Getting a grip on heaviness perception: A review of weight illusions and their probable causes

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Getting a grip on heaviness perception: A review of weight illusions and their probable causes

Gavin Buckingham

Department of Psychology

School of Life Sciences

Heriot-Watt University

Edinburgh, UK

Abstract

Weight illusions – where one object feels heavier than an identically-weighted counterpart – have been the focus of many recent scientific investigations. The most famous of these illusions is the 'size-weight illusion', where a small object feels heavier than an identically-weighted, but otherwise similar-looking, larger object. There are, however, a variety of similar illusions which can be induced by varying other stimulus properties, such as surface material, temperature, colour, and even shape. Despite well over 100 years of research, there is little consensus about the mechanisms underpinning these illusions. In this review, I will first provide an overview of the weight illusions which have been described. I will then outline the dominant theories which have emerged over the past decade for why we consistently misperceive the weights of objects which vary in size, with a particular focus on the role of lifters' expectations of heaviness. Finally, I will discuss the magnitude of the various weight illusions, and suggest how this largely-overlooked facet of the topic might resolve some of the debates surrounding the cause of these misperceptions of heaviness.

Keywords: size-weight illusion, material-weight illusion, object lifting, grip force, weight perception, expectations

Some of the earliest illusions to be formally described are illusions of heaviness, where objects subjectively feel lighter or heavier than they actually are. These are most compellingly demonstrated in situations where identically-weighted objects are made to feel as if they weigh different amounts from one another. This article is intended to provide a brief overview of the weight illusions which have been described since the late 1800s, and provide an up-to-date commentary on the possible causes of the size-weight illusion. This article is not intended to be a review of the history of weight illusion research, and the interested reader can read comprehensive historical treatments from other authors (Ross 1969; Murray et al. 1999; Nicolas et al. 2012).

1.1 - A brief taxonomy of weight illusions

The obvious place to start this review is with the famous 'size-weight illusion' (SWI), which is by far the most well-studied of all the illusions of heaviness. The SWI occurs when small and large objects are adjusted to have identical masses. When these identically-weighted objects are lifted, the smaller object invariably feels heavier than the larger object (Charpentier 1891). The illusion is cognitively impenetrable, meaning that the illusion is equivalent even if you are told the objects weigh the same amount as one another (Flournoy 1894).. It can be induced with haptic feedback of the size differences (i.e., perceiving the objects' sizes with your sense of touch alone) or visual feedback of the size differences (i.e., lifting the differently-sized objects with a handle attached to the top surface). Lifting per se isn't even required to experience the illusion – a misperception of mass can be generated by gently pushing different-sized objects which are dangling from strings (Plaisier and Smeets 2012). The SWI is experienced by children as young as two years old (Robinson 1964; Pick and Pick 1967) and, interestingly, the magnitude of the illusion appears to diminish throughout childhood ((Gordon et al. 1992). The SWI does not diminish with repeated experiences or interactions with the illusion-inducing objects, and recent neuroimaging research suggests that its neural locus is in the left ventral premotor cortex (Chouinard et al. 2009).

The next-most famous illusion of heaviness is the 'material-weight illusion' (MWI). As the name suggests, the illusion is induced though variations in the surface material, rather than the size, of identically-weighted objects. In this case, objects which appear to be made from a heavy-looking material, such as metal, will feel slightly lighter than identically-weighted objects which appear to be made from a low density material, such as polystyrene (Wolfe 1898; Seashore 1899; Harshfield and DeHardt 1970; Buckingham et al. 2009). Ellis and Lederman (1999) demonstrated that this illusion could be evoked without actually touching the objects' surfaces, indicating that the effect must stem participants' learned associations between material properties and object weight rather than peripheral factors such as differences in the friction of the different materials (see also Buckingham et al. 2011). However, the effect is at its most impressive when the lifter is allowed haptic feedback (with or without visual feedback) of the material properties, suggesting some these expectations may combine in an additive way with peripheral factors.

There exists a category of weight illusions which can be understood entirely as learned, top-down, effects. Ellis and Lederman (1998) created an illusion based on golfers' expertise with similar-looking, but (in the real world) much lighter, practice golf balls. When the practice golf balls were adjusted to weigh the same amount as the real golf balls, expert golfers judged the altered practice balls as feeling heavier than the real golf balls. Non-golfers, who had no prior expectations regarding the weight of practice golf balls, did not experience this illusion, detecting no differences in weight between the identically-weighted real and practice balls. More surprisingly, Dijker (2008) demonstrated that the SWI can be enhanced with social cues, such that female dolls feel far heavier than one would expect them to in comparison to larger male dolls (relative to the SWI generated with a variety of cans which had similar volume and mass relationships to the dolls). As this effect disappeared participants lifted these dolls with their eyes closed, this weight illusion presumably reflected participants' expectations that females will weigh less than males. There has even been recent evidence that embodiment-style effects can cause differences in how heavy objects feel when they are lifted. Schneider et al. (2011) demonstrated that, when casually told by an experimenter that a book is important (in a scholarly sense), subjects judged it as feeling up to one third heavier than individuals who were given no information about the importance of the book. Interestingly this effect did not appear to be mediated by participants' expectations about how valuable the book was, which led the authors to conclude that the effect represents the embodiment of an abstract linkage between the concepts of mass and importance. It does, however, remain an open question as to whether these effects may be mediated by the perceived volume of the books, which would seem to be an equally plausible mechanism (i.e., more important books might contain more information and thus be larger).

