How prior expectations influence older adults' perception and action during object interaction

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Abstract

The apparent size of an object can influence how we interact with and perceive the weight of objects in our environment. Little is known, however, about how this cue affects behaviour across the lifespan. Here, in the context of the size-weight illusion, we examined how visual size cues influenced the predictive application of fingertip forces and perceptions of heaviness in a group of older participants. We found that our older sample experienced a robust size-weight illusion, which did not differ from that experienced by younger participants. Older and young participants also experienced a real weight difference to a similar degree. By contrast, compared to younger participants our older group showed no evidence that size cues influenced the way they initially gripped and lifted the objects. These results highlight a unique dissociation between how perception and action diverge across the lifespan, and suggest that deficits in the ability to use prediction to guide actions might underpin some of the manual interaction difficulties experienced by the older adults.

Keywords: Ageing; grip force; load force; size-weight illusion

Humans use a range of cues to make predictions about their environment, which in turn are used to guide their actions. This is particularly true in the case of object interaction, where grip and load forces are applied in a single, feedforward, pulse. When lifting familiar objects, individuals' fingertip forces will typically be guided by a sensorimotor memory based on their last interaction with that object (Gordon, Westling, Cole, & Johansson, 1993; Hermsdörfer, Li, Randerath, Goldenberg, & Eidenmüller, 2011). However, this predictive behaviour is evident even when confronted with novel objects, at which point participants will use a range of visual cues to predict how heavy something is likely to be. Thus, objects which appear to be made from a heavy-looking material will be lifted with more force than those which appear to be made from a lighter-looking material (Buckingham, Cant, & Goodale, 2009; Buckingham, Ranger, & Goodale, 2011a), and large objects are invariably lifted with more force than small objects (Gordon, Forssberg, Johansson, & Westling, 1991). The effect of size cues on fingertip forces is such that larger objects will be gripped and lifted with a higher rate of force than small objects, even when the lifter is unaware of the change in volume from one trial to the next (Cole, 2008). With repeated lifts, however, individuals will refine their predictions for individual objects, which they will subsequently grip and lift with forces that reflect their actual, rather than their apparent, mass (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006).

An individual's expectations about how heavy something might be does not only influence the way it is acted upon, but also how it is perceived. A number of studies over the past century have shown that cues to object mass will have a profound effect on how heavy an object feels (for review, see Buckingham, 2014). The most common example of this is the size-weight illusion (SWI), first reported over 100 years ago (Charpentier, 1891; Murray, Ellis, Bandomir, & Ross, 1999; Nicolas, Ross, & Murray, 2012). In the SWI, small objects feel substantially heavier than larger objects of the same weight. This powerful perceptual effect is long-lasting, cognitively impenetrable, and appears to be to be independent from the force rates used to lift the objects (Flanagan & Beltzner, 2000; Mon-Williams & Murray, 2000). The illusion is experienced almost ubiquitously in normal populations (Buckingham, Michelakakis, & Rajendran, 2016) and a wide range of special populations

(Buckingham, Bieńkiewicz, Rohrbach, & Hermsdörfer, 2015; Buckingham, Milne, Byrne, & Goodale, 2015; Ellis & Lederman, 1993; Li, Randerath, Goldenberg, & Hermsdörfer, 2011).

Little is known however about how these effects, or other situations where prior expectations influence perception and action, change across the lifespan. Indeed, in the context of object interaction, the majority of the work on this topic has focussed on younger participants. In terms of fingertip force application it has been shown that size cues do not affect grip and load force application prior to three years of age; although children who are older than 3 years of age tend to show a greater effect of size on their fingertip force rates than adults (Gordon, Forssberg, Johansson, Eliasson, & Westling, 1992). In the context of the perceptual SWI, all evidence suggests that young children are certainly capable of experiencing the illusion (Kloos & Amazeen, 2002). The developmental trajectory of the perceptual illusion is, however, unclear, with some researchers noting that the illusion decreases over the course of early childhood (Robinson, 1964) and others finding that the effect gets larger or remains unchanged throughout childhood, depending on whether the size cues are obtained through vision or haptics (Pick & Pick, 1967).

