A meta-analysis of the size-weight and material-weight illusions

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Published online: 1 May 2019
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Abstract

The current study comprises the first systematic meta-analysis of weight illusions. We obtained descriptive data from studies in which subjective heaviness estimates were made for pairs or groups of objects that had the same mass and different volumes (size–weight illusion; SWI) or different apparent material properties (material–weight illusion; MWI). Using these data, we calculated mean effect sizes to represent illusion strength. Other study details, including stimulus mass, volume, density, and degree of visual and somatosensory access to the stimuli were also recorded to quantify the contribution of these variables to effect sizes for the SWI. The results indicate that the SWI has a larger mean effect size than the MWI and that the former is consistent in strength when information about stimulus size is gained through somatosensory channels, regardless of visual access. The SWI is weaker when only the visual system provides size information. Effect sizes for the SWI were larger when there was a greater difference in volume across the stimuli. There was also a positive correlation between SWI strength and the difference in physical density across the different experimental stimuli, even after controlling for volume differences. Together, we argue that these findings provide support for theories of weight illusions that are based on conceptual expectancies as well as those that are based on bottom-up processing of physical density. We further propose that these processes, which have been considered dichotomously in the past, may not be mutually exclusive from each other and could both contribute to our perception of weight when we handle objects in everyday life.

Keywords Size-Weight illusion · Material-Weight illusion · Weight perception

Introduction

Research into weight illusions, where objects with the same mass feel different in weight, paints a complex picture of weight perception. Weight illusions demonstrate how our conscious experience of an object's weight is subject to influence by its other features. For example, size (Charpentier, 1891), material composition (Seashore, 1899; Wolfe, 1898), distribution of mass (Amazeen & Turvey, 1996), shape (Dresslar, 1894; Kahrmanovic, Bergmann Tiest, & Kappers, 2011), and colour (De Camp, 1917; Walker, Francis, & Walker,

2010) are known to influence an object's perceived weight. This line of research points to a complex process by which the brain considers multiple types of visual and somatosensory information to make sense of an object's weight.

The size–weight illusion (SWI) is the most studied weight illusion. Charpentier (1886, 1891) was the first to document the SWI, in which the smaller of two objects of equal mass is typically reported as heavier. Greater differences in size between SWI objects tend to result in greater differences in perceived weight (Ellis & Lederman, 1993; J. Ross & Di Lollo, 1970). The illusion is so robust that it is still experienced even when the perceiver is told that the two objects have the same mass (Flanagan & Beltzner, 2000). Likewise, the perceptual experience of the illusion persists even following *motor* adaptation to the objects' true weight (Buckingham, Ranger, & Goodale, 2011b; Chang, Flanagan, & Goodale, 2008; Chouinard, Large, Chang, & Goodale, 2009; Flanagan & Beltzner, 2000; Flanagan, Bittner, & Johansson, 2008; Grandy & Westwood, 2006). To explain, fingertip forces measured while participants lift two different-sized objects of the same mass typically reflect a greater degree of force applied for

Electronic supplementary material The online version of this article (<https://doi.org/10.3758/s13423-019-01604-x>) contains supplementary material, which is available to authorized users.

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the larger one than for the smaller one, but only during initial lifts. Over subsequent lifts, the applied forces for the two objects become more similar as the motor system learns the objects' real weight. Yet, the perceptual experience of the SWI endures.

There has been extensive research into weight illusions since they were first documented more a century ago. Many theories have been proposed to explain them (for reviews, see Buckingham, 2014; Saccone & Chouinard, 2019; Dijkster, 2014); however, none can account for all relevant findings. Accordingly, the mechanisms underlying weight illusions, as well as weight perception more generally, remain unclear. Many theories of weight illusions can be classified under the broad category of *conceptual expectancies*, as elaborated below and in Fig. 1. However, there is evidence that the SWI is not entirely explained by these accounts. Other accounts of weight perception propose an influence of bottom-up processing of object features (see Fig. 1). These processes might also contribute to the SWI. The present investigation comprises a systematic meta-analysis that aimed to shed light on these two processes, which have, at times, been treated dichotomously in previous research.

Conceptual expectancies

Conceptual expectancy accounts of weight illusions typically emphasise how our understanding and knowledge of objects affects how we perceive their weight (see Fig. 1). According

to these accounts, the SWI reflects our learned understanding of the relationship between size and weight (Buckingham & Goodale, 2010, 2013; Buckingham & MacDonald, 2016; Plaisier & Smeets, 2015). Size is often a reliable indicator of object weight, and experience has taught us to expect that larger objects are typically heavier than smaller ones. This size–weight relationship, which frequently holds in the real world, is violated in the SWI. In this instance, a person's sensory input during lifting contradicts their expectations based on their understanding of the relationship between size and weight. It is this contradiction that causes the smaller object to feel heavier, because it weighs more than expected, and the larger object to feel lighter, because it weighs less than expected. Some believe that expectations may contribute to perception in a top-down manner (Buckingham, 2014). The logic here is that some conceptual understanding of the object is computed before experiencing its weight, which then influences weight perception.

Conceptual expectancy accounts are supported by studies that manipulate expectations of object weight (Buckingham & Goodale, 2010; Ellis & Lederman, 1998; Flanagan et al., 2008). For example, Buckingham and Goodale (2010) produced an SWI based entirely on the expected rather than the actual size of objects. Participants were first shown a small or large cube. Then, participants' vision was obscured, and the experimenter replaced the small or large object with a medium-sized cube, which participants lifted with a handle. Despite lifting the

Fig. 1 Graphical depiction of the two types of accounts that might influence weight perception in the SWI

medium cube on every trial, the participants reported the cube as being heavier when they had previewed the smaller cube and lighter when they had previewed the larger cube, in line with the SWI. Flanagan et al. (2008) also demonstrated the influence of expectations on weight perception by contextually changing the participants' understanding of the size–weight relationship. Participants practiced lifting objects that were large and light, or small and heavy. After extensive training with these unusual stimuli, participants were then tested on the standard SWI, using two different-sized objects with the same mass. They experienced a weak but significant reversal of the SWI, reporting that the larger object felt heavier.

Aside from the SWI, research from other weight illusions also suggests that weight perception can be driven by conceptual expectancies. One such example was provided by Ellis and Lederman (1998). They asked experienced golfers and nongolfers to rate the heaviness of real and practice golf balls that had the same mass. Importantly, only the experienced golfers knew that practice golf balls are lighter than real ones. The nongolfers, who did not expect weight variations across the different types of golf balls, did not perceive any weight differences between the real and practice balls. Conversely, the experienced golfers reported the practice balls being as heavier. This finding is consistent with the SWI, whereby it reflects the opposite perceptual experience to that predicted by the typical, expected feature–weight relationship.