Finally, there are several less well-known weight illusions which appear to be conceptually related to the MWI. The brightness-weight illusion describes an effect whereby light-coloured objects feel slightly heavier than darker objects (De Camp 1917) –an effect mediated by individuals' expectations that dark-coloured objects will be heavier than light-coloured objects (Walker et al. 2010). The shape-weight illusion (Dresslar 1894), was originally described as differences in the perceived weight of flat sheets of lead as a function of their 2-dimensional shape, with more compact shapes feeling heavier than less compact shapes. This rather vague description has been somewhat clarified, with recent research indicating that there are large individual differences in how the 3-dimensional shape of objects (i.e., whether they are spheres, cubes, and tetrahedrons) can affect weight perception (Kahrimanovic et al. 2011), suggesting the shape-weight illusion is due to individuals' prior experiences with objects of these shapes rather than invariant conservation-style errors of a particular shape's volume. The final illusion in this vein was described in 1846 by Weber (translated by Ross and Murray 1996), who noted that an object's temperature will affect its weight, such that a cold coin placed on the forehead of a supine individual will feel heavier than the same coin at room temperature – the so-called 'Silver Thaler illusion' (more commonly known as the 'temperature-weight illusion').

<u>1.2 – Proposed causes of weight illusions</u>

The weight illusions outlined above not involving manipulations of size (e.g., Buckingham et al. 2011; Dijker 2008; Ellis and Lederman 1998) are thought to be caused by violated expectations: when lifters expect something to be heavy it feels comparatively light when it is lifted, and vice versa (Ross 1969). The contrastive nature of this perceptual effect is in itself interesting because many illusory effects have been described in terms of Bayesian-style integration, where priors are combined with sensory input to form the percept (see Ernst 2009 for a brief overview in the context of the SWI). Weight illusions, on the other hand, have been termed as 'anti-Bayesian' (Brayanov and Smith 2010) due to the way that sensory input appears to reflect an opposition, rather than an integration, with the expectations (i.e., the perceptual priors). These effects, it has been suggested, represent a unique way that our perceptual system deals with outliers in the statistics of the environment (such as what a particular material should weigh, see Baugh et al. 2012). It is not difficult to imagine that the ability to detect and tag an unusually-weighted object could be a useful skill in an evolutionary context in allowing an individual to predict, for example, if a fruit is not yet ripe or if a piece of firewood is too damp to be flammable. There is, however, far less consensus in the literature about whether this top-down view can account for the SWI, for which several competing hypotheses exist.

1.2.1 - Sensorimotor hypothesis

A promising early explanation for the SWI came in the form of a sensorimotor mismatch hypothesis, stemming from the predictive way in which our fingertip forces are parameterised when lifting objects (Davis and Roberts 1976). When lifting the large object in a SWI-inducing pair for the first time, it will invariably be lifted with a higher rate of force than the smaller object. Critically, this also means that the large object will be lifted with a higher rate of force than necessary and the small object will be lifted with a suboptimal (lower) rate of force, causing opposing mismatches between efference and afferance. The opposite direction of these mismatches between expectation and action for the small and large objects would lead to the inevitable percept that the small objects outweigh the large objects. These sensorimotor ‘errors’ appear to be a viable cause for the illusion during initial lifts of the SWI-inducing objects, where individuals do indeed overestimate the force requirements of lifting the large object and underestimate the force requirements of lifting the small object (Gordon et al. 1991). This hypothesis is compatible with a range of well-established peripheral effects which can impact an individual’s perception of how heavy an object feels, such as muscle fatigue (Jones and Hunter 1983; Burgess and Jones 1997), tactile sensitivity (Gandevia et al. 1980), gripping force (Flanagan et al. 1995), and even the fingers used to lift (Flanagan and Bandomir 2000). However, in a well-cited study Flanagan and Beltzner (2000) showed that the illusion is not dependant on these peripheral effects. In their study, when lifting SWI-inducing objects over multiple trials, individuals rapidly adapted their fingertip forces from the expectation-driven overestimations and underestimations to the actual (and identical) weights of the illusion-inducing objects over the course of a few lifts. In other words, a lifter's fingertip force errors will be rapidly corrected with practice, but their perceptual illusion remains strong and stable. This independence of the lifting errors from the perceptual illusion suggests that the SWI is unlikely to have a sensorimotor origin (see also Grandy and Westwood 2006; Mon-Williams and Murray 2000).

1.2.2 - Bottom-up hypotheses

In contrast of the efference-driven sensorimotor hypothesis, bottom-up explanations describe several different (although not mutually exclusive) hypothetical mechanisms where a lifter directly perceives an ecologically-relevant variable, related to the relationship between volume and mass, which they mistakenly interpret as heaviness.

The simplest form of this bottom-up argument suggests that lifters perceive an object's density (a small object is, by definition, more dense than an equally-weighted large object), which they erroneously report as its weight (Ross and Di Lollo 1970; Stevens and Rubin 1970). Thus, because perceived weight and physical density seem to have a strong positive relationship, individuals may be unable to readily disentangle one from the other. This idea is analogous to common naïve physics misunderstandings, such as the common belief that objects of different weight will fall at different speeds (Kozhevnikov and Hegarty 2001).

While this explanation is, on the face of it, plausible, it is unclear why we would accurately experience one physical dimensions (e.g., density) all the while inaccurately experiencing other clearly related physical dimensions (e.g., weight). This problem has been addressed by Gibson (1979), who proposed that we only perceive items in the environment in terms of their action-relevant properties (known as affordances), rather than abstract physical properties. Bottom-up explanations in this ecological vein tend to focus on properties which are overtly relevant for action. Noting that large objects will typically have a different centre of mass than smaller objects, regardless of their weight, Amazeen and Turvey (1996) demonstrated that altering the mass distribution of hammer-like rods had a much larger effect on the perceived heaviness than altering the mass itself. This finding suggests that our ability to detect an object's rotational inertia while being wielded (i.e., the property of inertia tensor) may underpin the haptic SWI. This explanation, however, does not appear to explain the effects that visual size information can have on perceptions of heaviness. Furthermore, it is worth noting that even if weight illusions can be induced through variations in rotational inertia, it is far from clear whether this is the way this effect is naturally obtained.

