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

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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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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