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Repetition Effects in Grasping

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The task in the present experiments was to reach out and grasp a novel object that afforded two possible grips. Different versions of the object were created that biased subjects to use one grip or the other. The dependent variable was the repetition effect, the tendency to repeat the grip that was used on the previous trial. In Experiment 1, two qualitatively different objects were used, and it was found that the repetition effect was specific to the object being grasped: There was much less tendency to use the same grip as the previous trial if the object being grasped was different. Moreover, the effect lasted over intervening trials and was even present with more than five intervening trials. In Experiment 2, the global context was manipulated, so that in some blocks one grip was much more likely than the other. However, this manipulation had little effect on the choice of grip and did not interact with the repetition effect. In Experiment 3, the hand used to grasp the object was manipulated, and there was little change in the repetition effect. Thus, a grip was more likely to be used if it was used on the previous trial, regardless of whether the previous grasp was performed with the left or right hand. In Experiment 4, a similar result was found for a manipulation of object location and orientation. Our interpretation of these results is that subjects prepare for an action by retrieving action features from memory, and that the object to be grasped provides a critical cue for that memory retrieval. In this view, the repetition effect is essentially a memory recency effect.

Keywords: action, repetition effect, motor control, memory for action

People tend to repeat actions. For example, in Rosenbaum and Jorgensen (1992), subjects selected between an underhand or overhand grip for grasping a bar. Over a sequence of trials, subjects moved progressively from situations in which the overhand grip was most comfortable for the target movement to one in which the underhand grip was more comfortable or vice versa. At some point, subjects reached a situation in which either grip could be used, and subjects continued to use the grip they had just been using. Kelso, Buchanan, and Murata (1994) found a similar "hysteresis" effect using a task involving wrist rotations. Dixon and Glover (2004) reanalyzed data from Glover and Dixon (2001) and found that subjects tended to repeat the hand orientation in grasping a dowel. Jax and Rosenbaum (2007) found that after subjects moved around a virtual obstacle to reach a target, they tended to use a similar trajectory even when the obstacle was no longer present. In all of these situations, subjects select one of several forms of an action, all of which can be used to achieve a goal, and there is a strong tendency to use the form of action used on the previous trial.

The tendency to repeat actions implies that the selected actions must be, in some sense, nonoptimal. That is, in any given situation, it is possible to identify which of several ways of achieving a goal is most efficient or incurs the least cost based on the existing biomechanical constraints. For example, Stelmach, Castiello, and Jeannerod (1994) found that the orientation of an elongated object dictated the choice of grip, and that other components of the motion trajectory were coordinated with that choice. The results from a similar manipulation by van Bergen, van Swieten, Williams, and Mon-Williams (2007) suggested that the grasping posture was selected to minimise the amount of wrist rotation. Rosenbaum and Jorgensen (1992) suggested that choice of grip was determined by relative comfort. However, a demonstration that subjects tend to repeat an action implicates a mechanism in selecting an action other than efficiency or cost. Thus, when an action is repeated rather selecting a different action based on biomechanical constraints, it must be, to some extent, the less optimal choice.

In the present research, we propose that repetition effects in action choice are determined by episodic memory. In particular, we assume that the current stimulus environment provides a memory cue that tends to evoke related prior episodes and that those episodes influence the choice of action in the current context. Such an account predicts action repetition because the most recently completed trial is likely to be readily available in episodic memory. Thus, if the current situation resembles the preceding situation, subjects will tend to produce the same action. An episodic account makes several predictions. First, although the most recent trial is likely to be readily available, other, more distant, trials may also be retrieved. Thus, repetition effects should not be limited to just the immediately preceding trial. Second, because episodes are retrieved on the basis of the current context, contextual similarity should be important. In particular, only episodes that are encoded as similar to the current situation should be retrieved. Finally, an episodic representation may include a range of information about

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the action, including relatively abstract descriptions of the features of the action and its effect on the environment. It need not, for example, be limited to the details of the movement trajectory.

In contrast, previous accounts of action repetitions have generally assumed some form of what may be termed "immediate perseveration": Some representation of an action persists for some period of time and influences the subsequent action. For example, Rosenbaum and Jorgensen (1992) argued that subjects, in selecting either an underhand or overhand grip, defaulted to the grip used on the previous trial and were only motivated to change the grasp posture when it became uncomfortable. Presumably, this entails maintaining a representation of the default grip from the previous trial. Jax and Rosenbaum (2007) in their analysis of movement trajectories suggested that a movement feature related to trajectory curvature was maintained in working memory and reused on subsequent trials. The mechanism of hysteresis described by Kelso et al. (1994) was explained by stable coordination dynamics that persist from trial to trial until the nature of environment encourages a reorganization of those dynamics. Although immediate perseveration involves memory, it is distinct from a more general episodic account in two ways. First, the presumed representations are short term and last only from one trial to the next. Thus, it is only the last action performed that influences action on the current trial. Second, immediate perseveration does not involve any retrieval. Thus, the similarity of the current context to the preceding trial should not affect the availability of the representation of the preceding action.

The present research extends the previous demonstrations of action repetition in several ways and demonstrates that an immediate perseveration account is not adequate. First, we provide evidence that repetition effects depend on the similarity of the context. Second, we show that the effects are not limited to the immediately preceding trial or action but extend across a number of intervening trials. Third, we find that these effects can occur at relatively high levels of abstraction in which repeated movements have no effectors in common. Thus, our conclusion is that these effects implicate more general memory mechanisms rather than simply immediate perseveration.

The Present Research

In the experiments reported here, subjects were simply asked to reach out, grasp, and lift a novel object. The objects were constructed so that there were two possible grasp postures, and we recorded which posture subjects selected. This choice was examined as a function of the choice of action on previous trials. In Experiment 1, we examined the role of intervening trials on the repetition effect; in Experiment 2, we evaluated whether action frequency affected choice strategy; and in Experiments 3 and 4, we assessed whether the effect transferred across different effectors and target orientations. Although the task subjects were asked to perform was simple, the design of the experiments and their analysis and interpretation may require some explanation. In this section, we first describe the general motivation for the design of the materials and depict how this was implemented in Experiments 1 and 2. Second, we discuss the nature of the data obtained from these experiments and our approach to the analysis. Finally, we describe how the results are presented and interpreted.

Our main goal in developing this paradigm was to investigate how subjects would select among possible actions when each of those actions sufficed for carrying out the experimental task. On each trial, subjects were asked to use their right thumb and index finger to grasp and lift an unfamiliar, amorphous object. However, the object was constructed so that there were two plausible grasp postures in which the thumb and index finger would contact the object at approximately parallel surfaces close to the object's centre of gravity. Subjects were free to use either of these two postures in grasping the object, and we recorded which posture subjects used on each trial. To ensure that the choice of grip would vary at least to some extent across trials, we used different versions of each object that varied in the affordance for the two possible grasp postures. For one version, the geometry of the grasp points was altered slightly to make one grasping posture relatively more effortful and the other relatively less effortful; in another version, the relative effort of the two postures was reversed. In this way, the tendency to repeat choices from trial to trial was pitted against the tendency to use the physically most appropriate grasp posture: If the repetition effect was relatively weak, the choice of posture would be determined primarily by physical affordance, while if the repetition effect was strong, it would tend to dominate the effect of affordance. Essentially, the magnitude of the repetition effect could be scaled in terms of the effect of physical affordance.

Figures 1 shows how these principles were implemented for the materials used in Experiments 1 and 2. On the left is a perspective depiction of two objects, and three versions of those objects are shown in plain view to the right. Subjects were instructed to grasp the objects with their thumb and forefinger using a pinch grip. For such a grip, the greatest ease would occur when the object surfaces contacted by the thumb and forefinger were parallel with each other. Consequently, the objects were designed so that there were two pairs of relatively parallel surfaces where the thumb and forefinger could be placed. One required that the hand be rotated in the clockwise direction to align the thumb and forefinger with the contact surfaces, while the other required that the hand be rotated in the counterclockwise direction. (We will refer to these two postures as the clockwise and counterclockwise grips, respectively.) The different versions of the object varied in terms of the extent to which the grasp points for the clockwise and counterclockwise grips were parallel. In the version shown on the left, the clockwise contact surfaces are nearly parallel and provide a good basis for a pinch grip. Although the counterclockwise contacts could be used for that object version, it would require more effort because the surfaces are not nearly as parallel. The reverse is true for the object versions on the right, where the counterclockwise grip would be easier. The object versions in the middle are intermediate. We will refer to the left version as the clockwise-object versions, those right versions as the counterclockwise-object versions, and those in the middle as the neutral-object versions. A critical ingredient in the design of the objects is that although the different object versions were designed to make the clockwise and counterclockwise grips more or less suitable, it was still physically possible to perform the task with either grip for all of the object versions.