In a similar action-driven vein, Zhu and Bingham (2011) examined participant's judgements for the diameter they could throw the furthest for a sphere of a given weight and noted that these judgements were well-matched to judgements of the perceived weight of spheres which varied in mass and volume. They concluded that, rather than a being a misperception of heaviness, the SWI is a consequence of our perceptual expertise in selecting, based on the relationship between mass and volume, which object from a set could be thrown the furthest – the property of 'throwability'. It is worth noting that this explanation gives no insight into the physical nature of the low-level variable which is perceived in the stead of an object's mass. However, a follow-up study examining throwing and weight illusions demonstrated that alterations to a sphere's centres of mass (i.e., manipulating their rotational inertia) does not affect throwability judgements or weight judgements for the different volume and mass relationships (Zhu et al. 2013), suggesting that the rotational effects described by Amazeen and Turvey (1996) are not be applicable to the classic hand-held SWI.

1.2.3 - Top-down hypothesis

The top-down explanation of the SWI takes a very different conceptual approach from bottom-up, ecological explanations. Here, instead of directly perceiving a variable which is consciously understood as weight, the percept of an illusory weight difference comes about through a combination of prior experience with current sensory input. In the case of the SWI, an individual's conscious perception of how heavy the objects feel reflects a contrast to their expectations of how heavy the large and small objects should be in relation to one another. It is worth noting that this variant of top-down, contrastive effect is not necessarily the same as the explanation outlined above for the MWI. In the SWI, the contrast can arise purely as a relational contrast with the other object(s) in the set; a short-term expectation for the object lifted 2nd in relation to the larger or smaller object lifted beforehand. The importance of this short-term, relational expectation is emphasised by the fact that many SWI paradigms use stimuli that do not have a clear visual cue to density (i.e., the material from which they are made is not readily identifiable). The MWI, on the other hand, reflects a contrast to long term prior expectations (i.e., that the heavy-feeling polystyrene is heavier than all other polystyrene objects which the lifter has encountered), and the visual identity of each object is obviously emphasised. Whether this distinction is a meaningful one to the perceptual system remains unclear, and needs further empirical investigation.

Recent work has provided a compelling demonstration of how statistical regularities in the objects we interact with can drive our subsequent perceptual experience (Flanagan et al. 2008). In several experiments, participants repeatedly lifted sets of objects which had an inverted size-weight relationship (i.e., the larger the object in a set, the lower its mass), in order to alter their prior expectations. The participants were then invited to judge the weight of similar-looking large and small objects which weighed the same amount as one another, in order to see if they experienced the usual SWI. Subjects who were given a relatively small amount of experience with the inverse-density objects (lifting them just over 1000 times in a single session) experienced a slightly smaller-than-normal SWI; the small object felt only moderately heavier than the large object. A second group, who lifted the inverse-density objects 1000 times a day for three consecutive days, did not experience the SWI at all – the identically-weighted large and small objects felt as if they weighed the same amount. Finally, and most convincingly, subjects who experienced the inverse density objects over a period of 11 days before lifting the identically-weighted objects reported that the large object felt substantially heavier than its identically-weighted smaller counterpart – an inverted version of the SWI. This study was the first to show a direct link between prior experience and subsequent weight perception in the context of weight illusions, providing the strongest rejection yet of bottom-up theories of weight illusions.

More evidence for the representational basis of the SWI comes from a recent study which demonstrated that the SWI can be evoked in a single, unchanging, object by priming a lifter's expectations of what they are about to lift (Buckingham and Goodale 2010a). Subjects in this task were shown a large, small, or medium cube before having their visual feedback removed. Then, unbeknownst to the subjects, the previewed cube was taken away and replaced by the medium-sized cube, which subjects lifted on every single trial with their vision blocked. Subjects experienced a robust SWI - when they saw the small cube in the preview phase, the medium-sized cube that they lifted felt substantially heavier than it felt after they had previewed the large cube. This study is also particularly difficult to reconcile with bottom-up theories of the SWI, as the perceptual illusion could not have been caused by anything other than participants' expectations of what they were about to lift, as the physical properties of the object they lifted did not change from trial to trial.

1.3 – Different types of expectations

In the SWI, the illusion-causing expectations about how heavy the object will be in relation to one another are built up across a lifetime of experiencing the regular positive correlation between size and weight with objects in the world. We repeatedly encounter objects with a positive size-weight association, leading us to expect (sensibly) that large objects will outweigh small objects (because, on average, they will). This statistical regularity leads individuals to predict that the large object will outweigh the small object. As outlined above, the illusion-inducing expectation is not the one that drives sensorimotor prediction; perception of the SWI appears to be unrelated to grip and load force rates on a given trial (Flanagan and Beltzner 2000). Furthermore, this expectation isn't even one which an individual could readily articulate; after picking up the lighter-than-expected large cube in a standard SWI experiment only once, the lifter will readily report that they don't expect the large cube to be particularly heavy. But nevertheless, the SWI does not get smaller with repeated lifts of the illusion-inducing stimuli. This observation has led many scientists to conclude that expectations are unlikely to play a role in the SWI. However, an alternative explanation is that there are multiple types of expectation, all of which play a role in various sensorimotor processes.