The material–weight illusion (MWI; Buckingham, Cant, & Goodale, 2009; Baugh, Kao, Johansson, & Flanagan, 2012; Ellis & Lederman, 1999; Seashore, 1899; Wolfe, 1898) is frequently cited to support conceptual expectancy accounts of weight illusions (Buckingham, 2014; Buckingham et al., 2009; Buckingham, Ranger, & Goodale, 2011a; Ellis & Lederman, 1999; H. E. Ross, 1969; Vicovaro & Burigana, 2017). The MWI is another well-studied weight illusion. In the MWI, a person lifts two objects of the same size and mass that appear to be made of different materials, such as polystyrene and aluminium (Buckingham & Goodale, 2013). In this context, it is the apparent material composition, rather than size, that informs weight expectations. If there are two equally sized objects made from either polystyrene or aluminium, our conceptual understanding of these materials tells us that the aluminium object should be heavier. The typical finding in the MWI is that the object apparently made from a lighter material (e.g., polystyrene) is perceived as being heavier than the other (e.g., aluminium; Baugh et al., 2012; Buckingham et al., 2009; Ellis & Lederman, 1999). Therefore, established material–weight associations are violated, producing the opposite perceptual experience, consistent with other weight illusions.

Overall, a conceptual expectancy account fits well with some of the weight illusion literature. However, some findings that are specific to the SWI create problems for this account, as we will discuss below. These findings suggest that a different mechanism might also contribute to the SWI.

Conceptual expectancies may not entirely explain the SWI

The first consideration is that the SWI might be stronger relative to other weight illusions (Buckingham, Bieńkiewicz, Rohrbach, & Hermsdörfer, 2015a; Buckingham & Goodale, 2013; Vicovaro & Burigana, 2017), potentially creating a dilemma for conceptual accounts of weight illusions. According to these accounts, it is our expectations, formulated by our conceptual knowledge that drives the misperception of weight in a top-down manner (Buckingham, 2014; Saccone & Chouinard, 2019). If weight perception truly operated in a top-down manner, then the type of concept driving these expectations should not matter, provided they afford similar predictive values. In this context, does one concept exert a stronger change in perceived weight than the other? If so, is this related to differences in predictive values, as one might expect from a conceptual expectancy account, or by some other explanation?

Findings from two studies by Buckingham and colleagues indicate that the SWI is a stronger illusion than the MWI (Buckingham, Bieńkiewicz, et al., 2015; Buckingham & Goodale, 2013), shedding some light on this issue. In one study, Buckingham, Bieńkiewicz, et al. (2015) conducted a neuropsychological investigation of weight illusions that also included a healthy control group. Participants lifted both SWI and MWI object pairs and stated which one of each pair was heavier. An SWI was evident when the smaller object was reported as being heavier than the larger object, and the MWI was present when the polystyrene object was reported as being heavier than the aluminium one. The control group experienced an SWI in 95.8% of trials, but the MWI in only 35.1% trials. Buckingham and Goodale's (2013) study also included both SWI and MWI stimuli. They compared the difference in heaviness ratings for the SWI (large vs small) and the MWI (polystyrene vs aluminium). The SWI appeared to be considerably stronger than the MWI, in that there was a greater difference in perceived weight between the large and small stimuli than between the volume-matched polystyrene and aluminium objects. These findings demonstrate that variations in stimulus surface material lead to smaller differences in perceived weight (Buckingham & Goodale, 2013) and differences that are less reliable (Buckingham, Bieńkiewicz, et al., 2015) than variations in size.

The question then arises as to whether these differences exist because size is a stronger predictor of an object's weight. To test this possibility, Vicovaro and Burigana (2017) had participants rate both the expected weight of objects that varied in size and/or apparent material before lifting as well as their perceived weight afterwards. Their results showed that material exerted a stronger influence on weight expectations before lifting than size did. Note that these effects could be specific to their stimulus set, given that material differences

appeared more pronounced than size differences (as shown illustratively in their Fig. 1). Nevertheless, they argued that conceptual expectancy explanations predict, in this case, that material should influence perception more strongly than size. However, contrary to what one might expect from these accounts, their results demonstrated that size influenced perception more strongly than material—despite the stronger predictive value of the latter on the expected weight.

These findings suggest that the SWI is a stronger illusion than the MWI, given that variations in size rather than surface material seem to produce larger and more reliable differences in perceived weight. This creates a dilemma for conceptual accounts of weight illusions, provided that size is not a greater predictor of weight than material. Whether or not the MWI is associated with smaller effect sizes than the SWI across the literature has never been systematically confirmed in a meta-analysis until now.

The second consideration relates to the role of different sensory input modalities in the SWI. Conceptual theories emphasise top-down influences driven by weight expectations that are based on an understanding of the relationship between an object's weight and its other features. By this logic, the SWI should be consistent regardless of the particular sensory modality providing reliable conceptual information about the size of the stimuli. However, some studies report that the SWI is stronger when information about the size of the stimuli is obtained through the somatosensory system than when the same information is presented visually (Ellis & Lederman, 1993), posing another problem for conceptual expectancy accounts.

Ellis and Lederman (1993) directly compared the influence of different sensory modalities. In their study, the authors varied the availability of somatosensory and visual information. In one condition, participants were blindfolded and only received somatosensory information about the size of the stimuli by hefting them. In this case, haptic information was received through the pressure exerted from the objects on the touch receptors in the skin. Kinaesthetic information was also obtained via the proprioceptors in the muscles as the objects were balanced in the palm of each hand. In a second condition, participants could see the objects, but all somatosensory information about their size was removed by having the participants lift the stimuli using strings. In a third condition, participants were permitted to see the objects while they hefted them, providing the participants with information about the size of the objects via both somatosensory and visual channels. Comparisons between the three conditions indicated that the SWI was weakest when only visual information about size was available. The strength of the SWI was greater when somatosensory feedback about size was available. Namely, there was a greater difference in perceived weight across the objects when size information was gained through haptic and kinaesthetic feedback. Furthermore, the availability of visual

information about size made no difference to illusion strength when somatosensory feedback was also available, a pattern also seen in Plaisier and Smeets's (2015) Experiment 4.

The findings described in this section suggest that conceptual expectancies do not entirely explain the SWI. A systematic meta-analysis of these studies could shed light as to whether or not obtaining size information through somatosensory or visual modalities matter for the illusion. Next, we discuss alternative explanations that propose a role of bottom-up mechanisms.

Bottom-up processing

Other accounts of weight illusions emphasise the role of a third-party object feature in driving weight perception. These accounts propose that aside from mass, there is another variable that is processed or computed during handling that influences or is construed as perceived weight in a bottom-up fashion (see Fig. 1; J. Ross & Di Lollo, 1970; Stevens & Rubin, 1970). This process could be similar to the same way that a person might mistake flavour for taste. For example, the perception of a 'hot'-tasting jalapeño does not arise from the taste buds, but rather from the pain receptors in the mouth and nose.

