Cognition 163 (2017) 121–127

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

Linking actions and objects: Context-specific learning of novel weight priors

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ARTICLE INFO

Article history:
Received 8 August 2016
Revised 24 February 2017
Accepted 25 February 2017

Keywords:
Explicit memory
Implicit memory
Weight predictions
Weight illusions
Active learning
Passive learning

ABSTRACT

Distinct explicit and implicit memory processes support weight predictions used when lifting objects and making perceptual judgments about weight, respectively. The first time that an object is encountered weight is predicted on the basis of learned associations, or priors, linking size and material to weight. A fundamental question is whether the brain maintains a single, global representation of priors, or multiple representations that can be updated in a context specific way. A second key question is whether the updating of priors, or the ability to scale lifting forces when repeatedly lifting unusually weighted objects requires focused attention. To investigate these questions we compared the adaptability of weight predictions used when lifting objects and judging their weights in different groups of participants who experienced size-weight inverted objects passively (with the objects placed on the hands) or actively (where participants lift the objects) under full or divided attention. To assess weight judgments we measured the size-weight illusion after every 20 trials of experience with the inverted objects both passively and actively. The attenuation of the illusion that arises when lifting inverted object was found to be context-specific such that the attenuation was larger when the mode of interaction with the inverted objects matched the method of assessment of the illusion. Dividing attention during interaction with the inverted objects had no effect on attenuation of the illusion, but did slow the rate at which lifting forces were scaled to the weight inverted objects. These findings suggest that the brain stores multiple representations of priors that are context specific, and that focused attention is important for scaling lifting forces, but not for updating weight predictions used when judging object weight.

1. Introduction

An essential component of smooth and dexterous manipulation of objects with the hands is the ability to make accurate predictions of their weights. Predictions about object weight used when lifting are supported by two complementary memory systems. When lifting an object for the first time people make predictions about weight on the basis of learned associations, or priors, that relate size and material to weight (e.g., Baugh, Kao, Johansson, & Flanagan, 2012; Buckingham, Cant, & Goodale, 2009; Flanagan & Beltzner, 2000; Flanagan, Bittner, & Johansson, 2008; Gordon, Forssberg, Johansson, & Westling, 1991; Gordon, Westling, Cole, & Johansson, 1993; Grandy & Westwood, 2006). Once an object has been lifted, people can make additional predictions about object weight on the basis of a complementary object-specific memory system (Trewartha & Flanagan, 2016), which has sometimes been referred to as sensorimotor memory (Flanagan, Bowman, & Johansson, 2006; Johansson & Cole, 1992; Johansson & Flanagan, 2009). When repeatedly lifting unusually weighted objects that are not well predicted by priors, object-specific memory allows for relatively rapid updating of weight predictions to support smooth and efficient lifts. When lifting objects that are erroneously predicted by priors, accurate predictions of object weight can be developed within about 5–40 lifts, depending on the number of objects being lifted and the nature of the violation of the prior (Flanagan & Beltzner, 2000; Flanagan, King, & Wolpert, 2001; Flanagan et al., 2008; Gordon et al., 1991, 1993; Grandy & Westwood, 2006; Johansson & Cole, 1992).

In addition to facilitating lifting performance, weight predictions based on priors also bias perceptual judgments about

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http://dx.doi.org/10.1016/j.cognition.2017.02.014
0010-0277/

weight. Such biases can be revealed by the size-weight illusion, whereby the smaller of two equally weighted, and otherwise similar, objects is perceived to be heavier (Flanagan & Beltzner, 2000; Flanagan et al., 2008). The size-weight illusion is thought to arise because weight is judged relative to expected weight based on priors. Strong evidence in favor of this view is provided by the demonstration that after repeatedly lifting unusually weighted objects the size-weight illusion can be attenuated, and even inverted with extensive experience (e.g., Flanagan et al., 2008).

The available evidence indicates that priors underlying weight predictions used when making perceptual judgments, and object-specific memory underlying weight prediction used when lifting previously lifted objects, are independent (Flanagan & Beltzner, 2000; Flanagan et al., 2008). However, until recently the precise nature of these memory processes was not well understood. We recently reported evidence that the ability to update weight predictions used for perception of object weight is correlated with implicit memory processes, whereas the updating of weight predictions used for lifting is associated with declarative memory (Trewartha & Flanagan, 2016). The current study builds on these observations to further explore the nature of the memory processes involved in updating weight predictions used for lifting objects and judging their weights.