Our approach to analysing the results from this paradigm may require some explanation as well. The data collected were binomial, in that subjects could make either of two responses (a clockwise grip or a counterclockwise grip) on each trial. Because

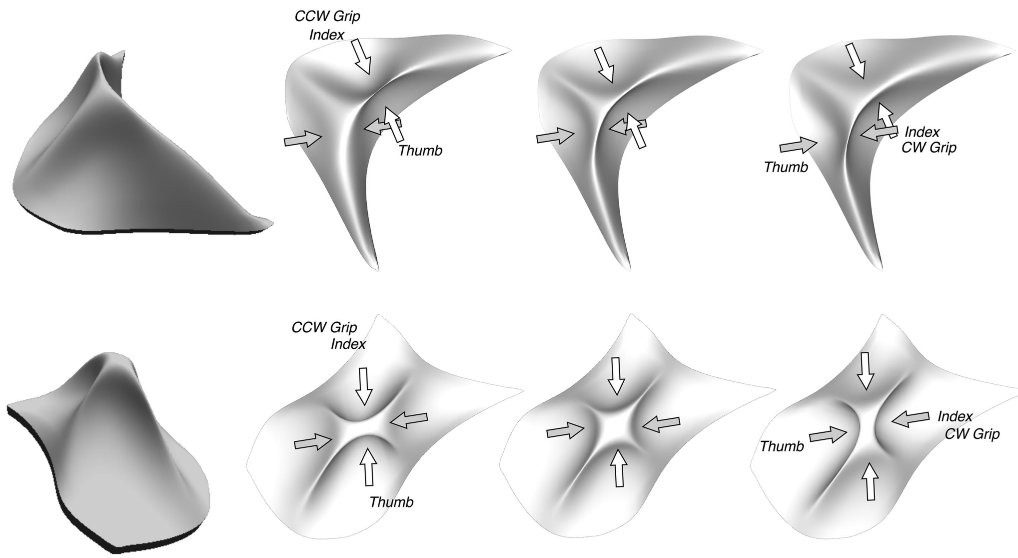

Figure 1. The leftmost drawings in each row provide a perspective depiction of the two objects used in Experiments 1 and 2. The object on the top was orange and the object on the bottom was green. To the right of each perspective drawing are depictions, in plain view, of the three different versions of each object illustrating the manipulation of affordance. In each row, the left object was biased to the counterclockwise grasp and the right object was biased to the clockwise grasp. The white-filled arrows indicate the grasp points for the counterclockwise grip, while the gray-filled arrows indicate the grasp points for the clockwise grip.

such data are discrete rather than continuous, it would be inappropriate to use analysis of variance or similar linear modelling techniques to analyse the results. A common technique for working with such discrete data is to use the proportion of (e.g.) counterclockwise grips in each condition as the data to be analysed. However, such data are constrained to the range 0–1, and ceiling (or floor) effect can arise that might distort the patterns of results. Further, because of the constrained range, the variance would not be equal across conditions and would vary systematically with the grip proportion. A more significant problem is that the main predictor of interest is the grip used on the previous trial, and because this was not experimentally controlled, it could vary across conditions and subjects. Under these circumstances, simple calculations of grip proportion can lead to averaging artifacts such as Simpson's paradox (Simpson, 1951) in which overall proportions do not reflect the patterns observed for individual subjects.

To address these and related issues, logistic regression is commonly recommended for binomial data such as those collected here (e.g., Allison, 1999; Everitt & Hothorn, 2006). In this approach, the logit or log odds of a counterclockwise grip is assumed to be a linear function of the predictor variables. The relation between log odds and grip proportion is shown in Figure 2. The logistic function has a straightforward relation to grip proportion, with proportions near 1 corresponding to large logit values, proportions near 0 corresponding to large negative values, and a proportion of .5 corresponding to a logit value of 0. Intuitively, logistic regression can be regarded as a technique for rescaling proportions from the constrained range of 0–1 to an unconstrained range of $-\infty$ to $+\infty$, thereby eliminating the distortions due to ceiling and floor effects. The estimated predictor coefficients can be thought of as strengths of the predictors (expressed in a logit scale), and the logistic regression procedure can be regarded as a technique for estimating those strengths from the dichotomous responses (Dixon, 2008).

The use of logistic regression in the present design provides an intuitive approach to conceptualising effects of repetition. For example, to measure the tendency to repeat the previous grip, we would enter two predictors in the regression equation: grasp affordance (i.e., whether an object version was used that made the clockwise or counterclockwise grip more suitable), and the grip used on the previous trial. The top panel illustrates the results of this regression when affordance is considered alone (based on the data to be presented in Experiment 1). For each of the six object versions, one would estimate a logit weight. Those weights provide the *x*-value for the six points plotted in the figure and describe the tendency to grasp that stimulus with (e.g.) a counterclockwise grip. The weights can be thought of as the affordances of the counterclockwise grip for the stimuli. Each weight corresponds to a proportion response as determined by the logistic function, and these proportions provide the *y*-values for each of the six points in the figure. The panel illustrates how the logistic function recodes proportion counterclockwise response (on the *y*-axis) into logits (on the *x*-axis). Because the manipulation of object version was similar but not identical for the two objects, there is no reason to anticipate that the affordances for the three versions will be the same across the two objects. In this case, the affordance for the green object happens to span a greater range than those for the orange object.

This effect of physical affordance provides the background against which to consider the effect of repetition. In particular, if the previous trial used a counterclockwise grip, there may have been a tendency to use a counterclockwise grip on the current trial, independent of the affordance of the current object. The nature of the previous response was added as an additive predictor to the

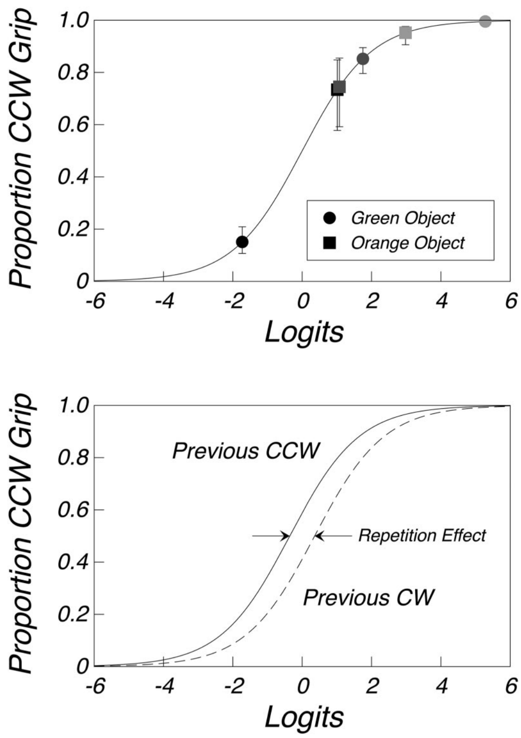

Figure 2. Measurement of the repetition effect in logits. The upper panel shows the logistic regression weight for each object and object version along horizontal axis and the corresponding proportion counterclockwise grip in Experiment 1 along the vertical axis. Grasp affordance is depicted in the gray scale of the points: Black for the clockwise version, light gray for the counterclockwise version, and medium gray for the neutral version. Error bars indicate the standard error of the affordance parameter estimate in a fit of the logistic model fit. The lower panel depicts the repetition effect as a shift in the logistic curve depending on the nature of the response on the preceding trial.

regression equation based on affordance (i.e., the fitted values shown in the top panel). Because of this additivity, one can conceptualise the repetition effect as a shift of the function depicted in top of Figure 2. This is shown in the bottom panel of Figure 2, where the two fitted curves are shown for trials preceded by a clockwise grip and those preceded by a counterclockwise grip. For trials preceded by a counterclockwise grip, the curve is shifted to the left, which entails that for any given point on the curve, the probability of making a counterclockwise grip will be increased. The reverse is true for trials preceded by a clockwise grip. The shift in the curves, measured in logits, provides an index of the magnitude of the repetition effect that we will use in describing the results from present experiments.

According to this analysis, one cannot express the magnitude of the repetition effect in terms of proportion response. The curves in Figure 2 make it clear that the same shift produces varying effects on the response proportion depending on where on the curve one starts. In particular, the effect of repetition on response proportion (i.e., the vertical distance between the two curves) is small if the proportion of counterclockwise responses is near 1 but much larger if it is near 0.5. Instead, the amount of horizontal shift (measured in logits) provides a more suitable index of the tendency to continue to use the grip from the previous trial. In the present results, the variables are coded so that positive logit values correspond to an increased tendency to use counterclockwise grips.

Experiment 1

In Experiment 1, we used the present repetition paradigm to assess the extent to which the repetition effect transfers across intervening trials and distinctive objects. This provides a strong test of immediate-perseveration accounts of repetition because such accounts would naturally predict that repetition should be a function only of the action on the preceding trial and that more distant trials should have little effect. Similarly, the nature of the object grasped on the preceding trial should not matter as long as the general form of the action is comparable. In the experiment, the objects shown in Figure 1 were presented in a random order, and we measured the choice of grip on trial *n* as a function of the grip used on trial *n-1* and on trial *n-2* and whether the object being grasped was the same or different. An immediate perseveration account would make two predictions: There should be minimal effect of the grip selected on trial *n-2*, and there should be minimal effect of the nature of the preceding object. Substantial effects of either of these variables would suggest that a mechanism other than immediate perseveration must be involved.

Method

Subjects. Twelve University of Alberta undergraduates served as subjects in the experiment in partial fulfillment of course requirements. All were right-handed and reported having normal or corrected-to-normal vision. All subjects were naive as to the specific purpose of the study and gave their informed consent prior to testing. A trial was counted as an error if subjects failed to use one of the two prescribed grips. One subject had an error rate of 26.1% and was not included in the analysis. The error rate for the remaining 11 subjects averaged 4.3%.

Stimuli. There were six free-form stimuli printed with a Spectrum Z510 3D Printing System. As shown in Figure 1, the stimuli were made up of two series of three objects each. Each object was 5.7 cm tall. Because we were interested in assessing repetition effects with distinct objects, we highlighted the distinctiveness of the two series of object versions by painting them different colours: One series was painted green while the other was painted orange. We will use the term “object” to refer to the series of stimuli with the same colour and overall configuration, and “object version” to refer to the smaller changes in grip affordance within each series. Each series had two clear, comfortable sets of grasp contact points, one that required the hand to be rotated in a clockwise direction and one that required a counterclockwise rotation. Although the two objects were distinctive in terms of overall appearance and configuration, the grasp points were designed so that the required clockwise and counterclockwise rotation was comparable. The end points of each series were constructed to strongly bias one of the two grips, and a more neutral object was created with an intermediate bias.