To date, no study has examined how size cues influence initial grip/lift forces and subsequent perceptions of heaviness in older populations. A recent study by Trewartha and Flanagan (2016) examined how age affected perceptions of heaviness and load force application to differently-sized and identically-weighted objects before and after experience with novel, inverted-density objects. The effect of the inverse-density training set on the magnitude of the SWI did not vary between the younger and older participants. However, although there was no difference between how younger and older participants updated their forces over the course of their training, the authors did note a correlation between fingertip force updating and explicit working memory scores in their older, but not younger, group of participants. This implied difference between fingertip force control in younger and older populations mirrors the findings of a reasonably large body of work, which has elucidated many facets of how older individuals control their fingertip forces in a range of tasks. In one of the first studies to examine which aspects of dextrous object manipulation were most affected by age, Cole, Rotella, and Harper (1998) showed that older participants required a far longer load phase duration (the time between initial object contact and eventual liftoff) when lifting a small metal sphere than younger counterparts. Follow-up research showed that, although older participants showed no deficit in utilizing sensorimotor memories when interacting repeatedly with objects, they tended to lift with an increased safety margin (i.e., a higher ratio of grip force to load force when the friction of the objects was varied (Cole, Rotella, & Harper, 1999), showed greater lateral biases in their force application (Cole, 2006; Kapur, Zatsiorsky, & Latash, 2010), and were less affected by the outcome of previous lifts (Kinoshita & Francis, 1996) compared to younger adults. Of most relevance to the current work, however, is a study by this group showing that older participants failed to learn arbitrary associations between an object's colour and its weight (Cole & Rotella, 2002). As it is necessary to learn an association before it can be used to guide actions, it is quite possible that older populations might have difficulties making efficient predictions about object properties based on their apparent weight. And, despite the power of volume cues to influence fingertip force parametrization (Buckingham, Ranger, & Goodale, 2011b), there has been no thorough examination of how size cues affect how novel objects are gripped and lifted. To this end, we examined the degree to which older individuals used visual size cues to guide their initial interactions with novel objects, and how these size cues affected their perceptions of object weight in a size-weight illusion task.

Materials and Methods

Participants

Twenty 20 older individuals and 20 young individuals were recruited to take part in this study. Older participants were recruited from an older person's information day and from several fitness classes running in the city of Edinburgh for older adults. The fitness classes included a carpet bowls group and an aqua aerobics class. Younger participants were recruited through the university research participation scheme in return for course credits.

The older adult group consisted of 18 females, and 2 males, with ages ranging from 60 to 91 years and a mean age of 70.5 years (SD = 8.4). The younger adult group consisted of 11 females and 9 males, with ages ranging from 18 to 28 years with a mean age of 22.9 years (SD = 2.8).

All participants gave written informed consent prior to taking part in this study, and all experimental procedures were approved by the ethics committee at Heriot-Watt University. Participants in the older adult group were screened for any cognitive pathological illnesses using the Mini Mental State Exam (MMSE - Folstein, Folstein, & McHugh, 1975). In order to participate in the study, participants had to have a MMSE score of at least 27 out of 30 (mean MMSE score = 28.65, SD = 0.88), be free from movement disorders or upper-limb mobility restrictions, and have normal or corrected-to-normal eyesight.

<u>Stimuli</u>

Participants lifted and judged the weight of four test objects: 7.5cm high black plastic cylinders which varied in size and mass. Two of the cylinders had a diameter of 10cm, one of which weighed 550g (large heavy) and one of which weighed 400g (large light). The remaining two cylinders had a diameter of 5cm, one of which also weighed 550g (small heavy) while the remaining one weighed 400g (small light). Participants also lifted a practice object - a black cylinder 7.5cm high and 7.5cm in diameter, weighing 550g. All objects had 4 rubber feet attached to their bottom surface to dampen sound cues and to ensure all objects had an equivalent contact area with the table surface.

Each cylinder had a plastic mount on the centre of its top surface which facilitated the quick attachment and removal of a plastic and aluminium handle which contained a single 6-axis force sensor (Nano17 transducer, ATI Industrial Automation, NC). Participants used this handle to grip and lift the object with their thumb and index finger on a pair of textured finger pads with a diameter of 25mm (Figure 1). The force sensor recorded forces and torques in three dimensions at 500Hz.

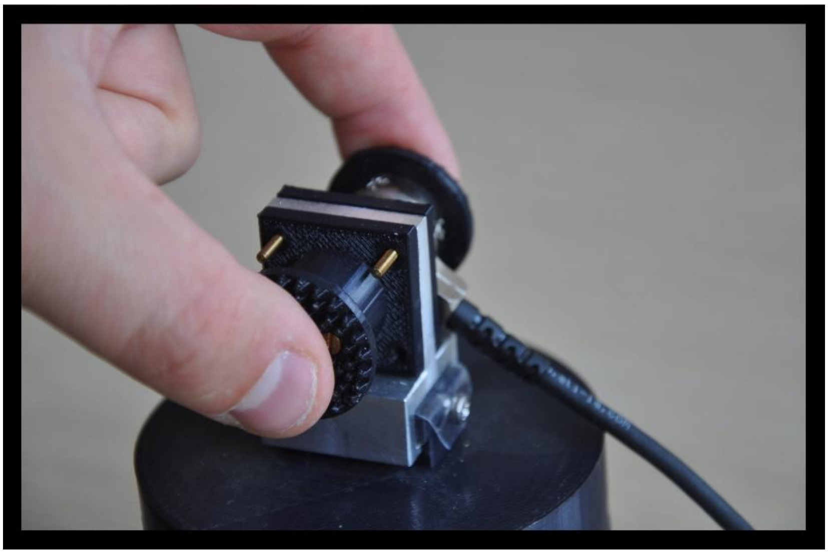

Figure 1. The handle containing the Nano17 force transducer which participants used to lift the experimental objects.