A remarkable feature of the size-weight illusion is that it is observed across a wide range of conditions under which the individual receives information about the size and weight of the objects involved. The illusion is observed at full strength when information about size and weight is obtained haptically, as when grasping and lifting the object, and is nearly as strong when size information is obtained only visually, as when lifting by strings (Ellis & Lederman, 1993). A strong illusion is also observed when the objects are placed on, and passively supported by, the hands or other parts of the body (see Ross, 1969), or if the mass of the objects is experienced by moving objects under zero-gravity conditions (Plaisier & Smeets, 2012).

A fundamental question is whether the updating of priors that occurs when interacting with unusually weighted objects is linked to the context in which these objects are experienced. If so, it would suggest that the brain does not store a single representation of priors—that can be updated and accessed independently of the way in which objects are interacted with—but, rather, that the representations of priors are context-specific. The first aim of the current study was to examine this question. Different groups of participants repeatedly experienced size-weight inverted objects either passively (with the objects placed on the hands) or actively (where participants lift the objects). For both groups, we periodically tested the size-weight illusion, both actively and passively, throughout the experiment. If updating priors is linked to the context in which the objects are experienced, we would expect a stronger change in the illusion when the mode in which the illusion is measured matches the mode in which the inverted objects are experienced. Alternatively, if adaptation of priors involves updating a single, global representation in memory, changes in the illusion—tested either passively or actively—should not depend on the mode in which the inverted objects are experienced.

The second aim of the current study was to explore the role of focused attention on the updating of weight predictions used for lifting and judging object weight, thought to rely on explicit and implicit processes respectively (Baugh, Yak, Johansson, & Flanagan, 2016; Trewartha & Flanagan, 2016). A key conceptual difference between implicit and explicit memory processes is that unlike explicit memory, implicit memory processes do not rely on conscious processing (see Schacter, 1992; Schacter & Tulving, 1994). A common approach for identifying tasks that can be performed without conscious attention is to assess performance under divided attention (i.e., dual task) conditions (Pashler, 1994; Watanabe & Funahashi, 2014). If performance of a primary task is not affected by the simultaneous performance of a secondary task the primary task can be performed automatically, and likely relies on implicit learning processes.

To investigate this second question, we included two additional groups of participants who, while experiencing the size-weight inverted objects either passively or actively, were required to perform a mental arithmetic task at the same time. We predicted that dividing attention would have little effect on experience-driven changes in the illusion, given that those changes have been associated with implicit memory, but that dividing attention would impact force scaling when lifting the weight inverted objects, as this form of learning has been associated with explicit memory (Trewartha & Flanagan, 2016).

2. Method

2.1. Participants

Forty-nine naïve participants (18–33 years old) were recruited to participate in this study. The participants were randomly assigned to one of four groups to participate in one of the four experiments: (1) full attention with passive interaction (n = 13), (2) full attention with active lifting (n = 12), (3) divided attention with passive interaction (n = 14), and (4) divided attention with active lifting (n = 10). All participants were recruited from the undergraduate and graduate student populations at Queen's University, Kingston, ON, Canada. All participants self-identified as right handed, were in good self-reported health, and were compensated for their time. Participants gave written informed consent to protocols approved by the Queen's University ethics committee.

2.2. Materials

Participants were seated in a comfortable chair with a tabletop in front and to the left of the chair. A Plexiglas platform containing two force/torque sensors (Nano 17 F/T sensors, ATI Industrial Automation, Garner, NC, USA), which effectively acted as weight scales, was located on the tabletop in front of the participants. Each sensor was capped with a circular (diameter 3 cm) flat cap upon which objects were placed. These sensors allowed us to measure the vertical load forces applied during lifting (sampled at 1000 Hz). Between the participant and the force platform was a moveable screen that could be drawn to prevent the participant from viewing the platform while the experimenter moved objects to and from the force platform. A super-cushioning polyurethane foam platform (18″ × 20″ × 2″ thick, 6 lbs./cu. ft. density) was located on the tabletop to the left of the participants providing a supportive resting platform on which participants rested their right hand during all passive trials (Fig. 1A).

We constructed a small (51 mm high × 51 mm diameter), heavy (720 g) cylinder and a large (82 mm high × 82 mm diameter), light (190 g) cylinder (see Fig. 1B). To test the size-weight illusion we also constructed a small and an equally weighted (455 g) large cylinder, equal in shape and volume to the small and large weight inverted objects, respectively. The outer surface of all four cylinders was made of hard white plastic and the mass was evenly distributed within each cylinder.