One of these accounts implicates physical density. This account is particularly relevant to the SWI because stimuli vary not only in size but also in density; the smaller of two objects of equal mass must also be denser. Although there are *apparent* or expected density differences in the MWI, there are no *physical* density differences in the MWI as there is in the SWI because MWI stimuli are identical in both size and mass. Accordingly, several research groups have considered how physical density may be implicated in the SWI (Chouinard et al., 2009; Harshfield & DeHardt, 1970; Peters, Ma, & Shams, 2016; H. E. Ross & Gregory, 1970; Stevens & Rubin, 1970; Thouless, 1931; Wolf, Bergmann Tiest, & Drewing, 2018). A number of SWI studies have examined how weight perception changes with density (J. Ross & Di Lollo, 1970; Stevens & Rubin, 1970; Wolf et al., 2018). One of these demonstrated that perceived weight can increase with density even when mass is held constant (J. Ross & Di Lollo, 1970).

Aside from density, other object features could be construed as weight. Some authors have emphasised how the processing of object properties that are relevant for action, or "affordances" (Gibson, 1979), might also influence weight perception. For example, Amazeen and Turvey (1996) demonstrated that perceived weight was predicted not only by an object's mass but also by the distribution of its mass. They attached weights to different locations on long rods, which varied the rotational inertia of the rods as they were held and manipulated by their participants. The participants perceived the objects' rotational inertia via the torques applied during the lift, which the authors argued was construed as a weight percept. Zhu and Bingham (2011) provide another study

examining affordances in weight perception. Their results indicated that differences in perceived weight in the SWI were related to judgements of how far objects can be thrown, or what the authors referred to as their *throwability* affordance.

These processes could still occur alongside conceptual expectancy mechanisms (Buckingham, 2014). As discussed, conceptual expectancies influence weight perception in a top-down manner (see Fig. 1); for example, knowing that lead is heavy will cause one to expect a lead object to be heavy and consequently influence weight perception, as in the MWI. However, the processing of another feature can also influence weight perception in a bottom-up manner. For instance, lifting a denser object without considering its material composition will cause one to perceive it as being heavier if the brain misinterprets density as weight. Note that density is the determining factor that influences weight in both examples. However, it is the conceptual knowledge about an object's expected or *apparent* density that influences weight perception in the first case, whereas it is the bottom-up processing of *physical* density in real time that gets translated or construed as weight in the second case. Thus, it is possible that both conceptual expectancies and bottom-up processing explain weight illusions. Considering both explanations could explain many findings that do not fit well with conceptual expectancy or bottom-up theories alone. An influence of bottom-up processing of physical density could account for a stronger SWI than MWI. However, bottom-up processing of density cannot explain the MWI because physical density is the same for both objects. Differences in density in the MWI are apparent, or expected, and thus differences are conceptual.

Unlike conceptual expectancy accounts, bottom-up explanations can allow for varying effects of sensory modality on the SWI given that sensory channels process information somewhat independently—at least in the earlier stages of sensory processing. Consider the ‘hot’ jalapeño analogy described earlier. A jalapeño feels excruciatingly more painful if it touches the eye than when it is inside the mouth. The same stimulus leads to two different levels of sensation when processed by these two independent channels. Compared with vision, information about an object's weight is processed most directly by the somatosensory system via the proprioceptors in the muscles (McGlone & Reilly, 2010; Rowe, 2002). Vision can certainly extract an object's weight, but only by observing how the limbs respond to an object's weight during lifting (Buckingham, Michelakakis, & Cole, 2016b; Buckingham et al., 2011b), which is conceivably a more demanding cognitive process. Computing an object's physical density requires information about both its size and its weight. In contrast to vision, the somatosensory system is designed to calculate both features more directly through haptic and kinaesthetic feedback (Ellis & Lederman, 1993). In this sense, the somatosensory system is arguably better placed to compute physical density with greater efficiency than the visual

system is and could therefore potentially exert a larger effect on the SWI if bottom-up processes play a role. However, studies that have compared different sensory modalities are mixed and few in number. A systematic meta-analysis of SWI studies could shed light as to whether or not obtaining size information through somatosensory or visual modalities matters for the perceptual experience of the illusion.

The current study

We conducted a meta-analytic review of the SWI and MWI to assess support for (a) conceptual expectancy and (b) bottom-up processing explanations for weight illusions. We obtained descriptive data from studies in which subjective heaviness estimates were made for pairs or groups of objects that had the same mass and different volumes (SWI) or apparent material properties (MWI). Differences in reported heaviness between stimuli were combined to produce an effect size measure, which served as a common metric of illusion strength across studies. Other study details, including stimulus mass and volume, and the degree of visual and somatosensory access to the stimuli, were also recorded to quantify the contribution of these variables to the strength of the illusory weight experience.

We tested the following predictions. If conceptual expectancies entirely explain the SWI, then the SWI and MWI should be similar in strength, assuming they predict weight to a similar degree. Specifically, effect sizes for the two illusions across the literature base should have a comparable magnitude. Furthermore, size information obtained through somatosensory and visual channels should produce a comparable SWI. Alternatively, a contribution of bottom-up processing of physical density predicts a stronger SWI than MWI. Unlike conceptual expectancy accounts, bottom-up processing accounts allow for a variable effect of sensory modality on the SWI. A further prediction is that physical density should relate to illusion strength in the SWI. Namely, if the bottom-up processing of physical density contributes to forming a weight percept, then a greater difference in density across SWI objects should be associated with a greater difference in perceived heaviness and, therefore, a stronger SWI. Accordingly, the current study had the following aims:

Aim 1: To quantify and compare the strength of the SWI and MWI to determine if the type of concept matters. Addressing this aim will shed light into the viability of conceptual expectancy accounts.

Aim 2: To quantify the contribution of vision and somatosensory information about stimulus size in the SWI to determine if the type of sensory processing matters. Addressing this aim will shed light into the viability of bottom-up processing explanations.

Aim 3: To investigate the relationship between SWI strength and physical density differences across stimuli. Addressing this aim will shed light into the viability of a specific bottom-up processing explanation that is centred on the influence of density processing.

Method

Sample of studies

The first author (E.S.) conducted literature searches in PubMed and Scopus for studies published before September 2017. Figure 2 provides a step-by-step illustrative account of how papers were searched and triaged by E.S. Using the search terms ‘size–weight illusion’ OR ‘material–weight illusion’, 179 published studies were found. Of these, 31 studies were excluded because they did not use stimuli that met criteria for either the SWI (same mass, different volume) or MWI (same mass, different apparent material). Twenty-four papers were excluded because they were review articles and/or did not report novel data (e.g., reanalysis or linguistic translation of previously published data). Nine studies were excluded because they did not employ a neurologically normal adult sample (e.g., children, neuropsychological cases with no control group). Thirty-eight papers were excluded because they did not include subjective, perceptual ratings of stimulus weight (e.g., participants gave a binary response indicating which one of two stimuli were heavier). A further 38 papers did not include sufficient information about experimental methodology, stimulus properties, or descriptive statistics to be included in the meta-analysis and were published prior to 2000, so it was deemed unlikely that the information could be obtained from the authors. For manuscripts with insufficient detail that were published in or after the year 2000, E.S. e-mailed authors for the additional information. Following this process, a further 16 studies were excluded because the required information could not be obtained. All authors who were contacted were also asked for any unpublished data sets or “file drawer” data. The final number of studies included was 28 (see Fig. 2). This sample included three unpublished data sets and 39 different experimental conditions.