Apparatus. Subjects sat at a 76 cm high table with their forehead resting on a headrest; seating height was adjusted so that the hand and forearm could rest comfortably on the table top. The position of the headrest meant that subjects’ trunk was adjacent to the edge of the table. Stimuli were placed on a 60 × 45 cm piece of white construction paper. To ensure consistent placement of the stimuli, an outline of stimulus was marked on the paper 40 cm from the edge of the table and centered in front of the subject. A white plastic "start disk" (2 cm in diameter and 0.4 cm thick) was attached to the table 10 cm from the edge. Subjects were required to start each trial with the thumb and forefinger of their right hand resting on the start disk. Because subjects' trunk was adjacent to the edge of the table, this constrained the range of comfortable starting positions, and subjects normally began each trial with their wrist resting on the table top and their elbow next to their body. Dim diffuse light was provided by an incandescent light reflected off a photographer's umbrella. Subjects viewed the table through liquid crystal goggles that could be either opaque or transparent (Milgram, 1987).

Procedure. Subjects were told to reach out and grasp the object presented on each trial and lift it momentarily off the table top. The experimenter illustrated the clockwise and counterclockwise grips for each object, and subjects were told to use one of those two grips on each trial. There were, of course, other ways in which a person might contrive to grasp the objects shown in Figure 1. They might, for example, use a power grip that encompassed the object with their whole hand. However, to simplify the nature and interpretation of the results, subjects were asked to limit themselves to the grips shown in Figure 1. Subjects began each trial of the experiment with the thumb and forefinger of their right hand resting on the start disk, their forehead in the headrest and the goggles switched to their opaque state. One of the six possible stimuli was randomly selected on each trial and was placed on the table in the prescribed position. The goggles were then switched to transparent, and the subject reached for the object, grasped it using the thumb and forefinger of their right hand, and lifted it off the tabletop momentarily. The experimenter recorded which of the two grips was selected and switched the goggles to the opaque state in preparation for the next trial. The two grips were easily distinguishable, and there was little ambiguity concerning which grip was used on each trial. Consequently, the response measurement consisted simply of tabulating the choice of response on each trial. Each subject completed a single block of 199 trials; the object was selected randomly (with replacement) on each trial.

Analysis. The data were analysed using a generalised linear mixed-effect model with the R program lmer, using the logistic function as the "link" function (Bates & Sakar, 2006; R Development Core Team, 2006). The generalised linear model approach is equivalent to logistic regression, in which the log odds (or logit) of a given response (selecting the counterclockwise grip in this case) is predicted as a linear function of the predictor variables. As described above, the predictors consisted of the particular object being grasped and the grip used on the preceding trials. Unlike traditional logistic regression, though, in a mixed-effects model, subjects can be treated as a random effect (Dixon, 2008). In fitting such a model, one specifies both the fixed effects (which are assumed to be fixed in the population) and the random effects (which can vary across subjects). Exploratory analyses were used to identify which factors should be allowed to vary over subjects to provide the best models; generally, the best models allowed the effect of object type and prior response to vary independently over subjects. The model comparisons of theoretical interest then used the same set of random effects but varied in terms of the fixed effects included in the model. The lmer program fits generalised linear mixed-effects model using a penalized iteratively reweighted least squares algorithm to maximize the Laplace approximation to the likelihood function (Pinheiro & Bates, 2000).

Null hypothesis significance testing was not used in our data analyses because of the wide range of well-known problems with this technique (e.g., Cohen, 1994; Dixon & O'Reilly, 1999; Gigerenzer, 2004; Wagenmakers, 2007). Instead, the evidence for different interpretations of the results was assessed by comparing nested models of the fixed effects in terms of an adjusted likelihood ratio (which we will denote as λ_{adj}). The likelihood ratio is the likelihood of the data given the best fit of one model relative to the likelihood of the data given the best fit of another model. Very large (or very small) values of the likelihood ratio indicate that one model provides a substantially better fit to the data than the other, and the likelihood ratio thus provide an intuitive index of the relative quality of the two model fits. Following the suggestion of Glover and Dixon (2004), the likelihood ratio was then adjusted for the differing number of parameters in the models based on Akaike Information Criterion (AIC; Akaike, 1973). Such comparisons are equivalent to selecting models based on AIC values, a common model selection procedure (e.g., Burnham & Anderson, 2002). By way of comparison, in some prototypical hypothesis testing contexts, a statistically significant effect would correspond to an adjusted likelihood ratio of about 3.

Results

The tendency to repeat the grip used on trials *n-1* and *n-2* was measured in logits (corresponding to a shift of the logistic curve depicted in Figure 2) and is shown in Figure 3. As can be seen, there was a substantial repetition effect due to both of the previous trials when the object used previously matched that on the current trial. The evidence for this pattern was assessed by comparing the fit of nested models. The null model against which more substan-

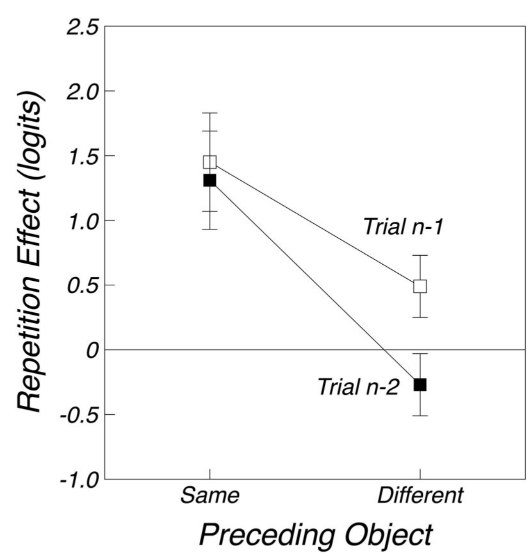

Figure 3. Repetition effect in Experiment 1 as a function of nature of preceding trials. Error bars indicate the standard error of the repetition parameter in the model fit.

tive models were compared included only the factors of object and object version. In other words, in the null model it was assumed that the tendency to use a counterclockwise grip varied only with the stimulus. A model that incorporated an effect of the grip used on the previous trial (trial *n-1*) with matching objects was superior to the null model, $\lambda_{adj} = 30.55$. The model improved further when it is also incorporated the repetition effect for matching objects on trial *n-2*, $\lambda_{adj} = 34.85$. Adding the repetition effects for mismatching objects on trials *n-1* and *n-2* improved the model only slightly, $\lambda_{adj} = 1.84$.

The repetition effect for trial *n-2* is shown in Figure 4 broken down by the nature of the intervening trial. Consistent with the results in the preceding figure, a substantial repetition effect for trial *n-2* was found only when the same object was used on trial *n* and trial *n-2*. However, there was some evidence that the effect was larger when the intervening trial used an object different from that on trial *n* and *n-2*, $\lambda_{adj} = 3.05$. These results are decomposed further as a function of the nature of the response on trial *n-1* in Table 1. There was no evidence that the *n-2* repetition effect varied with the nature of the response on trial *n-1*, and adding that factor along with the interaction with type of object did not improve the model, $\lambda_{adj} = 0.20$.

We were also interested in whether repetition effects could be found for trials more than two trials back. To do so, we selected trials preceded by 10 correct trials and then entered as predictor variables the nature of the response made on each of those preceding 10 trials when the object matched the current object. (In these analyses, we did not attempt to include the nature of the intervening trials as predictors because it would introduce a large number of additional predictors relative to the number of data points and because the effects of the intervening trial in Figure 4 was small.) Figure 5 shows the magnitude of the estimated repetition effect for these preceding trials. Generally, the magnitude of the effect decreased monotonically over trials, but the effect was still evident after more than 5 trials. A model including 5 preceding trials was substantially better than the model including only the preceding 2 trials, $\lambda_{adj} = 181.36$, and a model including all 10 preceding trials was better still, $\lambda_{adj} = 8.20$. However, it is clear from the figure that the magnitude of the effect becomes progressively smaller and was minimal for *n-9* and *n-10*. (For the purposes of illustration, an exponential decay function was fit to the estimated repetition effects in Figure 5.)

Table 1
Repetition Effects For N-2 Trials With Matching Object as a Function of Intervening Trial

Intervening Trial	Repetition Effect (logits)	Standard Error
Matching Object, CW Response	1.28	0.58
Matching Object, CCW Response	0.82	0.51
Mismatching Object, CW Response	1.67	0.77
Mismatching Object, CCW Response	2.20	0.44

Discussion

The results demonstrate that subjects tend to use the same grip that they used previously, in keeping with the results of Rosenbaum and Jorgensen (1992) and Kelso et al. (1994). Based on their results, Rosenbaum and Jorgensen suggested that subjects maintain the last movement plan in short-term memory and that this plan can be reused if it is subsequently needed. Kelso, et al. described a similar result as a hysteresis effect of the movement dynamics. However, the present results indicate that this effect is not limited to the immediately preceding trial but can occur after one or several intervening trials. Moreover, the similarity of the previously grasped object makes a difference: The tendency to use a clockwise grip was larger following a clockwise grip of the same object than after a clockwise grip of the other object. This pattern of results is difficult to explain in terms of immediate persevera-

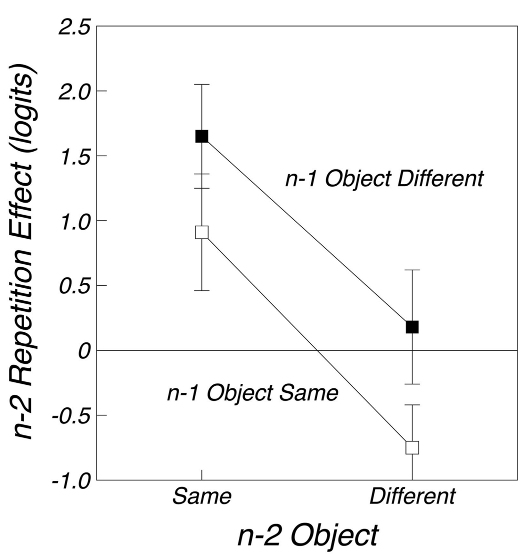

Figure 4. *n-2* repetition effect in Experiment 1 as a function of the nature of intervening (*n-1*) trial. Error bars indicate the standard error of the repetition parameter in the model fit.