Procedure

Participants were seated in front of a large table in a height-adjustable chair. At the start of each trial participants were asked to close their eyes, at which point an object was placed quietly on the table in front of them. An auditory cue then signalled participants to open their eyes and lift up the object on the table with a precision grip, using only their thumb and index finger. They were instructed to lift the object in a smooth, controlled, and confident manner, and to keep the object still at the apex of the lift. The correct lifting technique was demonstrated by the experimenter prior to the start of the experiment. Six seconds later, a second auditory cue signalled participants to place the object back on the table surface. Participants were then asked to give a numerical rating of how heavy the object felt to them, with large numbers indicating that the object felt heavy and small numbers indicating that the object felt light. This rating had no upper or lower limit, and was not made in reference to a standard (i.e., an absolute magnitude estimation - Zwislocki & Goodman, 1980).

Prior to lifting the large and small test objects, participants undertook five consecutive lifts of the medium-sized practice object. These practice trials served to (1) ensure that participants were lifting with the correct technique (2) allow participants to calibrate their perceptual rating scale and (3) provide a washout period to minimise the impact of hysteresis-like sensorimotor motor memory effects from object interactions prior to participation in the study (Cole & Rotella, 2002; van Polanen & Davare, 2015). After completing the practice lifts, participants first lifted the large heavy cylinder and then the small heavy cylinder, followed by the remaining objects in a randomized order. Our previous work has suggested that this particular initial order of a lighter-than-expected object followed by a heavier-than-expected object produced the most reliable effects on fingertip force rates (Buckingham, Michelakakis, & Cole, 2016). In total, participants lifted and rated the weight of each of the four test objects 10 times, for a total of 40 lifts (not including the practice lifts). This protocol took less than 30 minutes to complete.

Data reduction and analysis

Full Matlab code for the data pre-processing can be found at http://goo.gl/V8NgpP. In brief, the force applied perpendicular to the surface of the finger pad was defined as grip force and the vector sum of the remaining forces was defined as load force. These grip and load force traces were then differentiated with a 5-point central difference equation to yield grip force rate (GFR) and load force rate (LFR), and the peak value of these variables served as indices of sensorimotor prediction (Buckingham, Michelakakis, & Rajendran, 2016). The peak values were chosen to represent sensorimotor prediction (as opposed to the first peak – cf. Flanagan, Bittner, & Johansson, 2008) because it is simple easier to operationalize the selection of a peak value in comparison to the difficulties in distinguishing a ‘true’ first peak from the effects of spurious contact with the transducer handle prior around the time of contact with the handle. Each trial was, however, visually inspected by the researchers to ensure that the selected peak value of grip and load force rate was drawn from the time window around the lift itself. The perceptual ratings of heaviness on each trial were converted into Z-scores to account for individual differences in the range of numbers each participant used to rate felt object weight. One participant from the Young group and two participants from the Old group were removed as outliers, defined as having initial peak or grip force rates which were greater than two standard deviations above or below their respective group means.

It is well established that only the force rates on initial trials can serve as an index of sensorimotor prediction, before motor learning processes adapt the fingertip forces from the expected to actual mass of the objects (Buckingham, Goodale, White, & Westwood, 2016; Flanagan & Beltzner, 2000). Therefore to directly examine how size cues were used by each group to guide their initial sensorimotor predictions, we examined the peak GFR and LFR values on the first lift of the large heavy and small heavy objects (i.e., the two lifts immediately following the five lifts of the medium-sized practice object) in a 2 (size: large, small) × 2 (age-group: young, old) mixed ANOVA.

In contrast to the rapidly-adapting fingertip force rates, perceptions of real and illusory weight differences are relatively stable from one trial to the next (Buckingham, 2014). Therefore, to investigate how participants experienced the real and illusory differences in object weight, we examined the normalized rating given to each of the four test objects, averaged across all 10 lifts of each object, in a 2 (size: large, small) × 2 (weight: heavy, light) × 2 (age-group: young, old) mixed ANOVA. Significant interactions of particular relevance were followed up with standard and Bayesian paired-sample t-tests within each group to quantify the strength of evidence for the null and alternative hypotheses.