Recent evidence suggests that there may, in fact, be three separate expectations/representations which play a role when we lift objects. First, measured simply by asking individuals how heavy they expect an object to be, there are expectations which inform our conscious understanding of how heavy something should be. These expectations appear to be highly specific to material properties and the situational context of the lift. Second, by measuring fingertip forces, there are independent expectations which drive our sensorimotor prediction, which rapidly and precisely adjust on a trial-to-trial basis. The final expectations which come in to play are apparent when we judge the weights of objects and experience the SWI. Recent evidence indicates that this illusion-causing expectation does not appear to be specific to particular families of objects, unlike the sensorimotor prediction or conscious expectations of heaviness. Buckingham and Goodale (2013) investigated the magnitude of the SWI in various materials, noting that the illusion induced by large and small metal cubes was the same magnitude as the illusion induced by large and small polystyrene cubes. If the conscious expectations drove the illusion, subjects would have experienced a large SWI with the metal cubes, which they expected to have a far greater density than the polystyrene cubes. Thus, the representation which drives the SWI is not only independent from sensorimotor performance and/or expectation, but is also distinct from participants' cognitive understanding of the weight differences and density. It is important to note that, in the majority of situations in the real world, these various expectations are well-aligned. It is only in experimentally-contrived situations, such as when lifting illusion-inducing stimuli, that these expectations can be dissociated from one another.

1.4 - Strength of illusions

Expectation-driven contrast effects appear to explain the MWI and other classes of top-down weight illusions (e.g., Ellis and Lederman 1998; Dijker 2008). However, it is less clear whether expectations can fully account for the SWI. There are, in fact, several perspectives from which the SWI seems to be qualitatively different from other weight illusions. Most notably, the SWI is by far the most powerful weight illusion which has been documented. Although it is difficult to systematically compare the magnitude of the various weight illusions across laboratories, studies which have examined the visual size and material weight illusions using identical protocols and well-matched stimuli (700g cubes, lifted with a precision grip by handle on their top surface - Buckingham et al.

2009; Buckingham and Goodale 2013; Buckingham and Goodale 2010b) show the SWI to be approximately three times the size of the MWI.

There are also wide variations in the magnitude of the SWI, depending on the experimental protocol used to induce it. For one, the SWI is markedly reduced in the experiments which have provided the strongest evidence for expectations causing the misperception of weight (summarised in Section 1.2.3). The variant of the SWI induced in a single object by priming participants' expectations is only half the size of the normal SWI induced by lifting three objects with full vision (Buckingham and Goodale 2010a). Similarly, the magnitude of the inverted SWI (Flanagan et al. 2008) was less than half the size of the normal, un-inverted, SWI. Critically, the magnitude of the inverted illusion never became as strong as the un-inverted SWI, remaining stunted for a further 22 days of experiencing the inverted objects, suggesting there are limits to the plasticity of the SWI. As the studies which provide the strongest evidence for the role of expectations inducing the SWI show reduced-magnitude illusions, it is clear that the illusion-inducing expectations outlined in Section 1.3 cannot alone account for the 'full' experience of the SWI.

It has been known for some time that the haptic SWI is substantially larger than the visual SWI, and providing concurrent visual and haptic feedback does little to increase the illusion's strength over the haptic-only illusion (Ellis and Lederman 1993). As we are skilled at detecting variations in rotational inertia through haptics (Amazeen and Turvey 1996), it is possible that the fullest SWI comes about through a combination of top-down (i.e., expectation-driven) and bottom-up (i.e., ecological) effects. As outlined above, the top-down effects appear to account for about half of the illusion, presumably leaving various bottom-up effects to contribute to the remainder of the illusory differences in weight when they are permitted. The strength of these bottom-up effects likely vary as a function of the type of actions participants use to judge the weights of the objects in an experiment (i.e., precision-grip lifting, cupping and lifting the object in one's hand, or jiggling the object to sense it's torques). Thus, the smaller illusion experienced by participants in the single-object SWI study (Buckingham and Goodale 2010a) can be taken to reflect the lack of differences in bottom-up stimulus properties seen in usual, multi-object, SWI studies. Similarly, the consistently smaller magnitude of the inverted SWI (Flanagan et al. 2008) may stem from placing the top-down expectations and the bottom-up differences between the stimuli in opposition to one another. It is not yet clear which bottom-up factors may contribute most to the sense of heaviness, although it likely that this is dependent on dynamics of the lifting task and constrained by the shape of the object being lifted (Amazeen and Turvey 1996; Zhu et al. 2013).

In addition to the magnitude of the illusion, future work might benefit from studying the resilience of the illusion under various contexts. To date, only the SWI has been examined in this light, and has been shown to be remarkably robust to change, with thousands of trials over multiple days required to change the magnitude of the effect. Presumably this degree of resilience reflects some aspect of how the prior information (i.e., expectations of heaviness) associated with size cues are encoded and utilized by the sensorimotor system. It remains to be seen whether expectations derived from material or other more cognitive cues are similarly resilient to change.

1.5 - Summary

Taken together, the literature presented in this review suggests that, in isolation, none of the dominant hypotheses surrounding weight illusions can fully account for the SWI. However, it is likely that a combination of top-down (i.e., expectations of heaviness) and bottom-up (e.g., rotational inertia) effects can explain the illusory misperception of heaviness. Future work should aim to determine the nature of the bottom-up influences in weight perception as a function of the lifting task, in addition to identifying how these bottom-up effects interact with top-down expectations across the various types of weight illusion.

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Getting a grip on heaviness perception: A review of weight illusions and their probable causes

Gavin Buckingham

Department of Psychology

School of Life Sciences

Heriot-Watt University

Edinburgh, UK

Abstract

Weight illusions – where one object feels heavier than an identically-weighted counterpart – have been the focus of many recent scientific investigations. The most famous of these illusions is the 'size-weight illusion', where a small object feels heavier than an identically-weighted, but otherwise similar-looking, larger object. There are, however, a variety of similar illusions which can be induced by varying other stimulus properties, such as surface material, temperature, colour, and even shape. Despite well over 100 years of research, there is little consensus about the mechanisms underpinning these illusions. In this review, I will first provide an overview of the weight illusions which have been described. I will then outline the dominant theories which have emerged over the past decade for why we consistently misperceive the weights of objects which vary in size, with a particular focus on the role of lifters' expectations of heaviness. Finally, I will discuss the magnitude of the various weight illusions, and suggest how this largely-overlooked facet of the topic might resolve some of the debates surrounding the cause of these misperceptions of heaviness.

