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Prism adaptation of underhand throwing: Rotational inertia and the primary and latent aftereffects

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ABSTRACT

The effect of prism adaptation on movement is typically reduced when movement at test (with prisms removed) is different from movement at training. Previous research [J. Fernández-Ruiz, C. Hall-Haro, R. Díaz, J. Mischner, P. Vergara, J. C. Lopez-Garcia, Learning motor synergies makes use of information on muscular load, Learning & Memory 7 (2000) 193–198] suggests, however, that some adaptation is latent and only revealed through further testing in which the movement at training is fully reinstated. Movement in their training trials was throwing overhand to a vertical target with a mass attached to the arm. The critical test trials involved the same act initially without the attached mass and then with the attached mass. In replication, we studied throwing underhand to a horizontal target with left shifting prisms and a dissociation of the throwing arm's mass and moment of inertia. The two main results were that the observed latent aftereffect (a) depended on the similarity of training and test moments of inertia, and (b) combined with the primary aftereffect to yield a condition-independent sum. Discussion focused on a parallel between prism adaptation and principles governing recall highlighted in investigations of implicit memory: whether given training (study) conditions lead to good or poor persistence of adaptation (memory performance) at test depends on the conditions at test relative to the conditions at training (study).

A growing body of research suggests a potentially significant parallel between prism adaptation and memory phenomena [8]. A specific suggestion is that adaptation's persistence (realized as an aftereffect) is an instance of procedural memory [2], a subsystem of nondeclarative or implicit memory [17].

One major perspective on implicit memory (alias, long-term priming) is that its magnitude depends on the kinds of processes and conditions shared between the original experiencing of an event (called "study" or "training") and the subsequent testing of the memory for that event [5,8,15]. The shared aspects underlying transfer from study to test are particular to the specifics of the (a) stimulus situation at study, (b) stimulus situation at test, (c) task constraints at study, and (d) the task constraints at test [5]. Briefly, whether a form of study leads to good or poor performance on a memory test depends on the test's similarity to study.

Highlighting the aforementioned parallel between prism adaptation and the study-test similarity perspective on implicit memory is the observation that the magnitude of recalibration aftereffects, like the magnitude of priming, depends on the degree to which study (training with prisms on) and test (behavior with prisms off) are alike [13,14]. The key feature of the prism research in question is that it involves manipulations of the non-visual conditions of the adapted behavior. Prism adaptation fails to transfer fully when velocity of reaching is different from training to test [7], starting posture for a given movement differs from training to test [1], hand used differs from training to test [7], or the type of throw (overhand or underhand) differs from training to test [9]. Recalibration of movement control may not, however, be solely responsible for these transfer outcomes; realignment of spatial maps may also contribute [14]. Disentangling the two requires special manipulations and measures [14] and, in the absence of such, both must be assumed to affect the training-test relation.

Similarity between circumstances of training and test within a prism adaptation experiment exists on a continuum, allowing varying degrees of transfer from complete, to partial, to none [7,9]. A subtle means of evaluating this degree, and the conditions responsible for it, has been introduced by Fernández-Ruiz et al. [3] through what can be referred to as the extended prism adaptation paradigm. Participants in their experiment wore prisms that displaced gaze horizontally and threw a clay ball overhand at a vertically oriented, shoulder height, target. A weight attached to the wrist of the throwing arm affected the throw vertically. With weight and prisms removed, participants showed a horizontal aftereffect that diminished in the usual way. However, reattachment of the weight

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led to a further horizontal aftereffect that was apparently latent during the preceding testing without the weight. The theoretical significance of this latent aftereffect for the general understanding of perception-action relations (e.g., recalibration and realignment) within prism adaptation research [13,14] provides strong motivation for further investigation.

In their work, Fernández-Ruiz et al. [3] presumed that mass was the relevant dynamical variable in the task of throwing to a target. However, the limb's moment of inertia is of greater relevance to the act of throwing, and more likely to be the operative dynamical variable. Relative to the shoulder, a limb's moment of inertia is given by the product of its mass and the squared distance of its center of mass from the relevant axis of rotation in the shoulder.

The difference between mass (resistance to translational acceleration) and moment of inertia (resistance to rotational acceleration) provides a further motivation for revisiting the extended prism paradigm. In Fernández-Ruiz et al.'s [3] experiment, mass and moment of inertia were conflated. A lighter and a heavier mass attached at the wrist correspond to a smaller and a larger change in moment of inertia, respectively. It is unclear from their experiment whether the relevant condition of similarity between the training and test was limb mass, limb moment of inertia, or both.

The aim of present research was threefold: to (a) replicate and generalize the latent aftereffect, (b) evaluate the contributions of mass and moment of inertia to the training-test conditions of similarity, and (c) elucidate the hypothesized parallel between prism adaptation and the similarity perspective on implicit memory. In respect to the first aim, the present study generalized Fernández-Ruiz et al.'s [3] extended prism paradigm to the task of throwing underhand to a target on the floor. In respect to the second aim, the experiment included conditions in which a fixed magnitude weight was attached to the wrist or to the elbow, resulting in a larger or smaller change, respectively, in the resistance of the arm to rotational acceleration. In respect to the third aim, the experiment included manipulations of similarity between (a) conditions testing for the initial aftereffect and the conditions during training, and (b) conditions testing for the latent aftereffect and the conditions during testing for the initial aftereffect.