All statistical tests were performed in JASP version 0.7.5.5. An alpha of .05 was used to indicate statistical significance.

Results

In terms of subjective heaviness ratings, which we examined averaged across all trials (Figure 2A), we found a main effect of size ($F(1,35) = 230.1$, $p<.001$, $\omega^2=0.86$) with our participants reporting that the small objects felt heavier than the large objects (i.e., they experienced the SWI). We also observed a main effect of weight ($F(1,35) = 459.3$, $p<.001$, $\omega^2=0.92$), with participants reporting that the heavy objects felt more heavy than the light objects. Crucially, however, we found no main effect of age-group ($F(1,35) < 0.001$, $p=.99$, $\omega^2=0.00$), and no interaction between size and age-group ($F(1,35) = 0.89$, $p=.35$, $\omega^2=0.00$) or weight and age-group ($F(1,35) = 1.02$, $p=.32$, $\omega^2=0.03$), suggesting that young and old participants experience real and illusory weight differences to an equivalent degree ($BF_{10}=0.45$ for the illusory weight difference comparison and $BF_{10}=0.60$ for the real weight difference comparison; Figure 2B). Furthermore, the three-way interaction was not significant ($F(1,35) <.001$, $p=.99$, $\omega^2=0.00$).

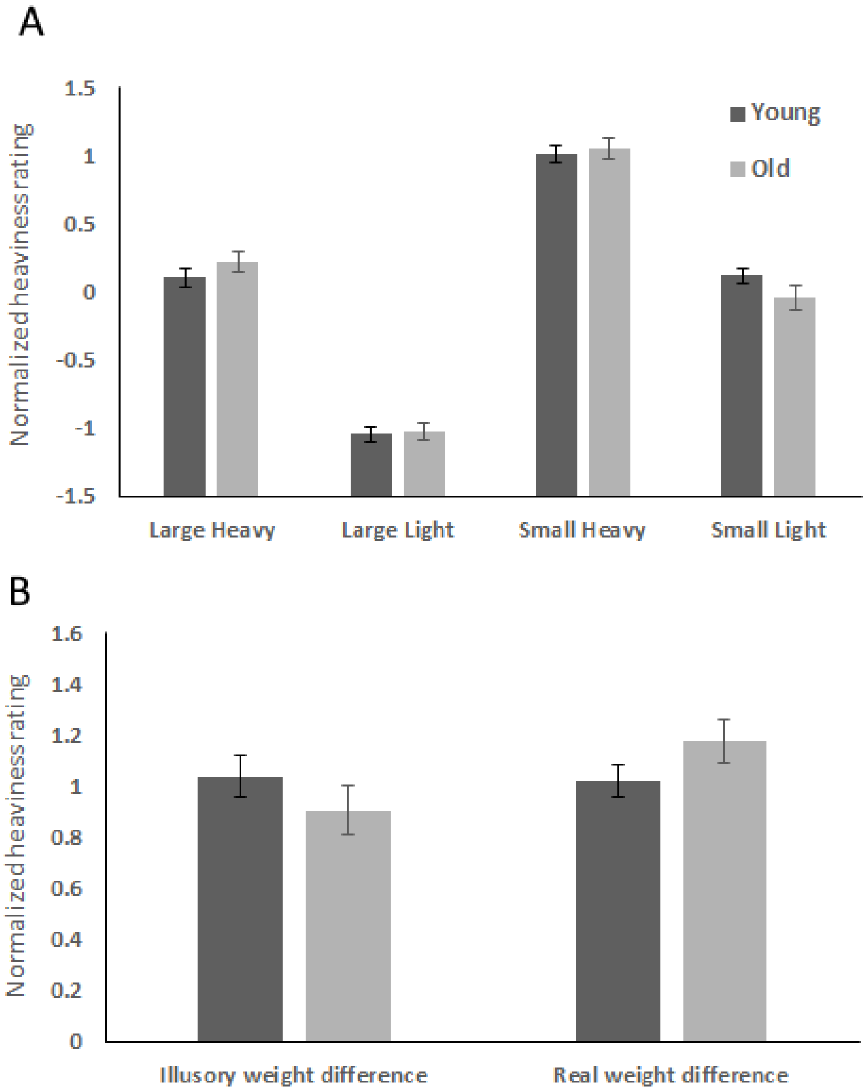

Figure 2. (A) The perceptual ratings of heaviness given to all objects, averaged across all trials and (B) the comparison of the magnitudes of the experience real weight differences (mean heavy – mean light) and the illusory weight differences (mean small – mean large). Error bars show standard error of the means.