Keywords: size-weight illusion, material-weight illusion, object lifting, grip force, weight perception, expectations

Some of the earliest illusions to be formally described are illusions of heaviness, where objects subjectively feel lighter or heavier than they actually are. These are most compellingly demonstrated in situations where identically-weighted objects are made to feel as if they weigh different amounts from one another. This article is intended to provide a brief overview of the weight illusions which have been described since the late 1800s, and provide an up-to-date commentary on the possible causes of the size-weight illusion. This article is not intended to be a review of the history of weight illusion research, and the interested reader can read comprehensive historical treatments from other authors (Ross 1969; Murray et al. 1999; Nicolas et al. 2012)~~(Murray et al. 1999; Nicolas et al. 2012; Ross 1969)~~.

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1.1 - A brief taxonomy of weight illusions

The obvious place to start this review is with the famous 'size-weight illusion' (SWI), which is by far the most well-studied of all the illusions of heaviness. The SWI occurs when small and large objects are adjusted to have identical masses. When these identically-weighted objects are lifted, the smaller object invariably feels heavier than the larger object (Charpentier 1891). ~~This effect is easy to induce – placing a brick inside a small cardboard box will make it feel heavier than the same brick inside a large cardboard box.~~ The illusion is ~~also~~ cognitively impenetrable, meaning that ~~(i.e., the~~ the illusion is equivalent even if you are told the objects weigh the same amount as one another ~~-~~ (Flournoy 1894).. It can be induced with haptic feedback of the size differences (i.e., perceiving the objects' sizes with your sense of touch alone) or visual feedback of the size differences (i.e., lifting the differently-sized objects with a handle attached to the top surface). Lifting per se isn't even required to experience the illusion – a misperception of mass can be generated by gently pushing different-sized objects which are dangling from strings (Plaisier and Smeets 2012). The SWI is experienced by children as young as two years old (Robinson 1964; Pick and Pick 1967) and, interestingly, the magnitude of the illusion appears to diminish throughout childhood ((Gordon et al. 1992)~~Pick and Pick 1967)~~. The SWI does not diminish with repeated experiences or interactions with the illusion-inducing objects, and recent neuroimaging research suggests that its neural locus is in the left ventral premotor cortex (Chouinard et al. 2009).

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The next-most famous illusion of heaviness is the 'material-weight illusion' (MWI). As the name suggests, the illusion is induced though variations in the surface material, rather than the size, of identically-weighted objects. In this case, objects which appear to be made from a heavy-looking material, such as metal, will feel slightly lighter than identically-weighted objects which appear to be made from a low density material, such as polystyrene (Wolfe 1898; Seashore 1899; Harshfield and DeHardt 1970; Buckingham et al. 2009)~~(Buckingham et al. 2009; Harshfield and DeHardt 1970; Seashore 1899; Wolfe 1898)~~. Ellis and Lederman (1999) demonstrated that this illusion could be evoked without actually touching the objects' surfaces, indicating that the effect must stem participants' learned associations between material properties and object weight rather than peripheral factors such as differences in the friction of the different materials (see also Buckingham et al. 2011). However, the effect is at its most impressive when the lifter is allowed haptic feedback (with or without visual feedback) of the material properties, suggesting some these expectations may combine in an additive way with peripheral factors.

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There exists a category of weight illusions which can be understood entirely as learned, top-down, effects. Ellis and Lederman (1998) created an illusion based on golfers’ expertise with similar-looking, but (in the real world) much lighter, practice golf balls. When the practice golf balls were adjusted to weigh the same amount as the real golf balls, expert golfers judged the altered practice balls as feeling heavier than the real golf balls. Non-golfers, who had no prior expectations regarding the weight of practice golf balls, did not experience this illusion, detecting no differences in weight between the identically-weighted real and practice balls. More surprisingly, Dijker (2008) demonstrated that the SWI can be enhanced with social cues, such that female dolls feel far heavier than one would expect them to in comparison to larger male dolls (relative to the SWI generated with a variety of cans which had similar volume and mass relationships to the dolls). As this effect disappeared participants lifted these dolls with their eyes closed, this weight illusion presumably reflected participants' expectations that females will weigh less than males. There has even been recent evidence that embodiment-style effects can cause differences in how heavy objects feel when they are lifted. Schneider et al. (2011) demonstrated that, when casually told by an experimenter that a book is important (in a scholarly sense), subjects judged it as feeling up to one third heavier than individuals who were given no information about the importance of the book. Interestingly this effect did not appear to be mediated by participants’ expectations about how valuable the book was, which led the authors to conclude that the effect represents the embodiment of an abstract linkage between the concepts of mass and importance. It does, however, remain an open question as to whether these effects may be mediated by the perceived volume of the books, which would seem to be an equally plausible mechanism (i.e., more important books might contain more information and thus be larger).