2.3. Procedure

2.3.1. Size-weight illusion assessment

For all participants we assessed the size-weight illusion prior to any experience with the size-weight inverted objects to establish a

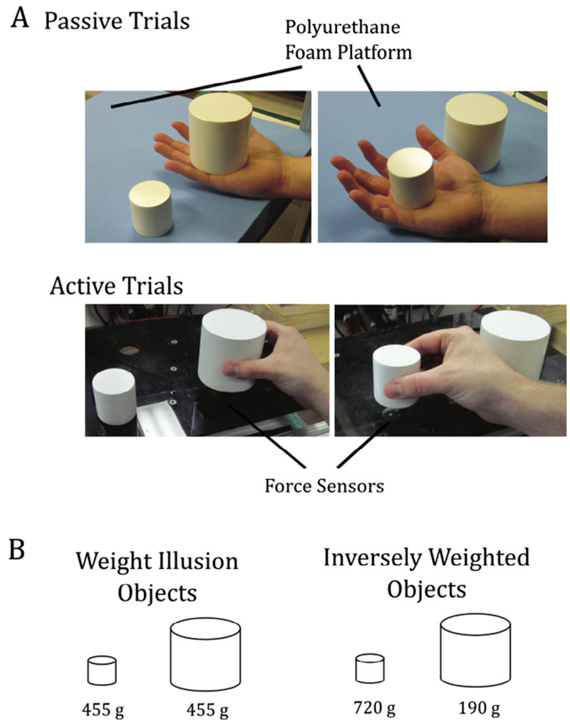

Fig. 1. Apparatus and stimuli. (A) The top panel shows the apparatus used for passive interaction trials. Participants rested their right hand on the foam platform while the objects were placed in their hand. The bottom panels show the apparatus used for active lifting trials. Participants lifted the objects using a precision grip with the tips of the index finger and thumb of the right hand on either side. Each object was lifted off a force sensor and replaced on the same sensor. (B) Equally weighted small and large objects for testing the size-weight illusion, and inversely weighted small and large objects used to measure the adaptation of lifting forces and elicit experience-driven changes in the size-weight illusion.

baseline magnitude of the illusion. Subsequently the illusion was assessed after each block of experience interacting with the inversely weighted objects (see below) so that changes in the magnitude of the illusion could be tracked. For all participants the illusion was measured once actively and once passively every time the illusion was assessed in order to determine the context specificity of changes in the illusion.

To assess the illusion we used the absolute-magnitude estimate procedure (Flanagan & Beltzner, 2000; Flanagan et al., 2008; Zwislocki & Goodman, 1980). In the active assessment trials participants first lifted one of the two equally weighted objects off of the force platform (e.g., the smaller weight illusion object) and, after replacing the object on the platform, assigned a number to represent the weight of the object. They were instructed to use any number of their choosing. They were then asked to repeat this estimation procedure for the second object (e.g., the larger weight illusion object). For the passive assessment trials the procedure was identical except that instead of lifting the objects participants rested their right hand, palm facing up, on the foam platform and the experimenter placed the objects on their palm prior to each estimation.

The strength of the illusion was quantified as the percentage increase from the smallest to the largest magnitude estimate. The percentage increase was assigned a positive value (multiplied by 1) if the small object was judged to be heavier, or a negative value (multiplied by −1) if the large object was judged heavier. Positive values would indicate a standard size-weight illusion.

2.3.2. Object interaction trials

After the initial size-weight illusion assessment all participants experienced the inversely weighted objects over 5 blocks of 20 interactions with each object (40 interactions total per block). In the two active lifting groups participants were instructed to grasp the sides of the object with the thumb and forefinger of the right hand using a precision grip. Each trial began with an auditory tone cuing participants to reach out and grasp the object. They were asked to pause briefly before lifting the object in order to ensure that forces related to lifting could be clearly distinguished from those related to grasp. Participants lifted the object and held it aloft until a second tone cued them to return the object to the sensor. The second tone was played 1000 ms after the participant lifted the object off the force sensor.

The two passive interaction groups were asked to face the tabletop on the left and place their right hand palm facing up on the foam platform. While participants rested their hand on the foam the experimenter placed one of the inversely weight objects on the participant's palm upon hearing the first auditory tone. Participants were asked to relax their hand while the object passively rested on their palm. Upon hearing the second auditory tone the experimenter removed the object from the participant's hand. Similar to the active interaction group, the second tone was played 1000 ms after the object was placed in the participant's hand. Thus, the only difference between the active and passive groups in terms of their experience with the inversely weighted objects was whether they actively lifted the objects, or experienced the weight of the objects passively.