Recorded/moderator variables

Details of the study design and stimulus properties from each experiment were recorded, including study *N*s, stimulus mass and volume, lifting style, degree of visual access, and experimental manipulations. To examine the effect of sensory input modality on illusion strength, the availability of visual and somatosensory information for each experimental condition was coded into the following dichotomous variables:

Somatosensory (some, none); Vision (some, none), as detailed in Table 1. Stimulus density was calculated by dividing mass by volume (g/cm^3).

Dependent measure

We recorded mean heaviness ratings for SWI or MWI objects (see [Supplementary Material](#) for the raw data). In most cases, these scores represented participants’ subjective magnitude estimates for two or more objects within an experiment or condition. In other cases, one of the objects was deemed the ‘standard’ and was allocated a certain heaviness value by the experimenter, against which participants gave a relative magnitude estimate of heaviness for the other object(s). If raw or standardised means and standard deviations (*SD*s) were not reported in the manuscript, and could not be estimated precisely from graphs, then we contacted authors for the required information.

We used observations of effect size to represent the difference in perceived heaviness between pairs of illusory objects within an experiment. Cohen’s *d* was chosen as the measure of effect size because it is a standardised and easily interpretable measure of the difference between two means. Using a standardised index of effect size enabled us to compare illusion strength across studies without the original response scales influencing the results. Each observation of Cohen’s *d* was calculated as the difference between two mean heaviness ratings, divided by the pooled standard deviation (i.e., using the standard deviations of the two means, which represents variability across participants), weighted by sample size (Card, 2011; Cohen, 1988; Lipsey & Wilson, 2001). Data were organised such that there was one observation of *d* per stimulus pair. Given that most SWI or MWI studies include more than two stimuli, there was typically more than one observation of *d* per experiment. For example, a single SWI experiment with a small, medium, and large stimulus would yield three observations of *d* (i.e., small vs medium, small vs large, medium vs large).

The meta-analysis required us to quantify illusion strength across all included studies. To do so, we determined mean weighted *d*s and 95% confidence intervals (CI) for each illusion. First, we calculated a single, pooled effect size for each experiment, then used these pooled *d*s to determine the overall mean *d*s for the different illusions. We used the experiment-wise pooled *d*s to calculate the means to ensure that experiments including more than two stimuli (and therefore multiple observations of *d*) were not overrepresented in the overall means. Pooled *d*s and their variances were calculated according to Borenstein, Hedges, Higgins, and Rothstein’s (2009) formulae for combining within-study effect sizes from multiple outcomes. Mean *d*s were weighted to account for sample size differences across experiments. The weighting procedure, including formulae for inverse variance weight values and

Fig. 2 Flow chart summarising search and screening processes for the meta-analysis study inclusion

$SE_{Mean\ weighted\ d}$ were taken from Card (2011; also see Lipsey & Wilson, 2001). This weighting procedure is commonly used in meta-analyses (e.g., Landry & Al-Taie, 2016). We interpreted values of d according to the following criteria: 0.2–0.49 = small effect size, 0.5–0.79 = medium effect size, and <0.8 = large effect size (Cohen, 1988).

To achieve Aim 1, mean weighted d s were calculated separately for the SWI and MWI. To achieve Aim 2, mean weighted d s were calculated independently for three versions of the SWI, according to the different levels of the vision and somatosensory variables as defined in Table 1: (1) SWI-vision (vision: some; somatosensory: none); (2) SWI-somatosensory (vision: none; somatosensory: some); and (3) SWI-vision and

somatosensory (vision: some; somatosensory: some). Thus, for the purpose of Aim 2, these three variations of the SWI were treated as independent illusions.

To achieve Aim 3, we investigated the relationship between SWI strength and physical density differences across stimuli. In investigating the effect of density differences, it was important to account for volume differences, which are inherent in the SWI and have been shown to vary with illusion strength (Ellis & Lederman, 1993; J. Ross & Di Lollo, 1970). Accordingly, we conducted a hierarchical regression analysis to examine the relationship between illusion strength and density differences, after controlling for the effects of volume. Note that the experiment-wise pooled d s could not be used

Table 1 Key variables, variable levels and examples of experimental conditions that were included in each variable level for Aims 1 (SWI vs MWI) and 2 (comparing sensory modalities in the SWI)

Key variables	Variable levels	Examples
AIM 1		
Illusion	SWI	Small and large stimuli of same mass
	MWI	Apparent polystyrene and aluminium composition; same size and mass
AIM 2		
Vision	Some	Complete access (i.e., before and during lift) Before but not during lift Partial/poor vision
	None	Vision completely obscured
Somatosensory	Some	Full haptic lift (i.e., lifted object directly with hand) Full haptic lift with another person Lifted via a handle attached to object Pushed object on trolley
	None	Lifted via string/pulley system Pushed stimulus which was suspended via string

as the dependent variable for this analysis because differences in volume and density across objects were averaged within the pooled d s. Accordingly, the dependent variable for this analysis comprised the original observations of d , which represent the difference in perceived weight for pairs of stimuli within a particular experiment or condition. For each observation of d , we calculated the difference in both volume and density across the object pair. The volume of the smaller object of the pair was expressed as a percentage of the larger one. Density differences were calculated by subtracting the density of the larger object from that of the smaller object. Note that stimulus volume (and therefore density) was unknown for a small number of objects (e.g., the trolleys in Schmidler & Bengler's, 2016, experiments), as seen in Table 3. These data points were excluded from this analysis. The [supplementary material](#) details the volume and density differences for all included object pairs and their observations of d .

Results

Mean weighted d s for the different illusions are presented in Table 2. Table 3 summarises all included experiments and their pooled d s, which were combined to produce the overall mean d s. Table 3 also contains the mean volume and density differences between SWI stimuli within each experiment. Forest plots displaying the pooled d s are presented separately for the MWI (Fig. 3) and each variant of the SWI (Fig. 4). The [Supplementary Material](#) contains detailed information about all collected

observations of d , including the nature of the stimulus pair comprising each observation (e.g., small vs medium; medium vs large), as well as the mass, volume, density, and mean heaviness estimates for all stimuli.