In order to determine the degree to which size cues affected sensorimotor prediction, we examined the force rates used to lift the objects on the first lifts of the large heavy and small heavy objects (the first two lifts of the experimental stimuli). Descriptive plots of the average and individual participant grip force rate and load force rates, and the forces from which they were derived, are plotted in Figure 3.

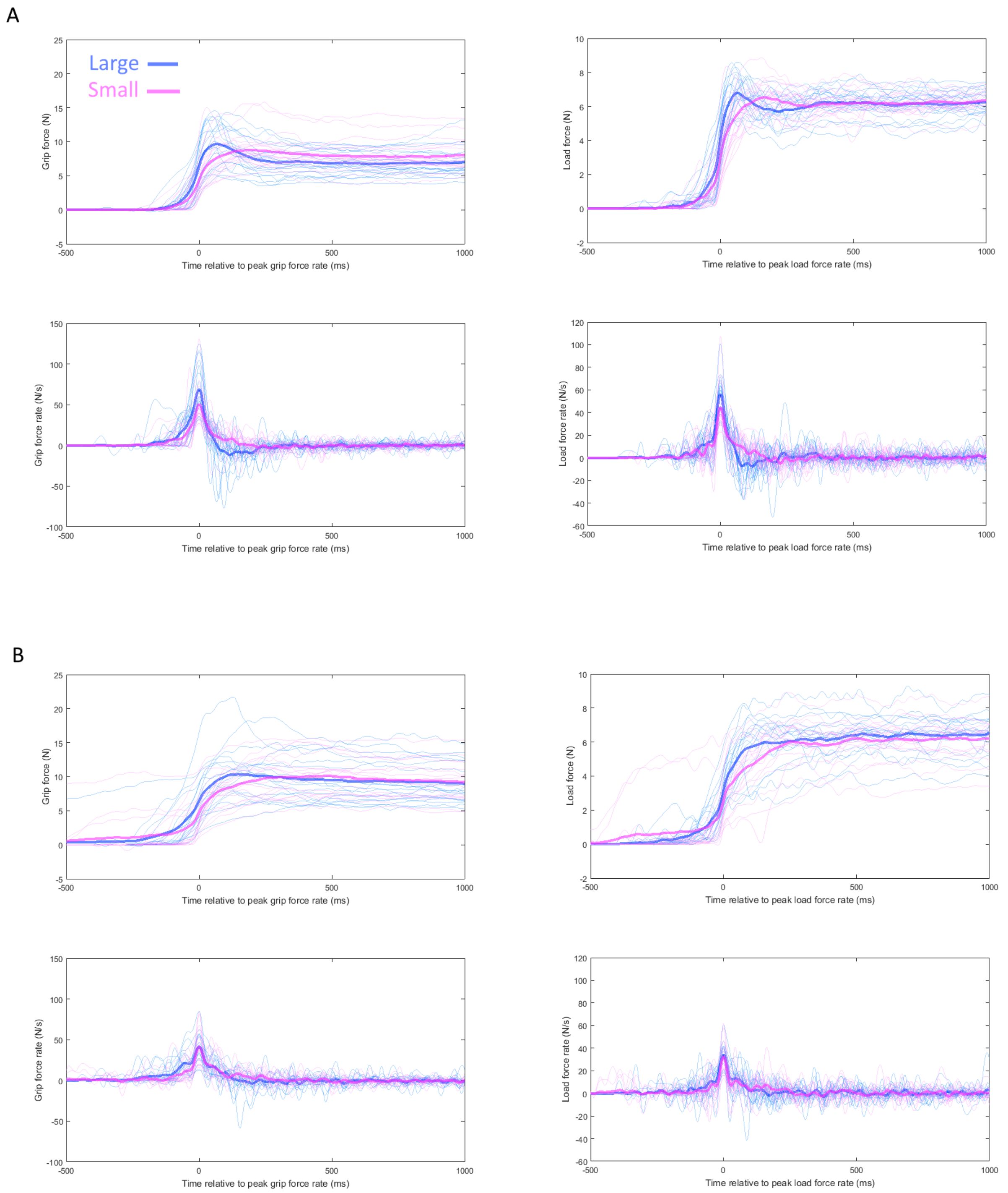

Figure 3. The first trial forces and force rates for (A) the Young group and (B) the Old group. Grip forces and grip force rates (left figures) are shifted to be centred around peak grip force rate, whereas load forces and load force rates (right figures) are shifted to be centred around the peak load force rate. Bold lines show the average forces and force rates over time for each condition, with thin lines representing individuals' traces. Note this figure is for descriptive purposes, and statistics were performed on individual peak force rate values.