2.3.3. Secondary task for divided attention conditions

For the two divided attention groups participants were asked to perform a concurrent mental arithmetic task while interacting with the inversely weighted objects. Participants wore a microphone headset over which the auditory stimuli were presented and vocal responses were recorded. The secondary task was a subtract-seven task in which participants heard a number between 12 and 99 played over the headset and participants were required to mentally subtract seven from that number and vocalize their response as quickly as possible. For the active lifting group the auditory stimulus was triggered by the liftoff of the object from the force sensor. For the passive experience group, the auditory stimulus was played 500 ms after the first auditory tone, which coincided with the time at which the experimenter placed the object in the participant's hand. Thus, for both groups the mental arithmetic task was performed while participants experienced the weight of the object on each trial. Vocal recordings on each trial were used to determine the accuracy of each response.

2.3.4. Data analysis

The vertical lifting (or load) forces were digitally smoothed with a fourth-order, low-pass Butterworth filter using a cut-off frequency of 14 samples per second. The rate of change of load force was obtained by differentiating the smoothed load force using a first order central difference equation. Previous research has shown that when people lift objects just off a surface they increase load force to a target level slightly exceeding the predicted weight of the object (Flanagan & Beltzner, 2000; Johansson & Westling, 1988). The peak rate of change in load force typically occurs when the load force is approximately half the predicted weight. We refer to this peak rate of change of load force as the first peak in load force rate because, when the object is heavier than expected, additional increases in load force, associated with additional peaks in load force rate, are observed. To measure how well participants scaled their lifting forces when lifting the inversely weighted objects, we determined the load force produced at the first peak in load force rate, which we will denote as $LF_{1st\ peak\ rate}$ (Flanagan et al., 2008).

The analysis of lifting forces was focused on the small heavy object, consistent with previous research (e.g., Flanagan et al., 2008), but it is important to note that predictions of the weight of unexpectedly light and heavy objects lifted in alternation adapt in parallel (Flanagan & Beltzner, 2000). Focusing on the small heavy object ensured accurate measurement of the initial peak in load-force rate because measurements using the lighter objects are less reliable. Specifically, when an object is much lighter than expected, lift-off may occur before the time at which the first peak in load force rate would have occurred had the weight matched the expected weight.

All of our analyses focused on trial blocks. To assess the lift performance of participants in the active interaction groups, we calculated the average $LF_{1st\,peak\,rate}$ in each block of 20 trials. To assess the secondary task performance of participants in the divided attention groups, we determined the proportion of correction responses in the subtract-seven task for each trial block. Experimental effects were assessed using repeated measures and mixed ANOVAs. Pairwise comparisons, used to further assess these effects, are reported using a Bonferroni correction. A p value of 0.05 was considered to be significant.

3. Results

3.1. Weight illusions

Fig. 2 shows the strength of the size-weight illusion as a function of block and assessment method for the four groups examined in this study. To test whether the strength of the size-weight illusion differed when assessed actively or passively at baseline in each group we conducted paired-sample *t*-tests within each group using a Bonferroni correction. There was no significant difference in the strength of the illusion when assessed actively and passively in the Full Attention – Passive Interaction group ($t(12) = -1.46$, $p = 0.17$), the Full Attention – Active Interaction group ($t(11) = -0.57$, $p = 0.58$), the Divided Attention – Passive

