of Neurophysiology*, 115, 1946–1953. doi:<https://doi.org/10.1152/jn.00318.2015>
- Buckingham, G., Ranger, N. S., & Goodale, M. A. (2011). The role of vision in detecting and correcting fingertip force errors during object lifting. *Journal of Vision*, 11(1), 4. doi:<https://doi.org/10.1167/11.1.4>
- Cant, J. S., & Goodale, M. A. (2007). Attention to form or surface properties modulates different regions of human occipitotemporal cortex. *Cerebral Cortex*, 17, 713–731. doi:<https://doi.org/10.1093/cercor/bhk022>
- Charpentier, A. (1886). Sur les sensations de poids (note présentée par M. D’Arsonval le 3 avril)[On sensations of weight (note presented by Mr. D’Arsonval on the 3rd of April)]. *Comptes Rendus Hebdomadaires des Séances et Mémoires de la Société de Biologie*, 38, 169–170.
- Charpentier, A. (1891). Analyse expérimentale de quelques éléments de la sensation de poids. *Archives de Physiologie Normale et Pathologique*, 3, 122–135.
- 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–weight illusion. *NeuroImage*, 44, 200–212. doi:<https://doi.org/10.1016/j.neuroimage.2008.08.023>
- Davis, C. M., & Roberts, W. (1976). Lifting movements in the size–weight illusion. *Perception & Psychophysics*, 20, 33–36. doi:<https://doi.org/10.3758/BF03198701>
- Day, R. H., & McKenzie, B. E. (1981). Infant perception of the invariant size of approaching and receding objects. *Developmental Psychology*, 17, 670–677. doi:<https://doi.org/10.1037/0012-1649.17.5.670>
- Diedrichsen, J., Yokoi, A., & Arbuckle, S. A. (2017). Pattern component modeling: A flexible approach for understanding the representational structure of brain activity patterns. *NeuroImage*. Advance online publication. doi:<https://doi.org/10.1016/j.neuroimage.2017.08.051>
- Dijker, A. J. M. (2014). The role of expectancies in the size–weight illusion: A review of theoretical and empirical arguments and a new explanation. *Psychonomic Bulletin & Review*, 21, 1404–1414. doi:<https://doi.org/10.3758/s13423-014-0634-1>
- Dresslar, F. B. (1894). Studies in the psychology of touch. *American Journal of Psychology*, 6, 313–368. doi:<https://doi.org/10.2307/1411644>
- Ellis, R. R., & Lederman, S. J. (1993). The role of haptic versus visual volume cues in the size–weight illusion. *Perception & Psychophysics*, 53, 315–324. doi:<https://doi.org/10.3758/BF03205186>
- Ellis, R. R., & Lederman, S. J. (1998). The golf-ball illusion: Evidence for top-down processing in weight perception. *Perception*, 27, 193–201. doi:<https://doi.org/10.1068/p270193>
- Ellis, R. R., & Lederman, S. J. (1999). The material–weight illusion revisited. *Perception & Psychophysics*, 61, 1564–1576. doi:<https://doi.org/10.3758/bf03213118>
- Ernst, M. O. (2009). Perceptual learning: Inverting the size–weight illusion. *Current Biology*, 19, R23–R25. doi:<https://doi.org/10.1016/j.cub.2008.10.039>
- Farah, M. J. (2004). Visual agnosia (2nd ed.). Cambridge, MA: MIT Press.
- Flanagan, J. R., & Beltzner, M. A. (2000). Independence of perceptual and sensorimotor predictions in the size–weight illusion. *Nature Neuroscience*, 3, 737–741. doi:<https://doi.org/10.1038/76701>
- Flanagan, J. R., Bittner, J. P., & Johansson, R. S. (2008). Experience can change distinct size–weight priors engaged in lifting objects and judging their weights. *Current Biology*, 18, 1742–1747. doi:<https://doi.org/10.1016/j.cub.2008.09.042>
- Flournoy, T. (1894). De l’influence de la perception visuelle des corps sur leur poids objects. *L’Année Psychologique*, 1, 198–208.
- Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B*, 360, 815–836. doi:<https://doi.org/10.1098/rstb.2005.1622>
- Gallivan, J. P., Cant, J. S., Goodale, M. A., & Flanagan, J. R. (2014). Representation of object weight in human ventral visual cortex. *Current Biology*, 24, 1866–1873. doi:<https://doi.org/10.1016/j.cub.2014.06.046>

- Gandhi, T., Kalia, A., Ganesh, S., & Sinha, P. (2015). Immediate susceptibility to visual illusions after sight onset. *Current Biology*, 25, R358–R359. doi:<https://doi.org/10.1016/j.cub.2015.03.005>
- Geisler, W. S., & Kersten, D. (2002). Illusions, perception and Bayes. *Nature Neuroscience*, 5, 508–510. doi:<https://doi.org/10.1038/n0602-508>
- Gibson, J. J. (1979). The ecological approach to visual perception. Boston, MA: Houghton Mifflin.
- Gilbert, J. A. (1894). Researches on the mental and physical development of school-children. *Studies From the Yale Psychological Laboratory*, 2, 40–100.
- Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, 15, 20–25. doi:[https://doi.org/10.1016/0166-2236\(92\)90344-8](https://doi.org/10.1016/0166-2236(92)90344-8)
- Gordon, A. M., Westling, G., Cole, K. J., & Johansson, R. S. (1993). Memory representations underlying motor commands used during manipulation of common and novel objects. *Journal of Neurophysiology*, 69, 1789–1796. doi:<https://doi.org/10.1152/jn.1993.69.6.1789>
- Grandy, M. S., & Westwood, D. A. (2006). Opposite perceptual and sensorimotor responses to a size–weight illusion. *Journal of Neurophysiology*, 95, 3887–3892. doi:<https://doi.org/10.1152/jn.00851.2005>
- Granrud, C. E. (2006). Size constancy in infants: 4-month-olds' responses to physical versus retinal image size. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 1398–1404. doi:<https://doi.org/10.1037/0096-1523.32.6.1398>
- Gregory, R. L. (1963). Distortion of visual space as inappropriate constancy scaling. *Nature*, 199, 678–680. doi:<https://doi.org/10.1038/199678a0>
- Gregory, R. L. (1968). Perceptual illusions and brain models. *Proceedings of the Royal Society B*, 171, 279–296. doi:<https://doi.org/10.1098/rspb.1968.0071>
- Gregory, R. L. (1980). Perceptions as hypotheses. *Philosophical Transactions of the Royal Society B*, 290, 181–197. doi:<https://doi.org/10.1098/rstb.1980.0090>
- Hanley, C., & Zerbolo, D. J. (1964). Application of the up-and-down method in measuring perceptual development. *Child Development*, 979–984. doi:<https://doi.org/10.2307/1126522>
- Harshfield, S. P., & DeHardt, D. C. (1970). Weight judgment as a function of apparent density of objects. *Psychonomic Science*, 20, 365–366. doi:<https://doi.org/10.3758/bf03335692>
- Hartmann, D. P., Gelfand, D. M., Courtney, R. J., Jr., & Malouf, R. E. (1972). Successive presentations of elements of the Mueller-Lyer figure and CA, MA, and IQ: An age extension and unsuccessful replication. *Child Development*, 43, 1060–1066. doi:<https://doi.org/10.1111/j.1467-8624.1972.tb02061.x>
- Haxby, J. V., Gobbini, M. I., Furey, M. L., Ishai, A., Schouten, J. L., & Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science*, 293, 2425–2430. doi:<https://doi.org/10.1126/science.1063736>
- Helmholtz, H. (1867). *Handbuch der physiologischen Optik* (Vol. 9). Berlin, Germany: Voss.
- Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, 56, 550–564. doi:<https://doi.org/10.1007/bf00237997>
- Kloos, H., & Amazeen, E. L. (2002). Perceiving heaviness by dynamic touch: An investigation of the size–weight illusion in preschoolers. *British Journal of Developmental Psychology*, 20, 171–183. doi:<https://doi.org/10.1348/026151002166398>
- Laycock, R., Crewther, D., & Crewther, S. (2008). The advantage in being magnocellular: A few more remarks on attention and the magnocellular system. *Neuroscience & Biobehavioral Reviews*, 32, 1409–1415. doi:<https://doi.org/10.1016/j.neubiorev.2008.04.008>
- Laycock, R., & Crewther, S. G. (2008). Towards an understanding of the role of the “magnocellular advantage” in fluent reading. *Neuroscience & Biobehavioral Reviews*, 32, 1494–1506. doi:<https://doi.org/10.1016/j.neubiorev.2008.06.002>
- Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science*, 240, 740–749. doi:<https://doi.org/10.1126/science.3283936>
- McGlone, F., & Reilly, D. (2010). The cutaneous sensory system. *Neuroscience & Biobehavioral Reviews*, 34, 148–159. doi:<https://doi.org/10.1016/j.neubiorev.2009.08.004>
- Méndez-Bértolo, C., Moratti, S., Toledano, R., Lopez-Sosa, F., Martínez-Alvarez, R., Mah, Y. H., . . . Strange, B. A. (2016). A fast pathway for fear in human amygdala. *Nature Neuroscience*, 19, 1041. doi:<https://doi.org/10.1038/nn.4324>
- Milner, D., & Goodale, M. (2006). The visual brain in action. New York, NY: Oxford University Press.
- Müller, G. E., & Schumann, F. (1889). Ueber die psychologischen Grundlagen der Vergleichung gehobener Gewichte. *Archiv für die gesamte Physiologie des Menschen und der Tiere*, 45, 37–112. doi:<https://doi.org/10.1007/bf01789714>
- Müller-Lyer, F. C. (1889). Optische urteilstäuschungen. *Archiv für Anatomie und Physiologie, Physiologische Abteilung*, 2, 263–270.