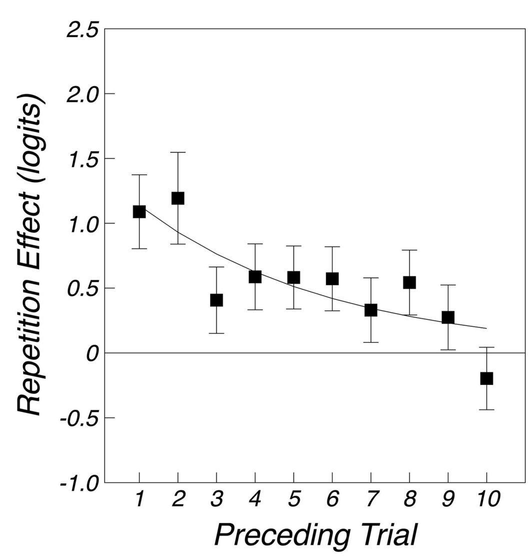

Figure 5. Repetition effect in Experiment 1 as a function of the number of intervening trials. Error bars indicate the standard error of the repetition parameter in the model fit.

tion, regardless of whether it arises in short-term memory or movement dynamics. For example, if there is a general tendency to make a clockwise rotation of the hand after doing so on preceding trials, the nature of the object being grasped would not be expected to have an effect. Similarly, one would expect motor perseveration to be purely a function of the last action performed, and effects of responses made 2 and 5 trials ago would be unexpected.

Jax and Rosenbaum (2007) also found a repetition effect that lasted over several intervening trials. However, the nature of the effect in their paradigm differed critically from the one observed here. Subjects moved a pointer to a target location and on some trials had to avoid a virtual obstacle in their path. When the obstacle was not present, subjects tended to produce a trajectory arc consistent with avoiding the obstacle, and this effect could occur even if that obstacle had not been present for several trials. Importantly, though, the intervening trials without an obstacle did not require a response that was incompatible with avoiding the obstacle. Thus, it is possible to explain the results by assuming that subjects maintained something akin to an "arc" feature in working memory over several trials. In contrast, the present paradigm required one of two incompatible responses on each trial. Thus, any tendency to activate one response feature should have been eliminated when the other response was made. Nevertheless, as shown in Table 1, repetition effects persisted across intervening trials with incompatible responses, mediated by the similarity of the objects. Clearly, a different kind of explanation is required to account for this pattern.

Another important aspect of these results is that there was little tendency to repeat the grip used with the other object. For example, when grasping the green object, the grip used on the previous trial had little effect if the orange object was presented on that trial; there was only an effect of the previous grip when the objects presented on the trials were the same. This was true for both the *n-1* and the *n-2* repetition effect. In other words, subjects tended to repeat the last grip used with the current object, regardless of whether that object was encountered on the immediately preceding trial or the one before that. This result eliminates an explanation for the results based on starting position of the hand. For example, after rotating the hand clockwise to grasp the object with a clockwise grip, subjects may fail to return their hand to a completely neutral starting posture. As a consequence, subjects may be more likely to use a clockwise grip on the following trial because the hand is already rotated clockwise to some extent. However, such an effect of starting position should affect the choice of grip regardless of the nature of the object, unlike the present pattern of results. Thus, the tendency for subjects to repeat actions only if the object is the same as that used on the previous trial is inconsistent with an account based on biased starting positions. Further, the observation of a repetition effect across intervening trials in which a different grip was used (as in Table 1) would be difficult to explain on such an account.

The results are easier to explain in terms of episodic memory. In this view, the current object provides a cue that evokes previous episodes with that object; in turn, this means that features of previous actions will become activated. The action performed on the immediately preceding trial would be available due to recency, but features of other, more distant, actions could also be retrieved if the cue (i.e., the current object) is sufficiently distinctive. This interpretation fits with the decay function observed in Figure 5: Recent actions performed on the last trial or two are readily retrieved, but as the number of intervening trials increases, there would be progressively more retroactive interference, and the effect of the actions performed on those trials would diminish. However, we conjecture that this decay would be minimal if the intervening trials were sufficiently dissimilar.

This analysis is consistent with the results of Flanagan, King, Wolpert, and Johansson (2001). They measured the load force to lift cubes of different sizes but similar weights. Initially, force was correlated with the size of the objects, but this changed rapidly over the course of a few exposures to the objects as subjects learned the actual weights of the objects. Importantly, this learning persisted over 15 min, and there was some evidence that it even lasted 24 hrs. From our perspective, this result implies that people can retain information in memory concerning features of the appropriate action and that this information can be retrieved after an extended period of time. Moreover, just as in the present research, it suggests that the memory is contextually determined and tied to the particular target object that must be lifted. In other words, the features of the action to be performed are cued by the object to be manipulated.

Experiment 2

There are two different ways in which an effect of memory for previous actions might be interpreted. On one hand, memory for previous actions might be part of the normal and largely unconscious process of action selection. In this view, action is generally affected by memory for previous actions, and the experimental task subjects are asked to perform is merely a constrained version of the action selection process that must take place all of the time. An alternative view, though, is that subjects' choice of grip was strategic and that the strategy was determined by the experimental situation. For example, after grasping an object with a clockwise grip, subjects might anticipate a similar object to be presented subsequently, and, as a consequence, they may prepare to use that grip on the following trial. In order to distinguish these two classes of interpretation, we manipulated the likelihood that the objects would be used in a block of trials: In clockwise-bias blocks, the clockwise version of an object was much more likely than the counterclockwise version, and in counterclockwise-bias blocks, the reverse was true. If subjects strategically anticipate grips of a particular form, the bias manipulation may produce a general shift in the tendency to use one grip or the other. For example, if a block of trials generally requires more clockwise grips, subjects may come to expect a clockwise grip and use it even it was not required for a given object version and even if it was not used on the previous trial.

Grip bias was manipulated either globally or in an object-specific manner. In global-bias conditions, the clockwise (or counterclockwise) version of both objects was more common. In contrast, to create an object-specific bias, in a block of trials the counterclockwise version of one object was presented most of the time while the clockwise version of the other object was presented most of the time. Thus, although a clockwise or counterclockwise grip could be anticipated on the basis of the object identity, there was no overall bias for the clockwise or counterclockwise grip across trials. This manipulation allowed us to assess whether strategic effects such as those hypothesised here are global or are specific to particular stimuli.

Method

Subjects. Twelve undergraduates (none of whom had participated in Experiment 1) served as subjects in exchange for course credit. One subject did not use the prescribed grips consistently (with an error rate of 40%) and was not used in the analysis.

Procedure. The procedure on each trial was the same as in Experiment 1. However, the probability of the object version to be presented on a trial varied with condition. In each block there were 120 trials, half of which used the orange object and half of which used the green object. There were four types of blocks, varying in terms of whether there was a clockwise or counterclockwise bias for the orange object and whether there was a clockwise or counterclockwise bias for the green object. To create a block with a clockwise bias, the 60 trials for an object consisted of 30 clockwise versions, 10 counterclockwise versions, and 20 neutral versions; the distribution was reversed to produce a counterclockwise bias. Global bias was manipulated for half of the subjects; in this case, both objects were typically presented in the clockwise version or both typically presented in the counterclockwise version. Object bias was manipulated for the other half of the subjects; here, one object was typically biased to the clockwise grip and the other was typically biased to the counterclockwise grip in each block. (The one subject not used in the analysis was in the global-bias condition.) Each subject received two blocks of trials, including a clockwise- and a counterclockwise-biased block for each object. The order of the two blocks was balanced across subjects.

Analysis. Only trials preceded by a correct trial (i.e., one in which one of the two prescribed grips were used) were included in the analyses. The error rate was 4.4% for the 11 subjects included in the analysis. As in Experiment 1, the results were analysed by fitting nested generalised linear mixed-effects models to data. As before, a binomial link function was used, rendering the approach tantamount to logistic regression. In this case, the predictor variables included the bias condition as well as the particular object being grasped and the response made on the previous trial. The relative appropriateness of these models was evaluated by calculating an adjusted likelihood ratio as in Experiment 1. The effect of bias condition, as well as the effect of repetition, was assumed to vary randomly across subjects.

Results

The logit values (and corresponding proportion of counterclockwise grips) for each object version is shown in Table 2. The pattern of repetition effects was similar to that obtained in Experiment 1, with a substantial effect when the same object was used on successive trials (0.95 logits with a standard error of 0.36) but little effect when different objects were used (0.21 logits with a standard error of 0.26). Figure 6 shows the overall tendency to select a counterclockwise grip as a function of counterclockwise or clockwise bias. As can be seen, bias had little effect on the choice of grip, either when it was manipulated globally or in an object-specific manner.

Although we did not hypothesise such an effect, bias could conceivably modulate the magnitude of the repetition effect. In particular, the effect of the previous trial might be enhanced (or reduced) if the bias in a given block was consistent with the response made on that trial. For example, if most responses in block involved clockwise grips, subjects may be more likely to repeat clockwise grip and less likely to repeat a counterclockwise grip. Alternatively, in a block of predominantly clockwise grips, a counterclockwise grip may be particularly salient, and lead to greater tendency to repeat. In either case, the magnitude of the repetition effect might vary as a function of whether the bias in a block matched the repeated response on that trial or not. We refer to such trials as bias-consistent trials and the latter as bias-inconsistent trials. The breakdown of the repetition effect in these terms is shown in Table 3. Although the repetition effect was numerically smaller on bias-consistent trials, this trend was small relative to the standard error, and there appeared to be little clear change in the magnitude of the repetition effect as a function of consistency in either global-bias or object-specific bias conditions.