In terms of participants' GFR we observed a significant main effect of size ($F(1,35) = 7.89$, $p=.008$, $\omega^2=0.13$), indicating that the large object was initially lifted at a higher rate of force than the small object. We also observed a main effect of age-group ($F(1,35) = 5.98$, $p=.02$, $\omega^2=0.12$), with younger participants applying grip force at a higher rate than older participants. These main effects were superseded by a significant interaction between size and age-group ($F(1,35) = 8.58$, $p=.006$, $\omega^2=0.15$), which was driven by the younger group showing a higher level of sensorimotor prediction from size cues than the older group (Figure 4). Post hoc t-tests confirmed that the young group gripped the large object at a higher rate than the small object ($p=.0007$, $BF_{10}=50.02$), whereas the older group used equivalent rates of force with both objects ($p=.93$, $BF_{10}=0.24$).

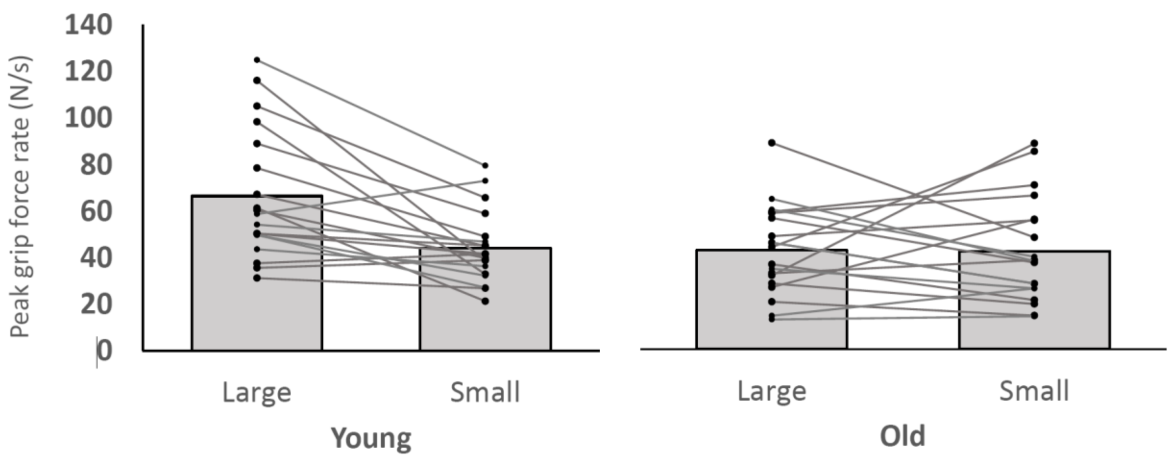

Figure 4. The peak grip force rate used by each age group for the first lift of the large heavy cylinder and small heavy cylinder. These lifts occurred immediately after the 5 practice lifts of the medium-sized heavy cylinder.

We found a similar pattern of results with LFR (Figure 5): a significant main effect of size ($F(1,35) = 6.64$, $p=.01$, $\omega^2=0.12$), a significant main effect of age-group ($F(1,35) = 18.95$, $p<.001$, $\omega^2=0.33$), and a significant group × size interaction ($F(1,35) = 5.68$, $p=.02$, $\omega^2=0.10$). Again, post hoc t-tests within each age-group showed that the younger participants lifted the large object at a higher rate than the small object ($p=.003$, $BF_{10}=10.83$), whereas the older participants used equivalent force rates to lift both objects ($p=.88$, $BF_{10}=0.25$).

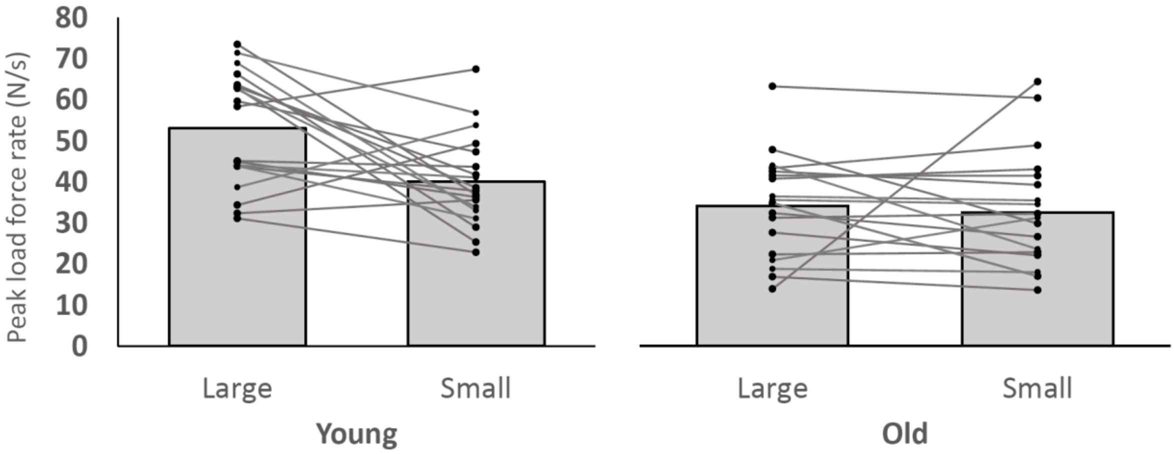

Figure 5. The peak load force rate used by each age group for the first lift of the large heavy cylinder and small heavy cylinder. These lifts occurred immediately after the 5 practice lifts of the medium-sized heavy cylinder.