- Noguchi, Y., Yokoyama, T., Suzuki, M., Kita, S., & Kakigi, R. (2012). Temporal dynamics of neural activity at the moment of emergence of conscious percept. *Journal of Cognitive Neuroscience*, 24, 1983–1997. doi:https://doi.org/10.1162/jocn_a_00262
- Oberle, C. D., & Amazeen, E. L. (2003). Independence and separability of volume and mass in the size–weight illusion. *Perception & Psychophysics*, 65, 831–843. doi:<https://doi.org/10.3758/bf03194818>
- Peters, M. A. K., Ma, W. J., & Shams, L. (2016). The size–weight illusion is not anti-Bayesian after all: A unifying Bayesian account. *PeerJ*, 2016. doi:<https://doi.org/10.7717/peerj.2124>
- Philippe, J., & Clavière, J. (1895). Sur une illusion musculaire. *Revue Philosophique de la France et de l'Étranger*, 40, 672–682.
- Piaget, J. (1941). Le mécanisme du développement mental et les lois du groupement des opérations. *Archives de Psychologie*, 28, 215–285.
- Piaget, J. (1969). The mechanisms of perception (G. N. Seagram, Trans.). London, UK: Routledge & K. Paul.
- Plaisier, M. A., & Smeets, J. B. J. (2015). Object size can influence perceived weight independent of visual estimates of the volume of material. *Scientific Reports*, 5, 17719. doi:<https://doi.org/10.1038/srep17719>
- Pollack, R. H. (1970). Mueller-Lyer illusion: Effect of age, lightness contrast, and hue. *Science*, 170, 93–95. doi:<https://doi.org/10.1126/science.170.3953.93>
- Ponzo, M. (1910). Intorno ad alcune illusioni nel campo delle sensazioni tattili, sull'illusione di Aristotele e fenomeni analoghi. Leipzig, Germany: Wilhelm Engelmann.
- Porac, C., & Coren, S. (1981). Life-span trends in the perception of the Mueller-Lyer: Additional evidence for the existence of two illusions. *Canadian Journal of Psychology*, 35, 58–62. doi:<https://doi.org/10.1037/h0081127>
- Rival, C., Olivier, I., Ceyte, H., & Ferrel, C. (2003). Age-related differences in a delayed pointing of a Müller-Lyer illusion. *Experimental Brain Research*, 153, 378–381. doi:<https://doi.org/10.1007/s00221-003-1559-5>
- Robinson, H. B. (1964). An experimental examination of the size–weight illusion in young children. *Child Development*, 35, 91–107. doi:<https://doi.org/10.2307/1126574>
- Ross, H. E., & Gregory, R. (1970). Weight illusions and weight discrimination—A revised hypothesis. *Quarterly Journal of Experimental Psychology*, 22, 318–328. doi:<https://doi.org/10.1080/00335557043000267>
- Ross, J., & Di Lollo, V. (1970). Differences in heaviness in relation to density and weight. *Perception & Psychophysics*, 7, 161–162.

- Rowe, M. J. (2002). The synaptic linkage for tactile and kinaesthetic inputs to the dorsal column nuclei. In S. C. Gandevia, U. Proske, & D. G. Stuart (Eds.), *Sensorimotor control of movement and posture* (pp. 47–55). Boston, MA: Springer US.
- Seashore, C. E. (1899). Some psychological statistics II. The material weight illusion. *University of Iowa Studies in Psychology*, 2, 36–46.
- Slater, A., Mattock, A., & Brown, E. (1990). Size constancy at birth: Newborn infants' responses to retinal and real size. *Journal of Experimental Child Psychology*, 49, 314–322. doi:[https://doi.org/10.1016/0022-0965\(90\)90061-c](https://doi.org/10.1016/0022-0965(90)90061-c)
- Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition*, 21, 177–237. doi:[https://doi.org/10.1016/0010-0277\(85\)90025-3](https://doi.org/10.1016/0010-0277(85)90025-3)
- Sperandio, I., & Chouinard, P. A. (2015). The mechanisms of size constancy. *Multisensory Research*, 28, 253–283. doi:<https://doi.org/10.1163/22134808-00002483>
- Stevens, J. C., & Rubin, L. L. (1970). Psychophysical scales of apparent heaviness and the size–weight illusion. *Perception & Psychophysics*, 8, 225–230. doi:<https://doi.org/10.3758/BF03210210>
- Trevartha, K. M., & Flanagan, J. R. (2017). Linking actions and objects: Context-specific learning of novel weight priors. *Cognition*, 163, 121–127. doi:<https://doi.org/10.1016/j.cognition.2017.02.014>
- Wolf, C., Bergmann Tiest, W. M., & Drewing, K. (2018). A mass-density model can account for the size–weight illusion. *PLoS ONE*, 13, e0190624. doi:<https://doi.org/10.1371/journal.pone.0190624>
- Wolfe, H. K. (1898). Some effects of size on judgments of weight. *Psychological Review*, 5, 25–54. doi:<https://doi.org/10.1037/h0073342>
- Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269, 1880–1882. doi:<https://doi.org/10.1126/science.7569931>
- Zhu, Q., & Bingham, G. P. (2011). Human readiness to throw: The size–weight illusion is not an illusion when picking the best objects to throw. *Evolution and Human Behavior*, 32, 288–293. doi:<https://doi.org/10.1016/j.evolhumbehav.2010.11.005>
- 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, 221–231. doi:<https://doi.org/10.1007/s00221-012-3301-7>