Table 2
Affordance (In Logits) of Object Versions in Experiment 2

Object Version	Affordance (logits)	Standard Error	Proportion CCW Grip
Green 1	−1.53	0.63	.179
Green 2	1.61	0.62	.833
Green 3	4.07	0.66	.983
Orange 1	0.12	1.46	.531
Orange 2	0.46	1.46	.613
Orange 3	2.97	1.47	.951

This interpretation is supported by the relative quality of the models. As before, the null model included just the effect of object and object version. A model that included a repetition effect on same-object trials was better than the null model without such an effect, $\lambda_{adj} = 6.89$, and there was no evidence that adding a repetition effect for mismatching objects improved the model, $\lambda_{adj} = 0.50$. Adding an overall effect of bias did not improve the model, for either global bias, $\lambda_{adj} = 1.03$ or object-specific bias, $\lambda_{adj} = 0.53$. Further, adding an interaction between bias and the repetition effect also failed to improve the model, either for object-specific bias, $\lambda_{adj} = 0.69$, or for global bias, $\lambda_{adj} = 0.39$.

Discussion

The results replicated the effect of repetition found in Experiment 1 and demonstrated that this effect cannot be attributed to strategic expectation in a simple way. In particular, the overall likelihood of a particular grip had little effect on choice of grip: Subjects were no more likely to select a clockwise posture (e.g.) when most trials used a clockwise grip than when most used a counterclockwise grip. This pattern was apparent regardless of whether the likelihood of a particular grip was manipulated with respect to a particular object (in the object-specific bias condition) or overall (in the global-bias condition). Our interpretation is the repetition effect is a product of memory for previous actions rather than a function of deliberate choice strategies.

Experiment 3

In this experiment, we investigated whether the effect of repetition should be regarded as a low-level motor phenomenon spe-

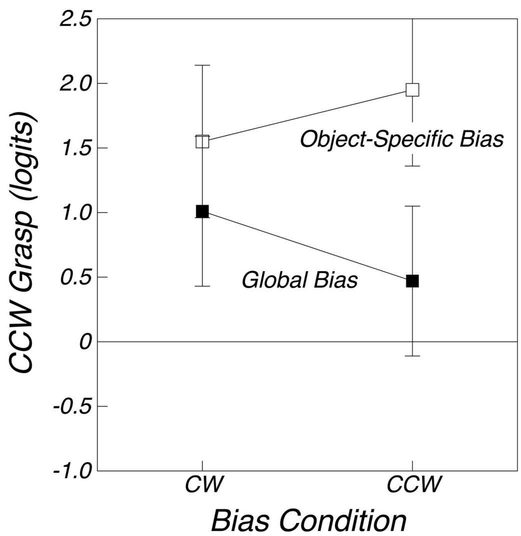

Figure 6. Effect of global and object-specific bias in the trial block on the overall tendency to use a counterclockwise grasp in Experiment 2. Error bars indicate the standard error of the parameter in the model fit.

cific to a given effector or whether it involves more abstract representations. In particular, we evaluated whether the effect of repetition transferred across hands. A plausible argument could be made that the effect should be specific to effector: After all, if one is retrieving information concerning the manner in which an action is carried out, it is natural to assume that a central element of that information is the hand with which the action is performed. Alternatively, one might argue there are many situations in which either hand could be used to accomplish a given goal, and it seems functional to be able to retrieve all of the relevant actions that might be used. For example, one can turn on a light switch equally well with the left or right hand, hold a briefcase equally well with the left and right, and so on. Consequently, if an object affords the use of either the left or right hand, previous actions with either the left or right hand might be equally relevant, and one might observe an effect of previous actions made with both hands. Consistent with that analysis, Rosenbaum (1980) and Dixon and Just (1986), using different forms of precuing techniques, both found evidence that choice of hand could be prepared independently of other features of a movement.

The objects used in Experiments 1 and 2 were not well suited to an investigation of intermanual transfer because it is not clear whether a clockwise grip with the left hand should be regarded as the same as a clockwise grip with the right (i.e., merely translated from left to right) or whether it should be regarded as the same as a counterclockwise grip (i.e., reflected as well as translated). Consequently, we used objects with grasping postures that could be unambiguously classified as same or different regardless of whether they were performed with the left or right hand. Two objects were designed with a knob on the front which could be grasped horizontally, with the thumb and index finger on either side of the knob, or vertically, with the index finger underneath the knob and the thumb on top. As shown in Figure 7, there were four versions of each, varying from a strong bias for a vertical grip to a strong bias for a horizontal grip.

Method

Subjects. Twelve undergraduates (none of whom had participated in the previous experiments) volunteered as subjects in partial fulfillment of a psychology course requirement.

Stimuli. As shown in Figure 7, there were four versions each of two different objects, one painted blue and one painted red. The blue object was 10.7 cm tall, and the red object was 18.0 cm tall. Although the overall appearances of the two objects were distinct, the front knob that was grasped was identical. The four versions of each object ranged from strongly biased to the vertical grip, moderately biased to the vertical grip, moderately biased to the horizontal grip, and strongly biased to the horizontal grip.

Procedure. The procedure used on each trial was comparable to that used in Experiments 1 and 2. Between trials, subjects rested their hands on the first 15 cm of the table top just to either side of their trunk. The object was placed at a distance of 45 cm from the edge of the table, offset from the subject's midline to either the left or right by 15 cm. Subjects were told to grasp the object with their left hand if it was placed on the left and with their right hand if it was placed on their right. Each of the eight object versions was grasped 12 times on the left and 12 on the right, for a total of the 192 trials, in a random order.

Analysis. Only data from correct trials preceded by a correct trial was used in the analysis. The same approach to the data analysis and model comparison was used as in the first two experiments, except that the dependent variable was the log odds of a vertical grip (rather than a counterclockwise grip).

Results

The affordance of the four versions of the two objects is shown in Table 4. The effect of repetition is shown in Figure 8 as a function of whether the same object was grasped on successive trials and whether the same hand was used. As in the previous experiments, there was a substantial repetition effect when the same object was used on successive trials. There was also a tendency to repeat grips used with the other object, although this trend was somewhat smaller. Importantly, there was clear evidence that these effects transferred across hand: Repetition effects were virtually the same regardless of whether the same or different hand was used from one trial to the next.

A comparison of nested models capturing these effects supported this interpretation. In this case, the base model incorporated

Table 3
Repetition Effect (In Logits) in Experiment 2 as a Function of Bias Condition and Preceding Object

	Same Preceding Object		Different Preceding Object	
	Repetition Effect	Standard Error	Repetition Effect	Standard Error
Global Consistent	0.72	0.56	0.13	0.43
Global Inconsistent	1.01	0.57	0.52	0.39
Object-Specific Consistent	0.70	0.56	0.06	0.42
Object-Specific Inconsistent	1.34	0.54	−0.07	0.39

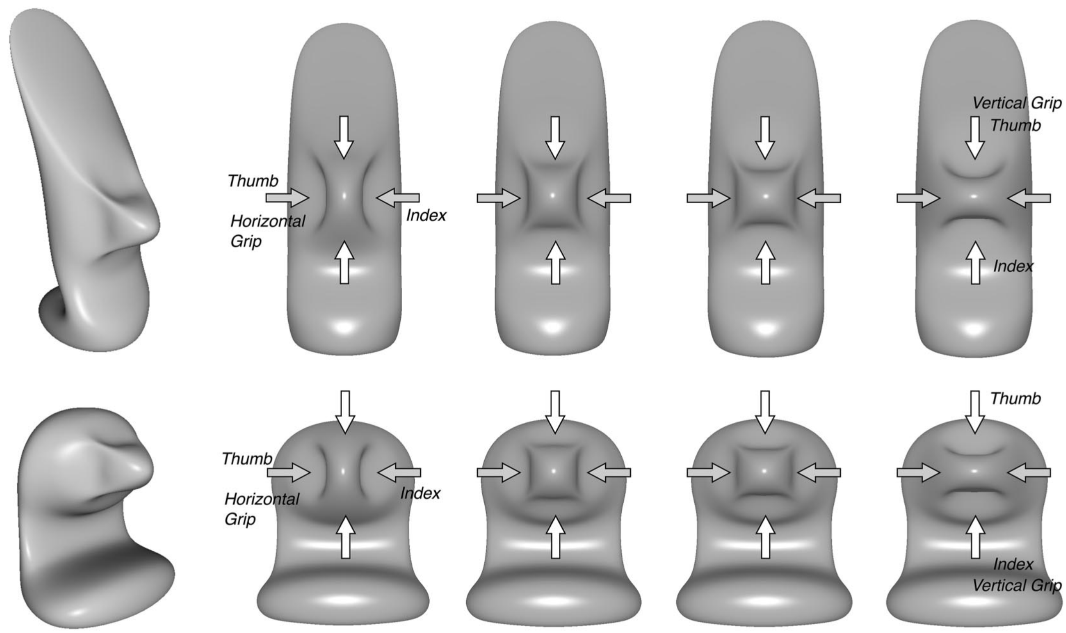

Figure 7. The leftmost drawings in each row provide a perspective depiction of the two objects used in Experiment 3. The object on the top was red and the object on the bottom was blue. To the right of each perspective drawing are depictions, in frontal view, of the four different versions of each object illustrating the manipulation of affordance. The affordance varies from strong horizontal bias at the left to strong vertical bias at the right. The white-filled arrows indicate the grasp points for the vertical grip, while the gray-filled arrows indicate the grasp points for the horizontal grip.

effects of object and object version as well as an overall effect of left and right hand that varied randomly across subjects. Adding a parameter for the effect of repetition of the same object improved the model, $\lambda_{adj} = 12.36$, and adding the effect of the grip of the different object improved the model, $\lambda_{adj} = 11.79$ as well. However, comparing this latter model to one that included the interactions with hand yielded an adjusted likelihood ratio of $\lambda_{adj} = 0.14$ or 7.00 in favour of the simpler model. Thus, the results provide clear evidence that the effect of repetition was the same, regardless of whether the same or different hand was used in grasping the object.