Aim 1: Overall effect of the SWI vs MWI

Mean weighted d s for the SWI and MWI are displayed in Table 2. Both illusions have large effect sizes. Regarding the weighted means, there is no overlap in the 95% CIs, demonstrating a significant difference between the two means. Thus, the results demonstrate that the SWI is significantly stronger than the MWI.

Aim 2: Comparing sensory modalities in the SWI

Table 2 displays the mean weighted d s for the SWI-somatosensory, SWI-vision, and SWI-vision and somatosensory. All variants of the SWI have large mean effect sizes. Examination of the 95% CIs for the means reveal that the SWI-somatosensory and SWI-vision and somatosensory are comparable in strength, whereas the SWI-vision is weaker than the other two variants. Table 2 also displays the overall mean volume and density differences across stimuli for the three versions of the SWI. The 95% CIs for the mean volume and density differences demonstrate that the SWI groups are sufficiently matched in this respect. The three variants of the SWI are discussed in more detail below.

The mean weighted d for the SWI-somatosensory is 1.74 (95% CI [1.46, 2.02]). This mean estimate comprises pooled d s from six unique experimental conditions (see Table 3 and Fig. 4). The pooled d s for this variant of the SWI range from 0.24 (Schmidler & Bengler, 2016) to 5.58 (Buckingham et al., 2011b).

The mean weighted d for the SWI-vision is 1.00 (95% CI [0.57, 1.43]). This mean effect size comprises pooled d s from four unique experiments (see Table 3 and Fig. 4). The pooled d s for this variant of the SWI range from -0.44 (Saccone, Goldsmith, Buckingham, & Chouinard, 2018) to 2.95 (Buckingham, Milne, Byrne, & Goodale, 2015b). As mentioned, the SWI-vision is a weaker illusion than the other two variants of the SWI. The upper boundary of the 95% CI for the SWI-vision is close to the lower boundary of the 95% CI for the SWI-somatosensory.

The mean weighted d for the SWI-vision and somatosensory is 1.95 (95% CI [1.80, 2.10]). This is the most common variant of the SWI. The mean effect size for this version of the SWI comprises pooled d s from 22 unique experimental conditions (see Table 3 and Fig. 4). The pooled d s range from values as low as -0.18 (Schmidler & Bengler, 2016) and as high as 8.92 (Buckingham & Goodale, 2013).

Table 2 Mean weighted *ds* and 95% confidence intervals (CI) for the MWI and SWI overall (Aim 1) and the three versions of the SWI according to visual and somatosensory feedback (Aim 2)

Illusion	No. of observations of <i>d</i>	No. of pooled <i>ds</i>	Mean volume difference (%) [95% CI]	Mean density difference (g/cm ³) [95% CI]	Mean weighted <i>d</i> [95% CI]
AIM 1					
MWI	17	6	-	-	1.00 [0.74, 1.26]
SWI (all)	152	32	27.16 [24.16, 30.24]	1.85 [1.52, 2.19]	1.82 [1.70, 1.95]
AIM 2					
SWI-somatosensory	24	6	34.58 [9.68, 59.49]	2.82 [1.45, 4.18]	1.74 [1.46, 2.02]
SWI-vision	21	4	29.333 [5.80, 52.87]	1.52 [-0.33, 3.37]	1.00 [0.57, 1.43]
SWI-vision and somatosensory	107	22	27.49 [20.00, 34.98]	2.18 [1.48, 2.87]	1.95 [1.80, 2.10]

Note. No. of observations of *d* refers to the total number of effect size observations collected from published studies for each illusion (detailed in the [supplementary material](#)). No. of pooled *ds* refers to the number of experiment-wise pooled *ds* that were used to calculate each mean. Mean volume difference refers to the mean difference across all stimulus pairs that comprise the mean weighted *d* (volume of smaller object presented as a percentage of larger object). Mean density difference refers to the mean difference across all stimulus pairs that comprise the mean weighted *d* (density of smaller object minus density of larger object)

Aim 3: Relationship between SWI strength and density difference

To address Aim 3, we examined the relationship between observations of *d* and physical density differences across SWI stimuli. First, two Pearson correlations were performed to test the independent relationships between SWI strength and both volume and density differences. The SWI was stronger when there was a greater volume discrepancy across the stimuli, $r(140) = -.297$, $p < .001$. A stronger SWI was also associated with greater differences in physical density, $r(140) = .466$, $p < .001$ (see Fig. 5).

Next, we performed a hierarchical regression analysis to test the relationship between SWI strength and density differences, while controlling for volume differences. Volume difference was entered in Step 1 of the analysis, $R^2 = .088$, $F(1, 140) = 13.524$, $p < .001$. Density difference was entered in Step 2, $R^2_{\text{change}} = .135$, $F_{\text{change}}(1, 140) = 24.147$, $p < .001$. These results demonstrate that density differences across SWI stimuli explain 13.5% of the variance in *d* after controlling for differences in volume.

Discussion

This study assessed support for (a) conceptual expectancies and (b) bottom-up processing explanations for weight illusions. To test predictions of these two types of accounts, the meta-analysis quantified and compared the strength of the SWI and MWI (Aim 1), as well as the influence of somatosensory and visual information about stimulus size on the SWI (Aim 2). As a further test of a contribution of bottom-up processing of physical density in the SWI, we also examined the relationship between SWI strength and physical density

differences across stimuli (Aim 3). Overall, this meta-analysis provides support for both types of accounts.

Our first aim was to compare the SWI and MWI. The number of SWI experiments and the number of effect size observations we could calculate from them far exceeded those for the MWI. The results demonstrated a larger mean effect size for the SWI than the MWI, which supports preliminary claims in the existing literature (Buckingham, Bieńkiewicz, et al., 2015; Buckingham & Goodale, 2013; Vicovaro & Burigana, 2017). This finding is potentially consistent with the idea that conceptual expectancies do not entirely account for the SWI and could support a contribution of bottom-up processes to the illusion. However, we still observed a large mean effect size for the MWI. In this case, it is the expected but not the actual physical density that must account for the illusion – one that is based on a conceptual understanding of different materials and how this understanding is used to predict weight. Given that bottom-up processing of physical density cannot explain the MWI, this finding bolsters accounts based on conceptual expectancies.

We also note a higher degree of variability in the effect sizes for the SWI than for the MWI. The experiment-wise pooled *ds* for the MWI ranged between 0.51 and 1.28 (see Table 3 and Fig. 3), and these data points do not appear to deviate much from the weighted mean. Conversely, the pooled *ds* for the SWI were highly variable across studies, ranging from less than zero (Saccone et al., 2018; Schmidtlér & Bengler, 2016, in Table 3 and Fig. 4) to more than 8 (Buckingham & Goodale, 2013, in Table 3 and Fig. 4). In addition, there appeared to be greater variability in sample sizes, methodologies, and experimental manipulations in the SWI than in the MWI, likely contributing to the greater variability in effect sizes for the SWI.