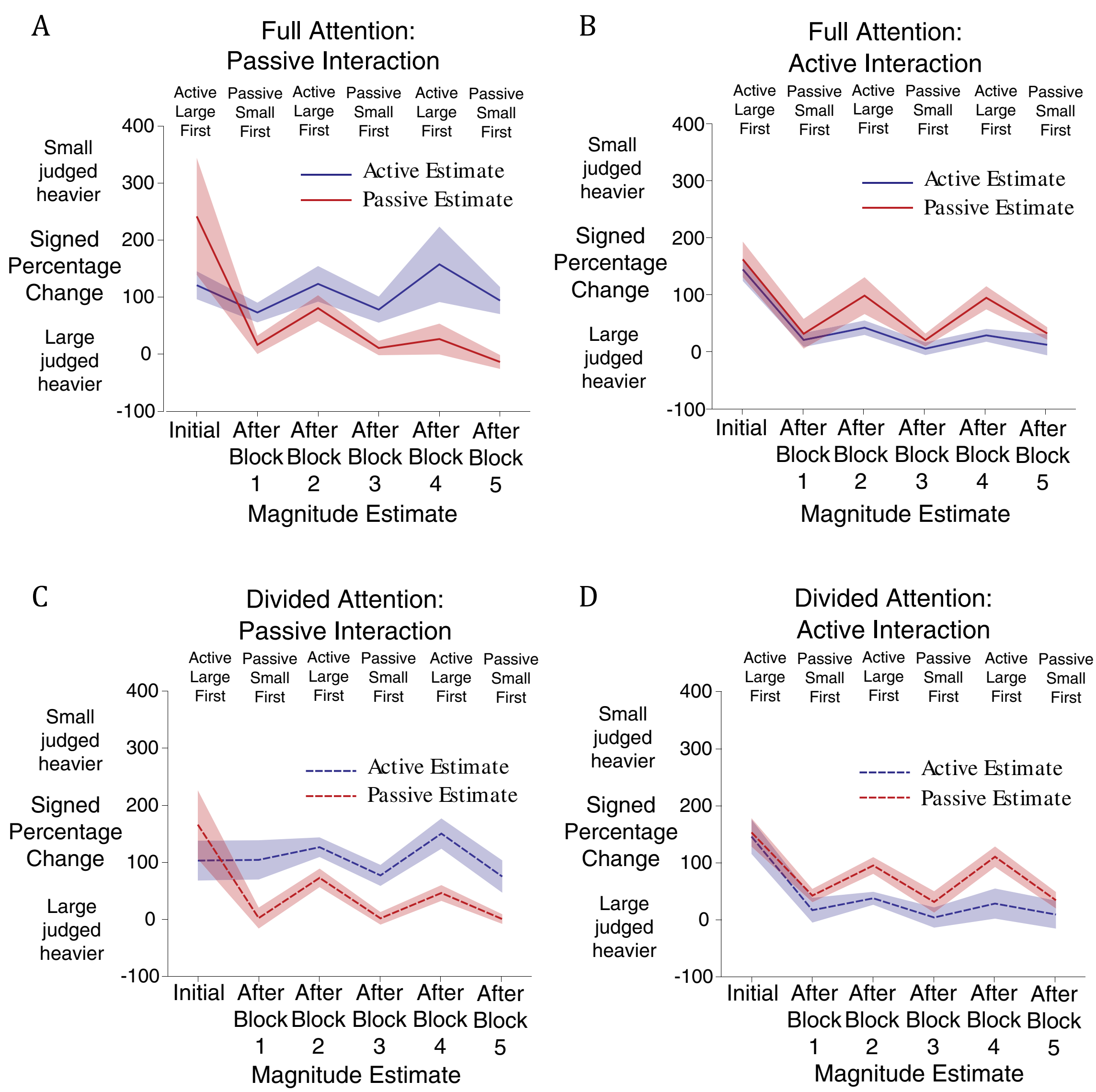

Fig. 2. Weight judgment results. (A) Weight judgments for the full attention and passive interaction group. (B) Weight judgments for the full attention and active interaction group. (C) Weight judgments for the divided attention and passive interaction group. (D) Weight judgments for the divided attention and active interaction group. (A–D) Strength and direction of the size-weight at baseline, and after every 20 interactions with the inversely weighted objects in each condition. The assessment method (active or passive) and the object that was encountered first on each weight-illusion assessment trial are labeled at the top. The blue traces represent the weight judgments made using the active assessment method and the red traces represent the weight judgments made using the passive assessment method. The shaded regions represent ±1 SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Interaction group ($t(13) = -1.85$, $p = 0.09$), or the Divided Attention – Active Interaction group ($t(9) = -0.426$, $p = 0.8$).

To test whether the learning process associated with updating weight predictions used when making perceptual judgments about weight depends on context and attention, we carried out a four-way ANOVA with block and assessment method as within-participant factors and interaction condition and attention as between-participant factors. There was a main effect of block ($F(5,41) = 24.4$, $p < 0.001$). Pairwise comparisons revealed that the illusion was stronger in the baseline assessment than the subsequent five assessments ($p < 0.05$). There were significant two-way interactions between assessment method and interaction condition ($F(1,45) = 45.5$, $p < 0.001$), and between assessment method and block ($F(5,41) = 3.5$, $p < 0.05$). Importantly, there was a significant three-way interaction between assessment method, block and interaction condition ($F(5,41) = 6.3$, $p < 0.01$). Pairwise comparisons revealed that for the passive interaction groups, the passively assessed size-weight illusion was attenuated after the first, third, fourth, and fifth blocks relative to the baseline assessment ($p < 0.05$), but that there were no differences between blocks for the actively assessed illusion. For the active interaction groups, the actively assessed illusion was attenuated after the first through fifth blocks relative to baseline ($p < 0.01$), and the passively assessed illusion was attenuated in the third and fifth blocks relative to the second and fourth blocks ($p < 0.05$). Thus, active interaction with the inversely weighted objects lead to some limited attenuation of the strength of the illusion when assessed passively, but the change was more robust when the illusion was assessed actively. No other main effects or interaction effects were significant ($p > 0.12$).