Discussion

The results of this experiment demonstrate unambiguously that the effect of repetition is not effector specific. Thus, the effect cannot be attributed to simple perseveration at the motor level (cf. Kelso et al., 1994). Rather, the results suggest that effect involves the retrieval or activation of relatively abstract action features that can be applied equally well (in this case) to either hand. Jax and Rosenbaum (2007) reached a similar conclusion concerning the repetition effect observed in their experiments. In their task, sub-

Table 4
Affordance (In Logits) of Object Versions in Experiment 3

Object Version	Affordance (logits)	Standard Error	Proportion Vertical Grip
Red 1	−5.00	0.69	.007
Red 2	0.36	0.43	.589
Red 3	2.13	0.45	.894
Red 4	4.42	0.60	.988
Blue 1	−6.63	1.16	.001
Blue 2	−1.91	0.47	.128
Blue 3	0.48	0.45	.618
Blue 4	4.88	0.69	.992

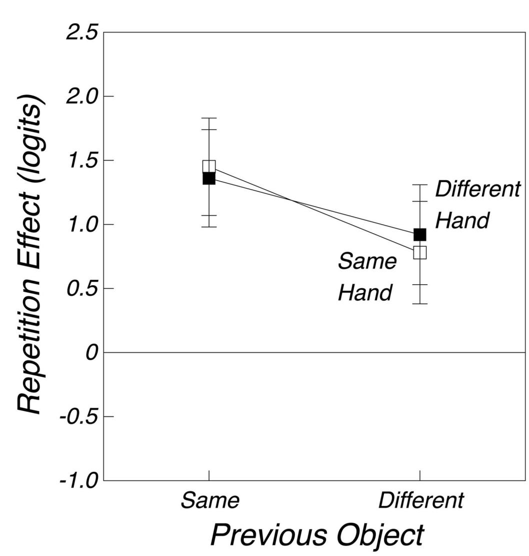

Figure 8. Repetition effect in Experiment 3 as a function of the nature of the preceding trial and same or different object. Error bars indicate the standard error of the repetition parameter in the model fit.

jects moved from a central starting position to one of several peripheral targets, avoiding an obstacle if present. They observed a repetition effect in which the movement trajectory tended to avoid the obstacle location even if it was not present on that trial. Notably, this effect seemed to occur regardless of the target location on that trial. Thus, the repetition effect in their experiments transferred across locations, just as it transferred across hand in the present data. In both cases, the results suggest that the effect must occur at a relatively abstract level at which a given movement feature can apply equally well to a variety of different movements.

There are a number of reasons to believe that selecting an action involves an abstract, movement-feature level of representation that might serve as a substrate for this repetition effect. For example, Dixon and Just (1986), Rosenbaum (1980), and Miller (1982) all found evidence that aspects of a movement, such as choice of hand or extent of a movement, could be prepared independently of other aspects of a movement. This suggests that features that determine those aspects of the movement can be activated and prepared without reference to a detailed motor plan that would determine the movement trajectory. In the present context, we suggest that there might be features indicating the orientation of the wrist or the thumb-finger axis that would dictate the use of a horizontal or vertical grip. Alternatively, the action features may be coded in terms of the distal environment, such as the intended contact points on the object. This would be in keeping with models of action sequencing (e.g., Cooper & Shallice, 2000) in which actions are specified in terms of schemas that produce intended effects rather than motor trajectories. Research on action slips suggests that there must be a level of representation responsible for the transposition or substitution of action features (e.g., Norman, 1981). Thus, there is ample precedent for an abstract, feature-based representation of action that might underlie the present effects.

Unlike Experiments 1 and 2, the repetition effect observed with these stimuli transferred to a large extent across objects. We argued previously that the object provided a memory cue that evoked actions that had been made previously with that object. A failure to find repetition effects across different objects in Experiments 1 and 2 was thus explained by assuming that the two different objects provided distinct memory cues that would serve to retrieve different sets of prior actions. Although the two objects used in Experiment 3 were also superficially dissimilar, it is possible that subjects noticed that the front knob served as a handle that was grasped in the same manner for both. As a consequence, the two objects may have been mentally represented by subjects as two versions of the same object, at least as far as the task of grasping the objects was concerned. According to our analysis of the role of memory in action, repetition effects should transfer across objects if they are represented similarly. It is unclear at this point what would lead subjects to encode superficially distinct objects as the same (as they seemed to do in Experiment 3) or different (as they seemed to do in Experiments 1 and 2). Further discussion of this issue is provided in the General Discussion.

Experiment 4

Although the results of Experiment 3 demonstrated that the repetition effect is not effector specific, the left-hand grips were homologous with the corresponding right-hand grips and intuitively quite similar. As a consequence, it is not clear whether the repetition effect would be sustained if the grasp postures were more distinctive. In Experiment 4, we evaluated whether the repetition effect would transfer across locations (as well as hand) when the locations required distinct trajectories to grasp the objects. In particular, the objects used in Experiment 3 were repositioned so that they could be grasped with the contralateral hand by moving across the midline and approaching the object from a different direction. With these possible object positions, we could test whether the repetition effect transferred across location and orientation of the objects.

Method

Subjects. Twelve undergraduates (none of whom had participated in the previous experiments) volunteered as subjects as partial fulfillment of a psychology course requirement. Data from one subject was not used because of a pattern of grip preference that was distinct from that of the other subjects. For example, among the objects with an intermediate bias, the discrepant subject used the horizontal grip 28% of the time, while others used the horizontal grip 81% of the time. (Including this subject in the analyses did not change the overall pattern of effects.)

Stimuli and procedure. The same procedure was used as in the previous experiment. However, only the red object was used. It was placed either near or far from the subject on either the left or right. Subjects were told to grasp the object with the ipsilateral hand when the object was near, and to reach across the midline to grasp the object with the contralateral hand when it was in the far position. The object was rotated 45° in the far position to make the required grasp more convenient. The near positions were 15 cm from the edge of the table while the far positions were 30 cm from the edge. Otherwise, the experimental setup was the same as that used before.

There were four different versions of the object and four different positions in which it could be placed (near left, far left, near right, and far right), for a total of 16 possible trial types. From trial to trial, the required grip could involve either the same or different hand, and, orthogonal to the hand, could involve either the same or different position. Subjects first completed 16 practice trials in which each trial type was used once and then performed 128 test trials in which each trial type was used eight times.

Analysis. Only data from correct trials preceded by a correct trial was used in the analysis. The overall error rate was less than 1%. The data were analysed in the same manner as Experiment 3.

Results

The affordance of the four object versions is shown in Table 5. As shown in Figure 9, there was an overall repetition effect of 1.05

Table 5
Affordance (In Logits) of Object Versions in Experiment 4

Object Version	Affordance (logits)	Standard Error	Proportion Vertical Grip
Red 1	−3.96	0.30	.019
Red 2	0.81	0.18	.693
Red 3	3.07	0.23	.956
Red 4	4.37	0.34	.987

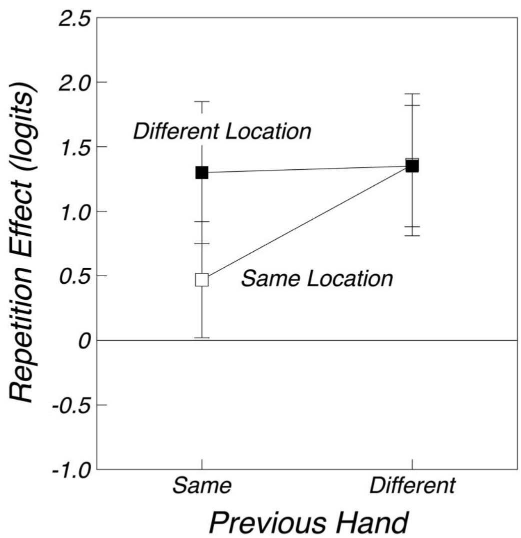

Figure 9. Repetition effect in Experiment 4 as a function of same or different hand and same or different distance. Error bars indicate the standard error of the repetition parameter in the model fit.

logits (with a standard error of 0.27), comparable to previous experiments, but there was no evidence that repetition effect was smaller when changing hands or locations. If anything, the effect was larger when changing hands or locations.

A comparison of nested models confirmed this assessment. The model improved substantially when the effect of repetition was added to the base model that included the effect of object version, hand, and location, $\lambda_{adj} = 45.85$. There was some suggestion that the repetition effect was actually larger when changing hands or locations. Such an effect might be due inhibition or fatigue. However, adding the interaction with same/different hand (λ_{adj} = 0.76), same or different location ($\lambda_{adj} = 0.62$), or both together as well as the interaction ($\lambda_{adj} = 0.26$) did not improve the model. Thus, we can conclude that the effect of repetition transferred across both hand and location.

Discussion

The results demonstrated that the repetition effect occurs at a relatively abstract level. In effect, a choice of horizontal or vertical grip applies equally well regardless of where on the table the object was positioned and which hand was used to grasp it. This was true even though the arm and wrist postures were significantly different for near and far positions. We hypothesise that the repetition effect is based on the retrieval of movement features that are relatively abstract and independent of other aspects of the action. This is similar to the proposal of Rosenbaum (1980). He argued that upcoming movements could be specified in terms of a number of independent features, such as hand, direction, and distance, and that these features could be specified in advance of the action on the basis of a precue. Our proposal is related. However, instead of a precue, we suggest that the specification of such features is influenced by memory for previous actions.