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Finally, there are several less well-known weight illusions which appear to be conceptually related to the MWI. The brightness-weight illusion describes an effect whereby light-coloured objects feel slightly heavier than darker objects (De Camp 1917) –an effect mediated by individuals’ expectations that dark-coloured objects will be heavier than light-coloured objects (Walker et al. 2010). The shape-weight illusion (Dresslar 1894), was originally described as differences in the perceived weight of flat sheets of lead as a function of their 2-dimensional shape, with more compact shapes feeling heavier than less compact shapes. This rather vague description has been somewhat clarified, with recent research indicating that there are large individual differences in how the 3-dimensional shape of objects (i.e., whether they are spheres, cubes, and tetrahedrons) can affect weight perception (Kahrimanovic et al. 2011), suggesting the shape-weight illusion is due to individuals' prior experiences with objects of these shapes rather than invariant conservation-style errors of a particular shape's volume. The final illusion in this vein was described in 1846 by Weber (translated by Ross and Murray 1996), who noted that an object’s temperature will affect its weight, such that a cold coin placed on the forehead of a supine individual will feel heavier than the same coin at room temperature – the so-called ‘Silver Thaler illusion’ (more commonly known a~~t~~s the 'temperature-weight illusion').

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1.2 – Proposed causes of weight illusions

~~The peripheral weight illusions are through to stem from various biomechanical factors, and will not receive discussion here.~~ The ~~top-down~~weight illusions outlined above not involving manipulations of size (e.g., Buckingham et al. 2011; Dijker 2008; Ellis and Lederman 1998) are thought to be caused by violated expectations: when lifters expect something to be heavy it feels comparatively light when it is lifted, and vice versa (Ross 1969). The contrastive nature of this perceptual effect is in itself interesting because many illusory effects have been described in terms of Bayesian-style integration, where priors are combined with sensory input to form the percept (see Ernst 2009 for a brief overview in the context of the SWI). Weight illusions, on the other hand, have been termed as 'anti-Bayesian' (Brayanov and Smith 2010) due to the way that sensory input appears to reflect an opposition, rather than an integration, with the expectations (i.e., the perceptual priors). These effects, it has been suggested, represent a unique way that our perceptual system deals with outliers in the statistics of the environment (such as what a particular material should weigh, see Baugh et al. 2012). It is not difficult to imagine that the ability to detect and tag an unusually-weighted object could be a useful skill in an evolutionary context in allowing an individual to predict, for example, if a fruit is not yet ripe or if a piece of firewood is too damp to be flammable. There is, however, far less consensus in the literature about whether this top-down view can account for the SWI, for which several competing hypotheses exist.

1.2.1 - Sensorimotor hypothesis

A promising early explanation for the SWI came in the form of a sensorimotor mismatch hypothesis, stemming from the predictive way in which our fingertip forces are parameterised when lifting objects (Davis and Roberts 1976). When lifting the large object in a SWI-inducing pair for the first time, it will invariably be lifted with a higher rate of force than the smaller object. Critically, this also mean that the large object will be lifted with a higher rate of force than necessary and the small object will be lifted with a suboptimal (lower) rate of force, causing opposing mismatches between efference and afferance. The opposite direction of these mismatches between expectation and action for the small and large objects would lead to the inevitable percept that the small objects outweigh the large objects. These sensorimotor 'errors' appear to be a viable cause for the illusion during initial lifts of the SWI-inducing objects, where individuals do indeed overestimate the force requirements of lifting the large object and underestimate the force requirements of lifting the small object (Gordon et al. 1991). This hypothesis compatible with a range of well-established peripheral effects which can impact an individual's perception of how heavy an object feels, such as muscle fatigue (Jones and Hunter 1983; Burgess and Jones 1997), tactile sensitivity (Gandevia et al. 1980), gripping force (Flanagan et al. 1995), and even the fingers used during lift (Flanagan and Bandomir 2000). However, in a well-cited study Flanagan and Beltzner (2000) showed that the illusion is not dependant on these peripheral effects. In their study, when lifting SWI-inducing objects over multiple trials, individuals rapidly adapted their fingertip forces from the expectation-driven overestimations and underestimations to the actual (and identical) weights of the illusion-inducing objects over the course of a few lifts. In other words, a lifter's fingertip force errors will be rapidly corrected with practice, but their perceptual illusion remains strong and stable. This independence of the lifting errors from the perceptual illusion suggests that the SWI is unlikely to have a sensorimotor origin (see also Grandy and Westwood 2006; Mon-Williams and Murray 2000).

1.2.2 - Bottom-up hypotheses

In contrast of the efference-driven sensorimotor hypothesis, ~~B~~bottom-up explanations describe several different (although not mutually exclusive) hypothetical mechanisms where a lifter directly perceives ~~certain~~ an ecologically-relevant variable~~s~~, related to the relationship between volume and mass, which ~~are~~ they mistakenly interpret~~ed~~ as heaviness.

The simplest form of this bottom-up argument suggests that lifters perceive an object's density (a small object is, by definition, more dense than an equally-weighted large object), which they erroneously report as its weight (Ross and Di Lollo 1970; Stevens and Rubin 1970). Thus, because perceived weight and physical density seem to have a strong positive relationship, individuals may be unable to readily disentangle one from the other. This idea is analogous to common naïve physics misunderstandings, such as the common belief that objects of different weight will fall at different speeds (Kozhevnikov and Hegarty 2001).

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While this explanation is, on the face of it, plausible, it is unclear why we would accurately experience one physical dimensions (e.g., density) all the while inaccurately experiencing other clearly related physical dimensions (e.g., weight). This problem has been addressed by Gibson (1979), who proposed that we on perceive items in the environment in terms of their action-relevant (known as affordances), rather than abstract physical properties. ~~More recent b~~Bottom-up explanations in this ecological vein tend to focus on properties ~~more~~ which are overtly relevant for action. Noting that large objects will typically have a different centre of mass than smaller objects, regardless of their weight, Amazeen and Turvey (1996) demonstrated that altering the mass distribution of hammer-like rods had a much larger effect on the perceived heaviness than altering the mass itself. This finding suggests that our ability to detect an object's rotational inertia while being wielded (i.e., the property of inertia tensor) may underpin the haptic SWI. This explanation, however, does not appear to explain the effects that visual size information can have on perceptions of heaviness. Furthermore, it is worth noting that even if weight illusions can be induced through variations in rotational inertia, it is far from clear whether this is the way this effect is naturally obtained.