Together these analyses support the general conclusion that the size-weight illusion was attenuated more readily when the assessment method for the strength of the illusion matched the context in which the inversely weighted objects were experienced. In addition, dividing attention had little affect on the strength of the size-weight illusion, or on the experience-driven changes in the strength of the illusion.

3.2. Lifting forces

To test whether dividing attention impacted the updating of lifting forces we compared the lifting forces between the Active Interaction – Full Attention and Active Interaction – Divided Attention groups. Fig. 3A shows the $LF_{1st\ peak\ rate}$ as a function of lift number for the two groups. The corresponding block averages of $LF_{1st\ peak\ rate}$ scores are shown in Fig. 3B. A two-way block by group ANOVA revealed a significant main effect of group such that the $LF_{1st\ peak\ rate}$ was larger for the full attention group than the divided attention group overall ($F(1,20) = 6.23$, $p < 0.05$). There was also a significant main effect of block ($F(4,17) = 26.0$, $p < 0.001$) such that $LF_{1st\ peak\ rate}$ was smaller in the first block than the subsequent four blocks overall (all $p < 0.01$). Finally, from visual inspection of Fig. 3B it appears that there is an interaction between group and block. Although this interaction failed to reach significance ($F(4,17) = 2.21$, $p = 0.07$), pairwise comparisons revealed that the $LF_{1st\ peak\ rate}$ was larger in the full attention group than in the divided attention group in the first, second, and fourth blocks ($p < 0.05$), but not in the third and fifth blocks ($p > 0.13$). These pairwise comparisons, together with visual inspection of Fig. 3B suggest that the groups differed especially in the first block of lifting trials. To test whether the rate of learning to scale lifting forces in the first block differed between the divided attention and full attention group we calculated the average $LF_{1st\ peak\ rate}$ in bins of five trials and compared these four bins in a two-way bin by group ANOVA. There was a significant main effect of bin ($F(3,18) = 5.3$, $p < 0.01$), a significant main effect of group ($F(1,20) = 12.8$, $p < 0.01$), and importantly a significant interaction between bin and group ($F(3,18) = 3.2$, $p < 0.05$). Pairwise comparisons revealed that the $LF_{1st\ peak\ rate}$ was significantly smaller in the divided attention group in bin 2 ($p < 0.01$), and bin 3 ($p < 0.01$), there were no differences between groups in bin 1 or bin 4 ($p > 0.06$). Thus, the groups produced similar lifting forces in the first five trials, but the full attention learned to scale their lifting forces faster than the divided attention group over the next ten trials before the divided attention caught up during the final five trials of the first block. These findings demonstrate that dividing attention had a significant impact on the rate at which participants learned to scale lifting forces to the unusually weighted objects.