The design of the experiment is depicted in Fig. 1. The initial or primary aftereffect (AE1) "test" is conducted in Trials 61–75. The latent or secondary aftereffect (AE2) "test" is conducted in Trials 76–90. There were three major predictions with direct bearing on each of the aforementioned aims. The basis for the three predictions was the expected consequences of degree of similarity between the test conditions for AE1 and the training conditions (Trials 31–60), and between the test conditions for AE2 and the test conditions for AE1. The ordinary aftereffect, AE1, should be magnified by greater similarity of its test conditions to the training conditions. In comparison, the extraordinary aftereffect, AE2, should be magnified by greater dissimilarity of its test conditions to those of AE1. Fernández-Ruiz et al.'s [3] conjecture about AE2 is that it is the memory of the prism adaptation not manifested in the test condition for AE1. If so, then the sum of AE1 and AE2 should be the same over variations in the conditions of training-test similarity and test–test similarity.

The first prediction was that AE1 should decrease from Group 1, to Group 3, to Group 5 and AE2 should increase from Group 1, to Group 3, to Group 5. In short, an interaction among groups (1, 3 and 5) and aftereffect were expected. In respect to AE1, all three groups threw with the arm unloaded. For Group 1, training and test were both with the unloaded arm. The moment of inertia of the unloaded arm was less than that for the arm loaded at the elbow (Group 3), which in turn was less than that for the arm loaded at the wrist (Group 5). In consequence, the difference between training conditions and AE1 test condition was least for Group 1, greater for Group 2, and greatest for Group 5. In respect to AE2, the three groups threw with different loadings of the arm. The loading difference between testing for AE2 and testing for AE1 was most for Group 5 and least for Group 1.

The second prediction was that groups 2 and 4 should exhibit larger AE1 and smaller AE2 than groups 3 and 5. This predicted interaction between groups (2, 4 versus 3, 5) and aftereffect (AE1 versus AE2) follows from two facts (see Fig. 1): (a) that the load at AE1 test and the load at training (Trials 31–60) were the same for groups 2 and 4 and different for groups 3 and 5, and (b) that the load at AE2 test and the load at training were different for groups 2 and 4 and the same for groups 3 and 5.

The third prediction was that for all five groups, the sum of AE1 and AE2 should remain constant.

The participants were 40 undergraduates (20 females, 20 males) enrolled in introductory psychology classes at the University of Connecticut participating for course credit. They were randomly assigned to one of the five groups, depicted in Fig. 1, with eight participants per group. All participants had normal or corrected-to-normal (via contact lenses) vision. By self-report, 36 participants were right-handed and four were left-handed. All participants gave their informed consent in accordance with the University of Connecticut's internal review board's regulations for studies with human participants, and in accordance with the Declaration of Helsinki. Proof of formal approval could be provided upon request.

As shown in Fig. 1, for each group the 90 trials were parsed into No Prism Trials 1–30, Prism Trials 31–60 and No Prism Trials 61–90. Following each throw, the experimenter measured the distance of the impact point from the target in both the *x*- and *y*-directions resulting in Cartesian coordinates (*x*, *y*) for every throw.

In Group 1 (Panel 1 in Fig. 1), the throwing arm was unloaded for all 90 trials. In Group 2 (Panel 2 in Fig. 1), a weight of 1150 g was attached to the participant's upper arm just above the elbow during No Prism Trials 16–30, Prism Trials 31–60 and No Prism Trials 61–75. The weight was detached for No Prism Trials 76–90. Group 3 differed from Group 2 on No Prism Trials 61–90. The weight was

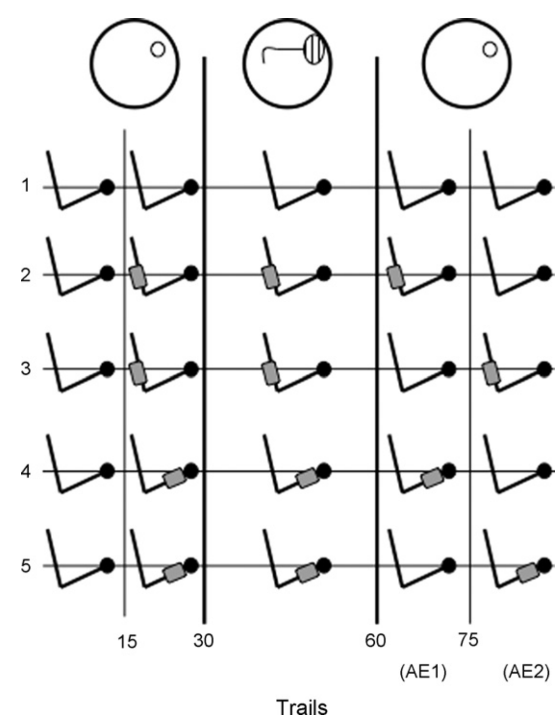

Fig. 1. Experimental design. Horizontal lines depict trials. Vertical lines denote important block boundaries. Drawings indicate when the weight was worn and whether it was at the elbow or wrist. AE1, first aftereffect test, AE2: second aftereffect test.