In some respects, the present results, where the repetition effect transferred across hand and location, seem inconsistent with the results of Experiments 1 and 2, where the effect failed to transfer across different objects. Our analysis of these differing results is that the features retrieved from memory depend on how subjects code the stimulus and the current context. If the object and the task are represented as similar to those in a given prior episode, action features from that episode are likely to be retrieved and influence action choice in the current situation. If they are represented as less similar, features of other actions may be more likely to be retrieved. In the present experiment, it seems plausible to suppose that subjects always interpreted the targets as the same object because its shape and overall appearance was the same. As a consequence, action features from the preceding action would be relevant regardless of the object's location. In contrast, our interpretation of the results of Experiments 1 and 2 is that the distinctive overall shape and appearance led subjects to think of the orange and green objects as dissimilar. On this interpretation, the orange and green objects provided different retrieval cues and, as a consequence, relatively little transfer resulted, despite the fact the grasping actions themselves had some similarity for the two objects.

General Discussion

The results of these experiments demonstrate the importance of memory for previous episodes in the selection of action. In particular, several aspects of the results implicate memory retrieval as a critical mechanism. First, the repetition effect is modulated by similarity: The extent to which subjects repeat an action made on previous trials depends on the similarity of situation. This is illustrated by the results of Experiments 1 and 2, in which the tendency to use the clockwise or counterclockwise grip varied with the nature of the object, even when the orientation of the hand for grasping the object was similar. Second, the effect of repetition can be long lasting: In Experiment 1, the effect was found out to 5 or more trials. Finally, the repetition effect decays over time, presumably as a function of the interference produced by the intervening trials. Indeed, similar decay functions can be found in studies of verbal memory (cf. Waugh & Norman, 1965).

The results rule out several alternative interpretations. First, they cannot be explained in terms of immediate perseveration in which subjects tend to repeat the most recently generated action. For example, in Experiments 1 and 2, the repetition effect tended to be specific to the particular object being grasped, suggesting that it is not merely a propensity to reproduce the previous action. Further, in Experiment 4, the effect was observed when a categorically similar action was performed using a different posture with a different effector. Thus, the same movement feature was used in service of distinct forms of action. Second, the results are also inconsistent with a model in which an action feature is maintained in short-term memory and then applied to the current task if applicable. In Experiment 1, the repetition effect was observed across intervening trials that required distinct actions (which would presumably displace any information being held in short-term memory). And third, the effect cannot easily be explained in terms of strategic expectation. In Experiment 2, varying the likelihood with which a particular grip was used in a block of trials had little effect on choice of grip.

One can distinguish at least two levels of representation in performing the present grasping task: a perceptual representation of the object and its context and an action-plan representation of how the object should be grasped. The role of each of these representations in the present repetition effect is discussed in turn. We then elaborate on how episodic retrieval might be involved.

Perceptual Representation of the Object

Inferences concerning the nature of the perceptual representation can be made by considering the parallel between the current task and absolute identification and categorisation. In the categorisation task, subjects are presented with one of a range of stimuli that vary on one (or possibly several) dimensions. The stimuli are grouped into several categories and subjects are asked to identify to which category the presented stimulus belongs (e.g., Stewart, Brown, & Chater, 2002). The absolute identification (or magnitude estimation) task is similar except that each category consists of only a single stimulus. In these tasks, the stimulus variation is sufficiently small that it may be difficult for subjects to discriminate to which category a given stimulus belongs, and interesting aspects of the results pertain to the patterns of errors. At an abstract level, the task we have used in the present research is comparable to the perceptual categorisation task. In this case, though, the categories consist of stimuli that should be grasped in each of two possible ways. The two possible responses subjects produced would then essentially be decisions about the category membership of the presented stimuli. Thus, in a sense, subjects were being asked to classify stimuli into clockwise versus counterclockwise grasping categories (in Experiments 1 and 2) and into vertical versus horizontal grasping categories (in Experiments 3 and 4).

Sequential effects in categorisation and absolute identification have been termed assimilation, in which there is a tendency to repeat the categorisation from the previous trial, and contrast, in which there is a tendency to use a different category from the previous trial. In absolute identification, the typical finding is that there is an assimilation effect; that is, subjects tend to repeat the response made on the previous trial (e.g., Lockhead & King, 1983). This result is consistent with the present data in which subjects tended to repeat the grip used on the previous trial. However, in absolute identification, *n-2* sequential effects often show contrast effects: Subjects tend to make a response that is different than that made two trials ago. Under many circumstances, there is a negative correlation between the magnitude estimated on one trial and the magnitude of the stimulus on the previous trial (e.g., Jesteadt, Luce, & Green, 1977), suggesting that assimilation is a response selection process rather than a perceptual one. Moreover, in a model of absolute identification, Brown, Marley, Donkin, and Heathcote (2008) ascribed the *n-1* assimilation effect to the process of selecting response and suggested that the perceptual representations show contrastive effects of the preceding stimulus. Thus, there is some reason to suspect that changes in perceptual representations do not underlie the repetition effect found here.

Using a production task, Zotov, Jones, and Mewhort (2011) found evidence that sequential effects were due to shifts in the representation of the categories, and that these shifts were modulated by whether successive stimuli were in the same or different category. While it makes some sense to view the present task as a form of categorisation task (as described above), it is difficult to know how to apply the Zotov et al. analysis to the present results because the categories were not explicitly defined. However, in terms of the analogy between the present task and the categorisation task, the categories correspond to the possible actions that might be used to carry out the task. Thus, the mechanism that Zotov et al. propose would imply that there should be a shift in the boundary between the two responses, rather than a change in the perceptual representation per se.

Both assimilation and contrast effects were obtained by Dixon and Glover (2004) in task that entailed grasping disks of various sizes. Early in the reach trajectory, grip aperture was larger following a grasp of a smaller disk, which can be characterised as a contrast effect. However, later in the reach trajectory, as the hand closed around target, the effect reversed and grip aperture was larger following a grasp of a larger disk; in other words, an assimilation effect was obtained. Dixon and Glover ascribed these two effects to two concurrent mechanisms: a perceptual mechanism that was affected by the sequential contrast between the current stimulus and the previous one, and a smaller and slower response selection effect due to a tendency to repeat the form of the previous response. Thus, their conclusion was that the perceptual representation showed a contrast effect and did not underlie a tendency to repeat the form of the previous response.

In sum, although both assimilation and contrast effects have been observed in tasks that index the nature of the perceptual representation, previous modelling and theoretical analyses have often concluded that the perceptual representation is susceptible to contrast effects and that assimilation effects occur in the selection of a response or identification of a response category. Thus, it seems unlikely that assimilation effects involving the perceptual representation could underlie the present repetition effects.

Representation of Action Plans

We assume that the control of action depends on a hierarchically organized representation of action features (e.g., Dell, Burger, & Svec, 1997; Schmidt, 1975). At the upper level of the hierarchy, the features are global and abstract (such as which hand to use or in which direction to move), while precise details of a motion would be specified at the lower levels. Generally, the features in this hierarchy must be activated based on the current situation and the actor's goals; this allows one to respond appropriately to the environment. The implication is that, in the current paradigm, the choice of action must depend to a large extent on the object that is presented. In particular, in order to grasp an object appropriately, the selection of the action features must depend on the nature of the object. However, of necessity, this dependence must be mediated by the perceptual representation of the object as well as memory. For example, previous episodes with a object can determine the choice of grasping posture: Johansson and Westling (1988) demonstrated that the choice of force for grasping an object is tuned to its weight, and when confronted with objects of varying density, this information must be learned from experience and stored in memory. Further, the functional use of object features (such as handles or grips) must be acquired with experience. Our analysis of the present repetition effect follows from this involvement of memory. In particular, if the current object serves to activate action features in memory, then the previous trial should provide similar episodic priming of those features. Thus, a feature may be activated on the current trial because it was used on previous, similar trials.

An analysis of action plans in terms of hierarchical levels provide a basis for distinguishing this role episodic memory that operates over several trials and visual memory of the object that might be lost in a few seconds. A variety of research has shown that the details of a movement trajectory change when performed open-loop (i.e., without visual feedback) compared to closed-loop (e.g., Jakobson & Goodale, 1991). Thus, one may conclude that visual information, when available, is used to determine details of the movement trajectory. We assume that such details correspond to low-level features of an action plan. This visual information appears to be lost over several seconds following the loss of vision on a trial. For example, Hesse and Franz (2009) found that maximum grip aperture during a grasping motion systematically increased with the delay between the loss of visual information and the execution of the movement. Their results suggest that precise information about object size was gradually lost over the course of 6 s. In contrast, the memory involved in the repetition effect found in the present experiments must last much longer. Our interpretation is that the present repetition effects are based on an abstract representation of the action in terms of the distal environment, while the precise execution of that action requires a mapping of those distal coordinates into egocentric space at a lower level of the action hierarchy.

Our account of repetition effects in terms of the action features evoked by the current context provides an account of a superficially inconsistent pattern of results concerning repetition priming of actions. Cant, Westwood, Valyear, and Goodale (2004) asked subjects to grasp a bar on the table top when it was either 45° or −45° with respect to the sagittal plane. They found that they nature of the previous grasp had little effect on movement initiation time; in other words, there was no repetition effect on initiation time (but, see Craighero, Fadiga, Rizzolatti, & Ulmita, 1998; Craighero, Fadiga, Umilta, & Rizzolatti, 1996). Similarly, Garofeanu, Króliczak, Goodale, and Humphrey (2004) failed to find repetition priming effects for grasping of common objects, although they did find such effects on naming. On the face of it, this failure to find repetition effects on movement initiation time seems inconsistent with the present finding of repetition effects on action choice. However, a deeper analysis based on how action plans are activated provides a coherent explanation. As indicated previously, an activation account entails that the principle determinant of a choice of action must be the stimulus and its context. Thus, if the object only admits of one possible grasping posture, the priming generated by previous episodes would have to be minimal because there is no ambiguity concerning the appropriate features to activate. In the Cant et al. (2005) experiments, there were only two possible bar orientations, and only one plausible grip for each of those. Consequently, there is no reason to anticipate any effect of previous episodes.