An important consideration, which we were unable to resolve, is that differences in effect sizes between the two

Table 3 List of all included experiments, number of participants (*N*), details of participants' visual access to stimuli, lifting technique, experiment/condition details, number of observations of *d* collected for each experiment, the pooled (mean) volume difference between stimuli for each experiment (volume of smaller object presented as a percentage of larger object), the pooled (mean) density difference between stimuli for each experiment (density of smaller object minus density of larger object), and pooled *ds* for each experiment with 95% confidence intervals (CI)

Study	<i>N</i>	Visual access	Lifting technique	Experiment/condition details	No. of collected observations of <i>d</i>	Pooled volume difference (%) [95% CI]	Pooled density difference (g/cm ³) [95% CI]	Pooled <i>d</i> [95% CI]
MWI								
Buckingham (2019), Experiment 1	18	Complete	Via attached transducer handle	Unknown	3	N/A	N/A	1.28 [0.58, 1.98]
Buckingham, Cant, and Goodale (2009), Experiment 1	26	Complete	Via attached transducer handle	Control experiment	3	N/A	N/A	1.09 [0.50, 1.68]
Buckingham and Goodale (2013), Experiment 1	28	Complete	Via attached transducer handle	Combined SWI and MWI	2	N/A	N/A	1.05 [0.50, 1.60]
Buckingham, Michelakakis, and Cole (2016b), Experiment 1	7	Complete	Via attached transducer handle	Case study control group	3	N/A	N/A	0.51 [−0.57, 1.59]
Buckingham, Ranger, and Goodale (2011a), Experiment 1	22	Before but not during lift	Via attached transducer handle	Investigated reduced visual access	3	N/A	N/A	0.74 [0.12, 1.35]
Paulun, Buckingham, Goodale, and Fleming, 2019, Experiment 1	24	Complete	Via attached transducer handle	Control condition	3	N/A	N/A	1.06 [0.46, 1.67]
SWI-somatosensory								
Buckingham, Ranger, and Goodale (2011b), Experiment 3	20	None	Via attached transducer handle following haptic preview of size before lifting with handle	No visual access, haptic preview of size before lifting with handle	3	28.10 [11.23, 44.97]	3.27 [0.94, 5.59]	5.58 [4.77, 6.38]
Butler, Héroux, and Gandevia (2015), Experiment 2	16	None	Lifted objects directly via variable axis	No visual access, haptic experience of varying stimulus width	3	–	–	1.57 [0.81, 2.33]
Plaisier and Smeets (2015), Experiment 4	40	None	Lifted objects directly	Control condition	1	66.70 [–]	0.92 [–]	2.19 [1.49, 2.89]
Schmidler and Bengler (2016), Experiment 1	29	None	Pushed large object on trolley	Condition: pushed object (which was on trolley)	2	–	–	0.24 [−0.28, 0.77]
Walker, Scallan, and Francis (2017), Experiment 1	28	None	Lifted objects directly	Investigated effects of perceived brightness and pitch	9	38.13 [29.55, 46.72]	2.84 [1.39, 4.29]	2.86 [2.25, 3.47]
Wolf, Bergmann Tiest, and Drewing (2018), Experiment 2	20	None	Condition 1: Lifted objects directly Condition 2: Lifted objects directly using precision grip	Investigating role of density	6	5.40 [–]	4.24 [2.44, 6.04]	1.92 [1.23, 2.61]
SWI-vision								
Buckingham, Milne, Byrne, and Goodale (2015b), Experiment 1	4	Before but not during lift	Via cable-pulley system	Control group (compared with blind echolocators)	6	11.93 [3.09, 20.78]	0.34 [0.14, 0.54]	2.95 [1.34, 4.57]

Table 3 (continued)

Study	N	Visual access	Lifting technique	Experiment/condition details	No. of collected observations of <i>d</i>	Pooled volume difference (%) [95% CI]	Pooled density difference (g/cm ³) [95% CI]	Pooled <i>d</i> [95% CI]
Plaision and Smeets (2012), Experiment 1	20	Condition 1: complete Condition 2: before but not after push	Pushed on a string	Condition 1: complete Condition 2: before but not after push	2	50.00 [–]	0.58 [–]	1.26 [0.59, 1.92]
Saccone, Goldsmith, Buckingham, and Chouinard (2018)	14	Complete	Via strings	Investigated liquid volume vs size	1	50.00 [–]	0.82 [–]	–0.44 [–1.13, 0.26]
Wolf et al. (2018), experiment 1	15	Condition 1: full Condition 2: poor vision (using goggles) Condition 3: medium vision (using goggles)	Via strings	Investigating role of density Condition 1: full Condition 2: poor vision (using goggles) Condition 3: medium vision (using goggles)	12	5.40 [–]	4.34 [3.22, 5.45]	2.26 [1.45, 3.07]
SWI-vision and somatosensory Buckingham, Byrne, Paciocco, van Eimeren, and Goodale (2014a), Experiment 1	18	Complete	Via handle of dumbbell stimuli	Weightlifting exercise	1	–	–	1.05 [0.35, 1.74]
Buckingham and Goodale (2010), Experiment 1	19	Complete	Via attached transducer handle	Control condition	3	28.10 [11.23, 44.97]	3.27 [0.94, 5.59]	4.76 [3.89, 5.63]
Buckingham and Goodale (2013), Experiment 1	28	Complete	Via attached transducer handle	Condition 1: aluminium cubes Condition 2: polystyrene cubes	2	12.50 [–]	4.90 [–]	8.92 [8.16, 9.68]
Buckingham, Goodale, White, and Westwood (2016a), Experiment 1	72	Complete	Via attached transducer handle	Condition 1: stimuli same colour Condition 2: stimuli different colour	2	50.40 [–]	0.49 [–]	1.00 [0.50, 1.48]
Buckingham and MacDonald (2016), Experiment 1	72	Complete	Stimuli placed in participants' hands	Natural weight sport/recreational balls	1	3.10 [–]	0.15 [–]	1.28 [0.93, 1.63]
Buckingham, Michelakakis, and Cole (2016b), Experiment 1	7	Complete	Via attached transducer handle	Case study control group	6	41.90 [30.59, 53.21]	1.24 [0.72, 1.76]	1.02 [–0.09, 2.13]
Buckingham, Michelakakis, and Rajendran (2016c), Experiment 1	80	Complete	Via attached transducer handle	Examined relationship with Autistic traits	3	41.87 [24.04, 59.69]	1.36 [0.49, 2.23]	5.40 [5.01, 5.79]
Buckingham et al. (2011b), Experiment 1	18	Before but not during lift	Via attached transducer handle	Participants saw stimuli briefly before they initiated reach and lift	3	28.10 [11.23, 44.97]	3.27 [–0.94, 5.59]	5.67 [4.82, 6.53]
Buckingham et al. (2011b), Experiment 2	23	Before but not during lift	Via attached transducer handle	Participant saw stimuli until they touched the transducer handle	3	28.10 [11.23, 44.97]	3.27 [–0.94, 5.59]	2.56 [1.90, 3.23]
Buckingham et al. (2011b), Experiment 4	23	Before but not during lift	Via attached transducer handle	Participants saw stimuli briefly before they initiated reach and lift	3	28.10 [11.23, 44.97]	3.27 [–0.94, 5.59]	5.95 [5.18, 6.71]