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In a similar action-driven vein, Zhu and Bingham (2011) examined participant's judgements for the diameter they could throw the furthest for a sphere of a given weight and noted that these judgements were well-matched to judgements of the perceived weight of spheres which varied in mass and volume. They concluded that, rather than a being a misperception of heaviness, the SWI is a consequence of our perceptual expertise in selecting, based on the relationship between mass and volume, which object from a set could be thrown the furthest – the property of 'throwability'. It is worth noting that this explanation gives no insight into the physical nature of the low-level variable which is perceived in the stead of an object's mass. However, ~~A~~a follow-up study examining throwing and weight illusions demonstrated that alterations to a sphere's~~'~~ centres of mass (i.e., manipulating their rotational inertia) does not affect throwability judgements or weight judgements for the different volume and mass relationships (Zhu et al. 2013), suggesting that the rotational effects described by Amazeen and Turvey (1996) ~~may~~are not be applicable ~~for~~to the classic hand-held SWI.

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1.2.3 - Top-down hypothesis

The top-down explanation of the SWI takes a very different conceptual approach from bottom-up, ecological explanations. Here, instead of directly perceiving a variable which is consciously understood as weight, the percept of an illusory weight difference comes about through a combination of prior experience with current sensory input. In the case of the SWI, an individual's conscious perception of how heavy the objects~~'~~ feel reflects a contrast to their expectations of how heavy the large and small objects should be in relation to one another. It is worth noting that this variant of top-down, contrastive effect is not necessarily the same as the explanation outlined above for the MWI. In the SWI, the contrast can arise purely as a relational contrast with the other object(s) in the set; a short-term expectation for the object lifted 2nd in relation to the larger or smaller object lifted beforehand. The importance of this short-term, relational expectation is emphasised by the fact that many SWI paradigms use stimuli that do not have a clear visual cue to density (i.e., the material from which they are made is not readily identifiable). The MWI, on the other hand, reflects a contrast to long term prior expectations (i.e., that the heavy-feeling polystyrene is heavier than all other polystyrene objects which the lifter has encountered), and the visual identity of each object is obviously emphasised. Whether this distinction is a meaningful one to the perceptual system remains unclear, and needs further empirical investigation.

Recent work has provided a compelling demonstration of how statistical regularities in the objects we interact with can drive our subsequent perceptual experience (Flanagan et al. 2008). In several experiments, participants repeatedly lifted sets of objects which had an inverted size-weight relationship (i.e., the larger the object in a set, the lower its mass), in order to alter their prior expectations. The participants were then invited to judge the weight of similar-looking large and small objects which weighed the same amount as one another, in order to see if they experienced the usual SWI. Subjects who were given a relatively small amount of experience with the inverse-density objects (lifting them just over 1000 times in a single session) experienced a slightly smaller-than-normal SWI; the small object felt only moderately heavier than the large object. A second group, who lifted the inverse-density objects 1000 times a day for three consecutive days, did not experience the SWI at all – the identically-weighted large and small objects felt as if they weighed the same amount. Finally, and most convincingly, subjects who experienced the inverse density objects over a period of 11 days before lifting the identically-weighted objects reported that the large object felt substantially heavier than its identically-weighted smaller counterpart – an inverted version of the SWI. This study was the first to show a direct link between prior experience and subsequent weight perception in the context of weight illusions, providing the strongest rejection yet of bottom-up theories of weight illusions.

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More evidence for the representational basis of the SWI comes from ~~another~~ a recent study~~,~~ which demonstrated that the SWI can be evoked in a single, unchanging, object by priming a lifter's expectations of what they are about to lift (Buckingham and Goodale 2010a). Subjects in this task were shown a large, small, or medium cube before having their visual feedback removed. Then, unbeknownst to the subjects, the previewed cube was taken away and replaced by the medium-sized cube, which subjects lifted on every single trial with their vision blocked. Subjects experienced a robust SWI - when they saw the small cube in the preview phase, the medium-sized cube that they lifted felt substantially heavier than it felt after they had previewed the large cube. ~~In this case~~This study is also particularly difficult to reconcile with bottom-up theories of the SWI, as the perceptual illusion ~~, the SWI~~ could not have been caused by anything other than participants' expectations of

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what they were about to lift, as the physical properties of the object they lifted did not change from trial to trial.

1.3 – Different types of expectations

In the SWI, the illusion-causing expectations about how heavy the object will be in relation to one another are built up across a lifetime of experiencing the regular positive correlation between size and weight with objects in the world. We repeatedly encounter objects with a positive size-weight association, leading us to expect (sensibly) that large objects will outweigh small objects (because, on average, they will). This statistical regularity leads individuals to predict that the large object will outweigh the small object. As outlined above, the illusion-inducing expectation is not the one that drives sensorimotor prediction; perception of the SWI appears to be unrelated to grip and load force rates on a given trial (Flanagan and Beltzner 2000). Furthermore, this expectation isn't even one which an individual could readily articulate; after picking up the lighter-than-expected large cube in a standard SWI experiment only once, the lifter will readily report that they don't expect the large cube to be particularly heavy. But nevertheless, the SWI does not get smaller with repeated lifts of the illusion-inducing stimuli. This observation has led many scientists to conclude that expectations are unlikely to play a role in the SWI. However, an alternative explanation is that there are multiple types of expectation, all of which play a role in various sensorimotor processes.