According to this analysis, priming from the previous trial should only be found when there are intermediate stimuli that admit of more than one possible grasping posture. Dixon and Glover (2004) reported this result from a task that was superficially very similar to the Cant et al. (2005) paradigm. Glover and Dixon (2001) placed a bar on a table top at a range of orientations and asked subjects to grasp it with either a clockwise or a counterclockwise grip. In this situation, most of the bar orientation would allow either possible grip. Dixon and Glover analysed those data for repetition effects and found that, just as in the present experiments, subjects tended to repeat the grip that they had used on the previous trial. It is plausible to suppose that this effect would also apply to movement initiation time, so that repeated movements would begin more quickly than nonrepeated movements.

The Role of Episodic Retrieval

We propose that episodic memory provides a link between the perceptual representation and the action plan representation. In particular, the essence of our proposal is that the perceptual representation of an object presented on a given trial elicits action features from previous response episodes. These features then contribute to the activation of action features on the current trial. This account is related to the body of literature suggesting that the visual perception of objects can prime compatible actions. For example, Tucker and Ellis (1998) found that left- and right-hand responses were faster when making a decision about an object that could be grasped with the left and right hands, respectively. Similarly, Tipper, Howard, and Jackson (1997) found that potential actions to nontargets in a visual array interfered with actions to targets, suggesting that actions to both targets and nontargets were evoked by the stimulus array. Following on the present results, we conjecture that the actions that are associated with an object are retrieved from episodic memory. Thus, for example, a picture of a knife with the handle to the right is a cue for the retrieval of previous episodes in which a knife is grasped with the right hand. This "right-hand" feature then primes a right-handed response. According to this analysis, action priming effects are mediated by episodic memory in the same way as the present repetition effects. Consistent with the present analysis of the role of stimulus encoding, Tipper, Paul, and Hayes (2006) demonstrated that such effects are mediated by attention to features of the object that determine the action affordances. For example, action-priming effects are found when subjects judge object shape but not colour.

The view that features of actions are retrieved from memory implies that choice of action should be susceptible to other forms of priming, just as found with memory retrieval generally. Indeed, a number of findings can be readily interpreted in this light. For example, Glover, Rosenbaum, Graham, and Dixon (2004) had subjects read nouns corresponding to objects with a characteristic size (e.g., "apple," "grape") and subsequently measured grip aperture when grasping a wooden block. Consistent with the view that the prime word activated features of related actions in memory, grip aperture was larger following words such as "apple" than they were following words such as "grape." Similarly, Bub, Masson, and Bukach (2003) found an object-colour congruence effect when subjects used gestures to make learned responses to object colour. Responses were faster when the gesture associated with the colour and the gesture appropriate for the object were consistent. This suggests that objects primed actions relevant for their use. More speculatively, we suggest that the priming of action features might be involved in the results of Bargh, Chen, and Burrows (1996). They found that priming behaviour stereotypes implicitly affected subsequent action. For example, when subjects were primed with an old-person stereotype, they walked more slowly after leaving the experimental session. In all of these situations, we assume that people retrieve features of actions from memory and that that retrieval is susceptible to priming by aspects of the current context.

However, the effectiveness of the object as a retrieval cue depends on how the object is encoded; thus, the action features that are retrieved depend on what is salient in the current situation. For example, we surmise that in Experiments 1 and 2, the distinctive shape and colour of the orange and green object was salient to subjects, and, as a consequence, the two objects were coded as different. Thus, the orange object would provide a cue to retrieve prior grasps of only the orange object, and the green object would provide a cue to retrieve prior grasps of only the green object. Other variations in the stimulus, such as the location of objects in Experiments 3 and 4, presumably were not the basis of distinctive memory cues. We cannot say for certain what features of the stimulus will be salient in selecting an appropriate action. Indeed, it seems possible that some aspects of the stimulus may be salient in some contexts even if they have no bearing on the nature of the appropriate grip. In other words, features of the environment (such as the colour of the object to be grasped) may be salient as a memory retrieval cue even if they are technically irrelevant to grip affordance.

Although we are not in a position to predict which features of the environment would be a salient part of a memory cue in any given situation, we assume that the history of prior experience in action selection is important in determining how environmental features are used. For example, an actor may have a history of experiences in which the handle on a coffee mug typically provides a useful grasp point. As a consequence, the handle on a tall, thin coffee mug is likely to be salient as a grasp point even when most comfortable choice might be a power grip around the middle of the mug. Our argument is that the handle is salient because it has commonly been useful in the past, even if it is not as relevant in the current context. Similarly, a hammer may be carried by grasping it near its end even though a grip near the centre of gravity would require less effort. Presumably, the endpoint grip is salient because it is used, on other occasions, in wielding the hammer as a tool. In general, we hypothesise that the salience of environmental features and the manner in which a stimulus is encoded could be manipulated with instruction or training.

Relation to Previous Views of Action and Memory

The present proposal that selection of an action depends on the history of previous actions is related to the posture-based model of movement planning (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). In that model, subjects select particular endpoint postures from memory and then calculate the movement trajectory needed to arrive at that posture. Under some circumstances, subjects may also include a "via" posture that must be approached in the course of moving to the target. Selecting a target posture from memory is comparable to the current suggestion that features of an upcoming movement are retrieved using the current context as a memory cue. However, as the posture-based model stands, the stored postures are represented in terms of the joint angles that correspond to a given posture. Consequently, the representation of the movements of different limbs or the different approaches to an object would have little in common, and the model would not predict the transfer effects found in Experiments 3 and 4. However, posture-based movement planning could be regarded as a mechanism for computing the details of movement trajectories after a final posture has been selected based on memory retrieval operations such as those hypothesised here.

In some ways, the present results are comparable to the movement precuing results of Rosenbaum (1980; see also Dixon & Just, 1986). In those results, features of an upcoming movement were specified by a precue. For example, in Dixon and Just, a cue such as "–X O–" meant that index fingers would be used to respond to the stimuli "X" and "O," while a cue such "–X – O–" meant that the middle fingers would be used. Interpretation of the precue required retrieving the movement feature indicated by the symbolic cue. It is possible that this retrieval is comparable to the retrieval of action features hypothesised in the present paradigm. In the present results, though, the object itself provided the memory cue, and we assume that the features of the movement were retrieved from memory for previous encounters with that object. What is common to the interpretation of both paradigms is that the features of the upcoming response are retrieved from memory based on the current context.

There are also a number of other important antecedents to our view of the role of memory in action. For example, Körding and Wolpert (2004) provided evidence that the brain represents the distribution of prior sensorimotor information concerning a motor task and uses Bayesian estimation to control performance on the current trial. Indeed, the phenomena of motor skill learning in general implies some form of memory for prior actions (cf. Mengelkoch, Adams, & Gainer, 1971). The assumption that performance is based on memory for previous responses is comparable to the basic assumption of Logan's (1988) instance theory of attention, except that here we were concerned about physical actions rather than abstract characterization of response categories. More generally, the approach is related to episodic accounts of priming phenomena (e.g., Neill, Valdes, Terr, & Gorfein, 1992), task performance (Waszak, Hömmel, & Allport, 2003), and repetition (Huettel & Lockhead, 1999). Thus, our proposal that action features are retrieved from memory is consistent with a broad range of phenomena and findings.

Conclusion

The evidence presented in this article supports the view that actions depend on episodic memory. The core idea is that action features are retrieved from memory based on the current stimulus and context. Thus, what action is performed can be influenced by memory retrieval processes. Critically, what this means is that everything we know about episodic memory also applies to action selection. The approach makes two general predictions: Action choice depends on previous relevant actions, and relevant action will be contextually determined. Thus, one will tend to repeat actions made in similar circumstances. Both of these predictions were confirmed by the present results.

Résumé

La tâche dans les présentes expériences était d'atteindre et de saisir un objet nouveau offrant deux prises possibles. Différentes versions de l'objet ont été crées, influençant le choix des participants quant â l'utilisation de l'une ou l'autre des prises. La variable dépendante était l'effet de répétition, la tendance â réutiliser la même prise qu'â l'essai précédent. Dans l'Expérience 1, deux objets qualitativement différents ont été utilisés et il fut observé que l'effet de répétition était spécifique â l'objet saisi : la tendance â saisir le même objet qu'â l'essai précédent était beaucoup moins grande si l'objet â saisir était différent. De plus, l'effet était préservé malgré des essais intercalés et était même présent avec plus de cinq essais intercalés. Dans l'Expérience 2, le contexte global était manipulé, de sorte qu'une prise était beaucoup plus probable que l'autre dans certains blocs. Cependant, cette manipulation a eu peu d'effet sur le choix de la prise et n'a pas interagi avec l'effet de répétition. Dans l'Expérience 3, la main utilisée pour saisir l'objet a été manipulée, ce qui a peu influencé l'effet de répétition. Ainsi, une prise était plus susceptible d'être utilisée si elle l'avait été dans l'essai précédent, peu importe si la prise précédente avait été effectuée avec la main droite ou gauche. Dans l'Expérience 4, un résultat semblable a été observé avec la manipulation de la localisation et de l'orientation de l'objet. Notre interprétation de ces résultats est que les participants se préparent â l'action en récupérant des caractéristiques de l'action en mémoire et que l'objet â saisir fournit un indice critique pour cette récupération en mémoire. Selon cette vision, l'effet de répétition est essentiellement un effet de récence en mémoire.

Mots-clés : action, effet de répétition, contrôle moteur, mémoire de l'action.

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