Table 3 (continued)

Study	N	Visual access	Lifting technique	Experiment/condition details	No. of collected observations of <i>d</i>	Pooled volume difference (%) [95% CI]	Pooled density difference (g/cm ³) [95% CI]	Pooled <i>d</i> [95% CI]
Buckingham, Ranger, and Goodale (2012), experiment 1	60	Complete	Via attached transducer handle	None but compared across handedness	3	28.10 [11.23, 44.97]	3.27 [0.94, 5.60]	6.51 [6.02, 7.00]
Buckingham, Reid, and Potter (2018), Experiment 1	40	Complete	Via attached transducer handle	None but compared across age (younger vs older)	2	25.00 [–]	2.42 [–]	3.25 [2.73, 3.77]
Buckingham, Wong, Tang, Gribble, and Goodale (2014b), Experiment 1	21	Complete	Via attached transducer handle	Condition 1: watched video of erroneous stimulus lifting beforehand Condition 2: watched video of appropriate stimulus lifting beforehand	2	12.50 [–]	4.90 [–]	1.31 [0.65, 1.97]
Dijker (2008), Experiment 1	19	Before but not during lift	Via attached handle	Control condition	15	25.73 [15.27, 36.18]	2.43 [1.44, 3.41]	2.28 [1.56, 3.00]
Fercho and Baugh (2016), Experiment 1	24	Complete	Lifted objects directly	Participants had EMG electrodes attached to lifting hand. Condition 1: participants told electrodes had “active” role Condition 2: participants told electrodes had “passive” role	2	3.70 [–]	4.57 [–]	1.52 [0.65, 2.39]
Jones and Burgess (1998), Experiment 1	10	Complete	Lifted objects directly	Control condition	1	7.00 [–]	1.44 [–]	1.48 [0.52, 2.43]
Li, Randerath, Goldenberg, and Hermsdörfer (2007), Experiment 1	5	Complete	Via attached transducer handle	Case study control group	1	5.40 [–]	1.40 [–]	2.30 [0.89, 3.71]
Naylor and Amazeen (2004), Experiment 1	32	Complete	Lifted objects directly together with partner	Two people lifted object together	24	31.77 [25.22, 38.31]	0.20 [0.11, 0.28]	1.13 [0.61, 1.65]
Naylor and Amazeen (2004), Experiment 2	16	Complete	Lifted objects directly	Control condition	24	31.77 [25.22, 38.31]	0.20 [0.11, 0.28]	0.49 [–0.22, 1.20]
Plaisier and Smeets (2012), Experiment 1	20	Complete	Lifted objects directly with precision grip	Control condition	1	50.00 [–]	0.58 [–]	2.04 [1.35, 2.74]
Plaisier and Smeets (2015), Experiment 4	40	Complete	Lifted objects directly	Control condition	1	66.70 [–]	0.92 [–]	2.60 [1.89, 3.32]
Schmidler and Bengler (2016), Experiment 1	29	Complete	Pushed trolley with object on top	Condition: pushed trolley containing object	4	–	–	–0.18 [–0.69, 0.33]

Note. Pooled *ds* are also displayed in Fig. 3 (MWT) and Fig. 4 (SWT). Volume (and therefore density) could not be calculated for three SWT studies

Fig. 3 Forest plot displaying all experiment-wise pooled d s (circles) and mean weighted d (dashed line) and 95% confidence interval (CI; dotted line) for the mean weighted d for the MWI. Error bars represent 95% CIs for the experiment-wise pooled d s

illusions may have been driven by scalar differences for volume versus apparent material. To explain, discrepancies in volume between objects influence effect sizes for the SWI, whereas discrepancies in expected densities between objects influence effect sizes for the MWI. Could it be the case that the former is stronger in this meta-analysis because there were greater discrepancies in volume than expected density in the published literature? One could potentially resolve this by performing correlations between effect sizes and these discrepancies. For the MWI, one might expect to find a correlation between effect sizes and expected density differences, as informed by surface material. For example, if a polystyrene object is rated against an aluminium one, the effect size for the MWI should be larger than when the aluminium object is compared with wood because there is a greater difference in expected density in the former than the latter pair (see Ellis & Lederman, 1999, for an example of this pattern). However, we did not have sufficient data points to test this possibility using a correlation analysis. Only four different surface materials have been employed (polystyrene, wood [oak], stone [granite], and aluminium; see Table S1 in the Supplementary Materials) in the MWI studies included in this meta-analysis, which is an insufficient number for fitting a correlation. In contrast, the SWI studies included in the meta-analysis varied considerably in volume differences (see Table S2 in the Supplementary Materials) and enabled us to perform a correlation between changes in size and weight perception. A comparison between these two correlations could have enabled us to establish if changes in size and material yielded similar or different changes in perceived weight.

The second aim of the meta-analysis was to examine the influence of somatosensory and visual information about stimulus size on the SWI. All three groupings of studies (i.e., SWI-vision and somatosensory, SWI-somatosensory, and SWI-vision) had large mean effect sizes. Thus, our findings suggest that the SWI is robust regardless of which sensory modality processes size information. The 95% CI for the SWI-vision appears greater than the other two variants, perhaps because there were fewer pooled effect sizes for the SWI-vision. In addition, the SWI-vision and somatosensory group

was considerably more prevalent in the literature than either of the other two groups. The SWI-vision and somatosensory group also appeared to have the most variability in the pooled effect sizes (see Fig. 4) and the nature of the experiments performed (see Table 3). For example, Schmidler and Bengler (2016) had participants push heavy stimuli atop a large trolley and had them rate ‘subjective strain’ as an indicator of perceived heaviness. Buckingham, Wong, Tang, Gribble, and Goodale (2014b) had participants witness erroneous or inappropriate lifts of the SWI stimuli before they lifted the stimuli themselves. These are unique SWI experiments whereas experiments in studies using SWI-somatosensory and SWI-vision designs tended to be more typical (see Table 3). This is expected for a greater number of studies within a particular group of studies given that novelty is expected in publications. A greater range of experiments may have contributed to the increased variability in effect sizes seen in the SWI-vision and somatosensory group.