Discussion

In the current work, we aimed to compare the degree to which old and young participants used prior expectations when interacting with, and perceiving, objects in their environment. To this end, we examined perceptions of heaviness and fingertip force application while participants lifted and judged the weight of objects in the context of the SWI. In SWI paradigms, individuals will typically report that smaller objects feel heavier than their identically-weighted counterparts. This effect is thought to be due, at least in part, to the lifter's initial expectation that large objects will outweigh small objects (Buckingham, 2014). Consistent with Trewartha and Flanagan (2016), we found that older participants experienced a robust SWI which was no different in magnitude that the illusion experienced by a group of younger participants. Similarly, we found no difference between younger and older participants in how they experienced a real 150g difference in object mass. It is worth noting that this congruency of the apparent magnitude of real and illusory weight differences is not trivial, as recent work using similar stimuli has demonstrated that IW (an individual with peripheral deafferentation) experiences a smaller SWI than matched controls, but normal discrimination of real differences in object mass (Buckingham, Michelakakis, & Cole, 2016).

Although the current work says little about how the ability to detect changes in mass (i.e., perceptual sensitivity) might change across the lifespan, our findings contribute to our understanding of the psychological and physiological underpinnings of weight perception. Given the well documented reduction in tactile acuity in old age (Gescheider, Bolanowski, Hall, Hoffman, & Verrillo, 1994), the lack of differences between how our older and younger participants experienced real and illusory weight differences suggests that bottom-up cues have a lower impact on this perceptual illusion than had previously been assumed (Buckingham, Michelakakis, & Cole, 2016). With regards to top-down cues on perception, our findings suggest that younger and older participants show similar expectations regarding how size cues should affect weight. This similarity is unsurprising, given that there is no reason to assume that an individual's experience of the correlation between size and mass in the real world should alter significantly in adulthood. Furthermore, this finding is also consistent with recent work showing that older individuals update their weight-illusion inducing perceptual priors at a similar rate to younger individuals (Trewartha & Flanagan, 2016). By contrast, the inconsistencies in studies that have demonstrated changes in the magnitude of perceptual illusion across early childhood (Pick & Pick, 1967; Robinson, 1964) can be more readily explained by individual differences in the reliability of the relationship between size and weight. For example, young children may have had a relatively inconsistent experience of the relationship between size and weight, resulting in a fuzzy prior that sharpens as they get older, accounting for the increased magnitude of the illusion as they age (Robinson, 1964). Alternatively, young children may learn more exceptions to the rule that 'larger equals heavier' across their early development, leading to a smaller SWI as they age (Pick & Pick, 1967). Whether this apparent plasticity in early life is due to a developmental 'critical period' where priors are formed, or simply due to the fact that with fewer experiences in total, each new experience is a higher proportion, is a topic which would need to be addressed longitudinally and experimentally. Further work is also needed to determine whether the magnitude of other, more obviously experience-driven weight illusions, might vary as a function of age. The limited research on the one such situation has received some investigation – the 'material-weight illusion' (where apparent object density affects experienced heaviness) has yielded mixed results. Trewartha and Flanagan (2016) found that there was no difference between the material-weight illusion experienced by younger and older participants. By contrast, Buckingham et al (2015) found no evidence of a material-weight illusion in a in a group of older individuals who were serving as age-matched control participants for patients with unilateral brain damage, suggesting that the effect of cognitive expectations on perception might follow a non-linear developmental trajectory.

The main finding from the current work is the clear difference between how old and young participants gripped and lifted the large and small objects on the initial trial. Studies using similar size-weight paradigms typically find that participants will grip and lift large objects with a higher rate of force than they will use to pick up small objects, regardless of their actual mass (Flanagan & Beltzner, 2000; Gordon et al., 1992; Grandy & Westwood, 2006). As the peak force rates occur prior to liftoff, and are thus unlikely to be driven by feedback mechanisms, they are considered as an index of sensorimotor prediction. Our younger participants showed the expected pattern of behaviour with these stimuli, gripping and lifting the large object at a higher rate of force than its equally-weighted smaller counterpart, indicating that they use size cues to guide their actions. By contrast, our elderly participants initially gripped and lifted the large and small objects with almost identical rates of force on average. It is worth noting that this difference between the groups was not a homogenous lack of effect in the Old age-group that would be simply characterised as an old-age impairment. Indeed, there were a number of older participants who did show size effects, and it is clear from Figure 3 that they did interact with the small and large cylinders in a different fashion from one another. However, in terms of initial sensorimotor prediction, our elderly sample showed a lesser inclination to use size cues to guide their fingertip forces when interacting with objects in their environment – a finding which is consistent with earlier work showing that older individuals tend not to utilize material cues when lifting objects (Kinoshita & Francis, 1996).