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Recent evidence suggests that there may, in fact, be three separate expectations/representations which play a role when we lift objects. First, measured simply by asking individuals how heavy they expect an object to be, there are expectations which inform our conscious understanding of how heavy something should be. These expectations appear to be highly specific to material properties and the situational context of the lift. Second, by measuring fingertip forces, there are independent expectations which drive our sensorimotor prediction, which rapidly and precisely adjust on a trial-to-trial basis. The final expectations which come in to play are apparent when we judge the weights of objects and experience the SWI. Recent evidence indicates that this illusion-causing expectation does not appear to be specific to particular families of objects, unlike the sensorimotor prediction or conscious expectations of heaviness. Buckingham and Goodale (2013) investigated the magnitude of the SWI in various materials, noting that the illusion induced by large and small metal cubes was the same magnitude as the illusion induced by large and small polystyrene cubes. If the conscious expectations drove the illusion, subjects would have experienced a large SWI with the metal cubes, which they expected to have a far greater density than the polystyrene cubes. Thus, the representation which drives the SWI is not only independent from sensorimotor performance and/or expectation, but is also distinct from participants' cognitive understanding of the weight differences and density. It is important to note that, in the majority of situations in the real world, these various expectations are well-aligned. It is only in experimentally-contrived situations, such as when lifting illusion-inducing stimuli, that these expectations can be dissociated from one another.

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1.4 - Strength of illusions

Expectation-driven contrast effects appear to explain the MWI and other classes of top-down weight illusions (e.g., Ellis and Lederman 1998; Dijker 2008). However, it is less clear whether expectations can fully account for the SWI. There are, in fact, several perspectives from which the SWI seems to be qualitatively different from other weight illusions. Most notably, the SWI is by far the most powerful weight illusion which has been documented. Although it is difficult to systematically compare the magnitude of the various weight illusions across laboratories, studies which have examined the visual size and material weight illusions using identical protocols and well-matched stimuli (700g cubes, lifted with a precision grip by handle on their top surface - Buckingham et al. 2009; Buckingham and Goodale 2013; Buckingham and Goodale 2010b) show the SWI to be approximately three times the size of the MWI.

There are also wide variations in the magnitude of the SWI, depending on the experimental protocol used to induce it. For one, the SWI is markedly reduced in the experiments which have provided the strongest evidence for expectations causing the misperception of weight (summarised in Section 1.2.3). The variant of the SWI induced in a single object by priming participants' expectations is only half the size of the normal SWI induced by lifting three objects with full vision (Buckingham and Goodale 2010a). Similarly, the magnitude of the inverted SWI (Flanagan et al. 2008) was less than half the size of the normal, un-inverted, SWI. Critically, the magnitude of the inverted illusion never became as strong as the un-inverted SWI, remaining stunted for a further 22 days of experiencing the inverted objects, suggesting there are limits to the plasticity of the SWI. As the studies which provide the strongest evidence for the role of expectations inducing the SWI show reduced-magnitude illusions, it is clear that the illusion-inducing expectations outlined in Section 1.3 cannot alone account for the 'full' experience of the SWI.

It has been known for some time that the haptic SWI is substantially larger than the visual SWI, and providing concurrent visual and haptic feedback does little to increase the illusion's strength over the haptic-only illusion (Ellis and Lederman 1993). As we are skilled at detecting variations in rotational inertia through haptics (Amazeen and Turvey 1996), it is possible that the fullest SWI comes about through a combination of top-down (i.e., expectation-driven) and bottom-up (i.e., ecological) effects. As outlined above, the top-down effects appear to account for about half of the illusion, presumably leaving various bottom-up effects to contribute to the remainder of the illusory differences in weight when they are permitted. The strength of these bottom-up effects likely vary as a function of the type of actions participants use to judge the weights of the objects in an experiment (i.e., precision-grip lifting, cupping and lifting the object in one's hand, or jiggling the object to sense it's torques). Thus, the smaller illusion experienced by participants in the single-object SWI study (Buckingham and Goodale 2010a) can be taken to reflect the lack of differences in bottom-up stimulus properties seen in usual, multi-object, SWI studies. Similarly, the consistently smaller magnitude of the inverted SWI (Flanagan et al. 2008) may stem from placing the top-down expectations and the bottom-up differences between the stimuli in opposition to one another. It is not yet clear which bottom-up factors may contribute most to the sense of heaviness, although it ~~has been noted~~likely that this is dependent on dynamics of the lifting task and constrained by the shape of the object being lifted (Amazeen and Turvey 1996; Zhu et al. 2013).

In addition to the magnitude of the illusion, future work might benefit from studying the resilience of the illusion under various contexts. To date, only the SWI has been examined in this light, and has been shown to be remarkably robust to change, with thousands of trials over multiple days required

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to change the magnitude of the effect. Presumably this degree of resilience reflects some aspect of how the prior information (i.e., expectations of heaviness) associated with size cues are encoded and utilized by the sensorimotor system. It remains to be seen whether expectations derived from material or other more cognitive cues are similarly resilient to change.

~~that alterations to a spheres' centres of mass (i.e., manipulating their rotational inertia) does not affect throwability judgements or weight judgements for the different volume and mass relationships (Zhu et al. 2013), suggesting that the rotational effects described by Amazeen and Turvey (1996) may not be applicable for the classic hand-held SWI.~~

1.5 - Summary

Taken together, the literature presented in this review suggests that, in isolation, none of the dominant hypotheses surrounding weight illusions can fully account for the SWI. However, it is likely that a combination of top-down (i.e., expectations of heaviness) and bottom-up (e.g., rotational inertia) effects can explain the illusory misperception of heaviness. Future work should aim to determine the nature of the bottom-up influences in weight perception as a function of the lifting task, ~~and aim to determine~~in addition to identifying how these bottom-up effects interact with top-down expectations across the various types of weight illusion.

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