Comparing the effects between sensory modalities on illusion strength yielded results that were consistent with preliminary claims from the existing literature. The mean effect sizes for the SWI-somatosensory and SWI-vision and somatosensory groups were comparable in strength. This finding accords with past research showing that the SWI is consistent in strength regardless of visual access to the stimuli when somatosensory feedback about size is available (Ellis & Lederman, 1993; Plaisier & Smeets, 2015). We also demonstrated that the SWI-vision is weaker than the other SWI variants, which supports previous findings regarding sensory input modality by Ellis and Lederman (1993). These results are inconsistent with conceptual accounts, suggesting that conceptual expectancies do not entirely explain the SWI. Instead, the findings support an influence of bottom-up processing mechanisms on the illusion. Importantly, variations in volume and density were matched across these groups. Therefore, we can rule out the possibility that differences in effect sizes between SWI variants were driven by differences in either volume or density.

Our third aim was to examine the relationship between physical density and the SWI. The meta-analysis revealed a

Fig. 4 Forest plot displaying all experiment-wise pooled d s (circles), mean weighted d s (dashed lines) and 95% confidence interval (CI; dotted line) for the *SWI-somatosensory* (top), *SWI-vision* (middle) and *SWI-vision and somatosensory* (bottom). Error bars represent 95% CIs for the experiment-wise pooled d s

strong, positive correlation between illusion strength and physical density differences between stimuli, which supports past research implicating density in the SWI (Chouinard et al., 2009; J. Ross & Di Lollo, 1970; Stevens & Rubin, 1970; Wolf et al., 2018). Our results demonstrated that the SWI is stronger when there is a greater difference in density between the test objects, and that this relationship persists after statistically controlling for volume differences. Specifically, our hierarchical regression analysis revealed that this relationship was weaker after accounting for volume, suggesting that the effect

of density in the SWI occurs partly but not entirely through the processing of physical size. These findings demonstrate that the postlift processing of density contributes to the SWI and that physical density contributes to our percept of weight more generally.

The findings of Aims 2 and 3 paint an interesting picture of how bottom-up processing of physical density might influence perception in the SWI. The results indicate that density contributes to the illusion and that size exerts a stronger influence on perceived weight when processed through

Fig. 5 Scatterplot displaying the correlation, between observations of SWI effect sizes (d) and differences in density between test objects comprising that observation of d (g/cm^3), $r(140) = .466$, $p < .001$. Blue circles depict observations of d from the SWI-somatosensory, orange squares depict observations of d from the SWI-vision, and grey triangles depict observations of d from the SWI-vision and somatosensory. The linear line of best fit is shown

somatosensory channels. Although visually derived size information can be used to compute density (e.g., Wolf et al., 2018), as we proposed earlier, the somatosensory system may perform this computation more efficiently because it is designed to calculate both size and weight more directly through haptic and kinaesthetic feedback (Ellis & Lederman, 1993; McGlone & Reilly, 2010; Rowe, 2002). Our results suggest that when both size and weight are processed through somatosensory channels, density is computed in a way that is more likely to influence perceived weight.

Our results also suggest the SWI-vision is comparable in strength to the MWI, whereas the other two SWI variants are significantly stronger. In this meta-analysis, information about size and material were not obtained through the somatosensory system in the SWI-vision and MWI studies, respectively. Thus, this finding could mean that a conceptual expectancies mechanism influences perception comparably when either size or material informs expectations, but only when the somatosensory system is not providing size information that is used to compute physical density. Therefore, density, when computed via somatosensory channels, could be an important contributing factor as to why the SWI is stronger than other weight illusions, including the MWI and presumably other weight illusions in which the only varied feature is a conceptual one.

Of note, Ellis and Lederman (1999) showed that the MWI can be elicited in blindfolded participants when the materials of the objects are felt by haptic exploration but are not seen. However, it is still possible that the illusion in this instance is driven by top-down mechanisms. Consider being blindfolded

and handling objects made from the various materials that are typically employed in the MWI, such as wood, polystyrene, and metal. Their tactile sensation can invoke visual images of these materials. This is evident from neuroimaging research demonstrating that the same areas in the visual cortex that are engaged in their visual presentation are also engaged when participants explore these materials by touch only (Podrebarac, Goodale, & Snow, 2014). This can only be explained by top-down mechanisms given that there are no known afferent projections from the spinal cord to the visual cortex.

Another consideration that we could not address directly in the current study is the potential for publication bias. This is particularly relevant for our comparison of the SWI and MWI because the number of published SWI experiments greatly exceeds that of the MWI. The current study included 32 experiment-wise pooled effect sizes for the SWI, but only six for the MWI. This disparity could suggest that unpublished null results or ‘file-drawer’ data exist for the MWI. If this were the case, our mean estimate for the MWI could be inflated. In this vein, it could be relevant that the demonstrated difference between the two illusions was not as great as previous studies suggested (e.g., SWI, $\eta_p^2 = .98$ vs MWI, $\eta_p^2 = .42$; Buckingham & Goodale, 2013). In his qualitative review, Buckingham estimated the SWI to be around three times as strong as the MWI, which does not accord with our findings. As mentioned earlier, we attempted to uncover file-drawer data in our correspondence with authors. Beyond this, we were unable to address publication bias statistically owing to the small number of published MWI studies.

We also note that there is a remaining theoretical issue regarding the comparison between the SWI and MWI. As this is the first meta-analysis to quantify and compare effect sizes for the two illusions as documented in the literature, we provide preliminary evidence that the SWI has larger effect sizes than the MWI. That is, variations in physical size result in larger differences in perceived weight than apparent material in weight illusion paradigms. This finding, considered alongside results from Aims 2 and 3 of our meta-analysis, informs on the relative contributions of conceptual expectancies and bottom-up processing of physical density in weight perception. However, as discussed above, it is still unknown whether *proportional* changes in the relevant defining variables for the SWI (i.e., volume) and the MWI (i.e., expected density based on apparent material) produce comparable changes in perceived weight. Further investigation into the MWI is required, given the paucity of studies on this illusion relative to the SWI. We suggest that the MWI is examined further using a greater range of materials. Only then can we fully understand how changes in material influence weight perception and whether or not this follows a similar scale as changes in size.

Overall, this meta-analysis demonstrates that both conceptual expectancies and bottom-up processing of physical

density contribute to the SWI. We demonstrated that the MWI has large effect sizes, consistent with conceptual expectancies accounts of weight illusions. However, the finding of an even stronger SWI, as well as the relationship between SWI strength and physical density differences, supports a contribution of density processing via the somatosensory system.

Last, not all individual findings in the literature are well explained by the conclusions drawn from this meta-analysis. For example, Plaisier and Smeets (2015) demonstrated an influence of physical size on perceived weight that was independent from volume of matter (which should inform conceptual expectancies) and physical density. It is expected that some studies will not accord with our meta-analysis. This does not negate their validity, nor does it negate the validity of our study. There are a number of possible reasons for disagreement. Meta-analyses aim to summarise and synthesise the existing literature as a whole, which in the process dilutes the effect of individual studies and their particular task and contextual constraints.

Acknowledgements This work was supported by the Australian Research Council (DP170103189). We have no conflicts of interest to declare.

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