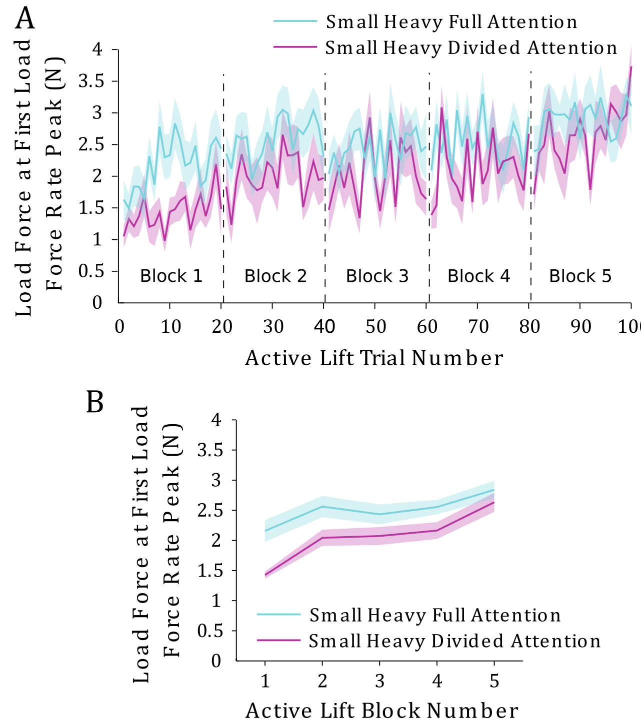

Fig. 3. Lifting performance. (A) Load force at the time of the initial peak in load force rate across all lifts of the heavy small object in the full attention – active interaction group (cyan), and the divided attention – active interaction group (magenta). (B) Summary plots of the load force at the time of the initial peak in load force rate averaged across each block of 20 lifts for each group. Note: the asterisks identify the pairwise comparisons that were significant between the groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In support of the idea that participants in the divided attention group were devoting attention at least partly to the secondary task we found that the accuracy of their responses to the subtract-seven task was quite high overall ($M = 90.2\%$, $SE = 4.1\%$). Across lifting blocks the average accuracy was consistently high (Block 1: $M = 88.3\%$, $SE = 6.5\%$; Block 2: $M = 90\%$, $SE = 5.5\%$; Block 3: $M = 91.8\%$, $SE = 3.1\%$; Block 4: $M = 90.5\%$, $SE = 3.8\%$; and Block 5: $M = 92\%$, $SE = 2.6\%$). Importantly, a one-way repeated measures ANOVA failed to reveal differences across blocks ($p > 0.6$) indicating that participants in the divided attention group maintained a similar level of attention to the secondary task throughout the experiment.

4. Discussion

The aim of this study was to investigate the nature of the memory processes underlying weight predictions used when lifting objects and making perceptual judgments of object weight. We manipulated the context in which participants experienced inversely weighted objects—active versus passive interaction—and compared assessments of the size-weight illusion obtained through both active and passive conditions to determine whether memory processes underlying weight predictions used when judging object weight are context specific. We also compared performance between groups of participants who either experienced the inversely weighted objects under full or divided attention to determine whether conscious attention is required to update predictions of object weight used when lifting objects or judging their weights.

We found that the strength of the size-weight illusions was attenuated to a greater extent when the illusion was assessed under the same condition in which the inversely weighted objects were experienced. Specifically, passive interaction resulted in larger changes in the illusion under passive assessment than active assessment, whereas active interaction resulted in larger changes in the illusion under active, compared to passive assessment. Dividing attention while interacting with the inversely weighted objects had little effect on the attenuation of the illusion. A second key finding was that dividing attention slowed the updating of weight predictions used when lifting objects. The Active Interaction – Divided Attention group was slower to scale their lifting forces to the inversely weighted objects than the Active Interaction – Full Attention group. Together these findings indicate that the memory processes underlying weight predictions used when making perceptual judgments about object weight are largely context specific, but are not dependent on conscious awareness. In contrast, the memory processes underlying weight predictions used when lifting objects are at least partly reliant on focused attention for rapid learning of object weights.

The current findings add to the view that two complementary memory systems contribute to ability to make predictions about object weight. The first time an object is lifted its weight is predicted on the basis of long-term priors linking weight to other object properties including size and material. These priors also bias perceptual judgments about weight, as measured in the size-weight and other weight illusions. Although size-weight priors are typically resistant to change (Baugh et al., 2016; Flanagan & Beltzner, 2000; Flanagan et al., 2008), they can be adapted relatively quickly under appropriate experimental conditions (e.g., Trewartha & Flanagan, 2016). The second memory system uses associative memory processes to learn the weight of specific objects through repeated lifts of the same objects. This object-specific memory allows for rapid updating of weight predictions used to scale lifting forces to the weight of specific objects and is especially important when lifting unusually weighted objects.

The stability of long-term priors enables us to reliably judge objects to be 'heavy' or 'light' given expected weight (Baugh et al., 2012). Evidence for the stability and robustness of long-term priors is provided by observations that the size-weight illusion is elicited under a variety of conditions through which the objects are encountered. For example, early reports suggested that the size-weight illusion is observed when the objects are placed passively on the hands or other parts of the body (Ross, 1969). The current findings corroborate this report and show that the strength of the illusion during initial assessments was similar when those assessments were measured through passive and active methods for all four groups.

Although typically stable, weight predictions used when making perceptual judgments about weight can be adapted through experience lifting unusually weighted objects that violate size-weight expectancies (Flanagan et al., 2008). The current findings demonstrate that the adaptation of such predictions is largely dependent on the context in which the unusually weighted objects are experienced. Information about object weight acquired through passive interaction with the inversely weighted objects does not transfer to perceptual judgments made through active interaction; however information gained through active interaction exhibits some limited transfer to perceptual judgments made through passive interaction. In general, these findings suggest that the brain maintains multiple representations of priors that are linked to the context in which objects are encountered. Experience-driven changes in the size-weight illusion likely reflect the adaptation of priors on the basis of distinct representations that include information about the mode in which objects are experienced, rather than the adaptation of a single, global prior that is independent of context.