One possible explanation for our fingertip force data is that, as we age, our ability to use cognitive priors (e.g., size or other relevant cues) is reduced. This explanation is consistent with research showing that additional cognitive resources are required in older age to compensate for age-related declines in sensorimotor processing (Blumen, Holtzer, Brown, Gazes, & Verghese, 2014; Lindenberger, Marsiske, & Baltes, 2000), which presents a supply and demand imbalance given that these cognitive resources also undergo age-related declines (Seidler et al., 2010). Thus older adults may employ alternative heuristics or strategies to reduce reliance on cognitive priors in order to redirect their cognitive resources to more demanding aspects of the task such as monitoring movements and maintaining normal and consistent movement patterns (Srygley, Mirelman, Herman, Giladi, & Hausdorff, 2009). For example, instead of using cognitive priors, older people may show a greater tendency to rely on hysteresis-like sensorimotor memories from previous interactions with stimuli. It is well established that individuals will typically apply forces which are similar to those used on the most recent lift, until more relevant cues to object weight are made available (Chouinard, Leonard, & Paus, 2005; Loh, Kirsch, Rothwell, Lemon, & Davare, 2010). This apparent shift from the use of long-term prior knowledge to prioritizing short term sensorimotor priors when interacting with novel stimuli in older individuals might be an adaptive measure which prioritises safe interactions over efficient interactions, which is an appropriate strategy in the face of sensory and motoric deficits that could hinder dexterity. Future work could explicitly test this hypothesis by examining averaging vs predictive strategies in fingertip force application across the lifespan (Mawase & Karniel, 2010).

Alternatively, and perhaps more parsimoniously, our fingertip force data could be taken as evidence of a compensatory strategy in the face of age-related perceptual or cognitive declines. Indeed, it is clear from Figures 3 and 4 that older participants tended to grip and lift both objects at a rate of force equivalent to that used by the young participants to grip and lift the small object. Further support for this conclusion can be found in the supplementary materials (Figure S1), where it can be seen that even on the five consecutive lifts of the medium-sized practice object the older participants used lower rates of grip and load force than their younger counterparts. This could be interpreted as the older participants interacting with objects in an overall more cautious (i.e., a lower overall rate of force application) fashion than younger adults – a finding consistent with earlier work suggesting that older populations may adopt a grip/lift strategy aimed to ensure that they don't crush objects they are holding, at the expense of an increased risk of dropping them (Gorniak, Zatsiorsky, & Latash, 2011).

Regardless of the mechanism, it is worth considering the real-world impact of the current findings in terms of some of the manual interaction difficulties experienced by the elderly on activities important to independent living, particularly when dealing with novel objects. This has important implications for improving the design of everyday home, work, and public environments to maximise independent living for longer. For example, age decrements in the ability to use size cues to make predictions for guiding manual actions increases the likelihood that older adults will initially apply insufficient force upon lifting certain manual items under novel conditions, such as when using new saucepans of different sizes and various contents. These inaccurate sensorimotor predictions, and resulting on-line corrections (Johansson & Flanagan, 2009), could disrupt action control and/or increase the risk of breakage and injury. Moreover, this risk may be further increased in the presence of a dual cognitive task (Lindenberger et al., 2000) such as following complex cooking instructions or conversing with another individual. Indeed, recent work has indicated that fingertip force updating and other motor learning processes appear to be related to working memory (Trewartha & Flanagan, 2016; Trewartha, Garcia, Wolpert, & Flanagan, 2014). The design of everyday objects should therefore seek to facilitate independent living by not disguising action-relevant object properties to avoid such problematic cues, so that users can see the contents directly and make cognitive judgements to make appropriate, non-automatic, predictions to guide their movements.

To sum up, our investigation of how ageing affects how we perceive the weight of, and interact with, objects which vary in size noted that while age has little effect on perceptions of real or illusory weight differences, it does appear to affect how participants interact with novel objects. These findings highlight a dissociation between how the way we lift objects and perceive their weight varies across the lifespan, as well as issues related to how the elderly interact with hand-held objects and how this knowledge could inform the design of home, work, and living environments to facilitate independent living for longer.

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