We found that passive interaction with the inversely weighted objects did not influence priors used when making perceptual judgments actively. Previous work on motor learning has shown that passive movements made under a visuomotor rotation have limited benefits on subsequent active performance (e.g., Lotze, Braun, Birbaumer, Anders, & Cohen, 2003; Sakamoto & Kondo, 2015). Additionally, although passive movements facilitate the learning of arbitrary associations between reach locations and visual symbols, such associative learning is better with active movements (Trewartha, Case, & Flanagan, 2015). The present results indicate that active movements also confer an advantage in terms of the updating of priors used for judging object weight, with such updating being broader when actively, in comparison to passively, experiencing unusually weighted objects. In general, it seems sensible to limit generalization of updating of well-established priors based on experience in a particular context (Flanagan et al., 2008), since these priors are extremely useful in guiding behavior. Our finding that such generalization did not occur when passively interacting with the inverted objects, may reflect the fact that this protective mechanism is even stronger when experiencing violations of priors under unusual and infrequently occurring circumstances. However, when experiencing violations under more common circumstances (i.e., active lifting), the brain may be more willing to broaden the context in which updated priors are applied.

One additional curious observation from the current data is that the strength of the illusion was generally lower when the illusion was assessed passively and with the small object first, compared to when the illusion was assessed actively and with the large object first for all four groups (Fig. 2). In designing our study, we did not anticipate this effect and therefore did not dissociate assessment method and object weight. Therefore, we cannot say whether the zigzag pattern is linked to which object size is lifted first or which assessment method is performed first. In any event, we currently have no explanation for why the order of object sizes or assessment methods would influence the illusion. While this result may warrant further investigation, we would emphasize that our major context effects can be observed in the illusion value obtained for both testing orders.

We recently reported that there is a correlation between experience driven changes in weight illusions and performance on an implicit memory task, suggesting that the memory processes underlying weight predictions used for perceptual judgments are implicit in nature (Trewartha & Flanagan, 2016). The current experimental evidence corroborates this view as changes in the size-weight illusion were largely unaffected by the addition of concurrent secondary task during interaction with the inversely weighted objects. Previous research on the generalization of motor learning found that adaptation to a novel load introduced gradually – without conscious awareness – does not exhibit transfer between limbs, whereas transfer does occur when the load is introduced abruptly and explicit cognitive strategies contribute to learning (Malfait & Ostry, 2004; see also Criscimagna-Hemminger, Donchin, Gazzaniga, & Shadmehr, 2002). Consistent with these observations, the current findings support the view that when motor learning primarily involves implicit memory resources—thereby operating outside conscious awareness (Schacter, 1992; Schacter & Tulving, 1994)—this learning does not generalize readily between task contexts. This view is consistent with recent research demonstrating better inter-limb transfer of explicit, compared to implicit components of visuomotor adaptation (Poh, Carroll, & Taylor, in press).

Although dividing attention had little effect on experience-driven changes in the size-weight illusion, it did have a significant effect on the early stages of learning to scale lifting forces to the weights of the inversely weighted objects. This finding provides evidence that the memory processes underlying weight predictions used when lifting objects are partly dependent on attention, consistent with the idea that explicit memory processes are involved (Schacter, 1992; Schacter & Tulving, 1994). This finding corroborates our previous observation that the ability to update object-specific memory during lifting is related to explicit working memory resources (Baugh et al., 2016; Trewartha & Flanagan, 2016).

In summary, the current findings taken together support the notion that two complementary, but dissociable memory systems underlie weight predictions used when lifting objects and making perceptual judgments about weight, respectively. Here we provide experimental evidence that the memory processes underlying weight predictions used when making perceptual judgments are implicit in nature. The current data also demonstrate that changes in the size-weight illusion due to experience are context-specific indicating that rapid changes in the strength of the size-weight illusion can occur due to implicit learning mechanisms that alter task-specific priors about object weight, rather than altering global priors about the relationship between size and weight (Flanagan et al., 2008). Lastly, our data show that the memory systems underlying our ability to adapt weight predictions used when lifting objects involve attentional resources that allow for conscious formation of associations between weight and specific objects, likely by relying on explicit associative memory processes.

Author contributions

K.M.T. and J.R.F. conceived of and designed the research; K.M.T performed the experiments; K.M.T. analyzed the data; K.M.T. and J.R.F. interpreted the results of the experiments; K.M.T. and J.R.F. prepared figures; K.M.T. drafted the manuscript; K.M.T. and J.R.F. edited and revised the manuscript; K.M.T. and J.R.F. approved final version of manuscript.

Acknowledgments

We thank Martin York and Sean Hickman for technical support. This work was supported by the Canadian Institutes of Health Research and the Natural Sciences and Engineering Council of Canada.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.02.014.

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