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ACTION AND MEMORY

Peter Dixon and Scott Glover

I. Introduction

In this chapter, we will advance a single principle as an explanation of a variety of effects in the control of action. Simply stated, that principle is that action is memory. More specifically, the selection and control of an action depends on what actions have been performed in similar situations in the past. In many ways, this is not a new idea, and the relationship between memory and action has a long history in motor control (cf. Kerr, 1983). The advance in the present work lies in three elaborations on this essential idea. First, we assume that a very large number of previous actions are effectively maintained in memory and that the use of that memory in the current context follows optimal (i.e., Bayesian) mechanics. Second, we extend the idea that memory determines action to the kinematics of actions rather than simply movement preparation or programming. Thus, memory determines movement dynamics as well as movement selection. Third, we apply this framework to a range of phenomena that are not typically conceived of in this way, including effects of repetition, perceptual and semantic context, and adaptation.

The chapter is organized as follows. First, in Section II, we present the core elements of our approach and summarize the critical variables that determine the interplay between action and memory. Second, in Section III, we review a variety of phenomena that bear on this analysis. These include repetition effects on posture choice and response time, effects of context-induced perceptual illusions on posture choice and movement

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trajectory, and effects of semantic context. In each case, we present some illustrative simulations to indicate how the model could be elaborated in order to apply to those results. Third, in Section IV, we discuss several other effects that would seem to provide compelling evidence for something like the hypothesized role of memory in action. These include effects of the predictiveness and reliability of contextual information, adaptation effects, and memory-contrast effects. Finally, in Section V, we discuss the common elements of and differences between our approach and a range of related theoretical ideas.

II. Basic Approach

The core assumption of this approach is that memory includes a vast repository of information about previous actions. In general terms, this assumption is consistent with instance-based models of memory such as those proposed by Hintzman (1976), Logan (1988), and Jacoby and Brooks (1984), among others. For the present purposes, it is not necessary to make any detailed assumptions about the format or content of those memories; we merely assume that portions of that information can be made available when it is relevant.

We assume that movements are specified by movement parameters and that these can be modeled as continuous real numbers. In any real movement, there are a large number of such parameters involved, and there are any number of complex dependencies among the parameter values. Further, we assume that movement parameters often have hierarchical relationships. For example, one parameter in a reaching movement may indicate whether a movement is to the left or right, a subordinate parameter may indicate whether the movement is near or far, and an even more detailed parameter may indicate whether the wrist is extended or flexed (cf. Rosenbaum, Kenny, & Derr, 1983). Alternatively, movement parameters may be conceived of as hierarchical constraints on movement dynamics (e.g., Saltzman & Kelso, 1983). Although we make no commitment to the content of such movement parameters at this point, we believe it is reasonable to assume that high-level parameters would specify a movement in relatively abstract terms, such as the egocentric location or direction of a goal or target, while lower-level parameters would be relevant to details of movement mechanics, such as the contraction of particular muscles or muscle groups. For the demonstrations in the present paper, we consider situations in which a single parameter can be used to model interesting aspects of behavior.

Given this background, the basis of our model is very simply that the task of movement selection amounts to estimating movement parameters based on previous actions and the current context. Formally, this is a straightforward problem in Bayesian estimation. The distribution of previous values of the movement parameter constitute the prior distribution, $f(m)$. For simplicity, we assume that the distribution is normal with mean μ_m. The current context, c, determines some subset of previous actions that are relevant to the current situation, and typically the posterior distribution, $f(m|c)$, is also a normal distribution that depends on the reliability of the contextual information and the variance of the prior. In particular, the mean of the posterior is a weighted sum of the expected value of the movement parameter based on the prior (i.e., μ_m) and the value of the movement parameter in similar contexts (m_c):

$$\mu_{m|c} = (1 - \rho_c)\mu_m + \rho_c m_c \tag{1}$$

where ρ_c is a correlation coefficient that indicates how diagnostic the context is of the appropriate movement parameter. This formulation is equivalent to predicting the movement parameter from memory using least-squares regression.

A central element of this framework concerns how actions are controlled. We assume that the current context c includes a mental representation of an actor's goals and intentional strategies, as well as a cognitive interpretation of the stimulus environment. Thus, the movement parameters that are retrieved from memory should only be those that are appropriate to those goals and interpretations, rather than simply responding to the immediate stimulus in a mechanical fashion. It is clear that such a mechanism suffices to control action in a general way. For example, eating actions will be retrieved for the food in front of you only if you are hungry. However, we envision a detailed hierarchy of such goals that are capable of controlling actions with much more precision. In particular, we assume that in general there will be a complex interplay between memory for previous actions, one's current goals and intentions, and the cognitive interpretation of the situation. In effect, one's intentions and interpretations determine how memory is used in the service of action (cf. Allport, 1980; Norman, 1981; Norman & Shallice, 1986; Schmidt, 1975). However, in the present development, we are primarily concerned with experimental tasks in which the subject's goals can be assumed to be fixed and the variation in movements can be analyzed in terms of the visual and experimental context.

III. Applications

The key to generating interesting results using this framework lies in analyzing the nature of the current context and what it indicates about the appropriate movement parameters. In this section, we consider several classes of effects and illustrate how those effects can be explained by a suitable analysis of the current context and its relationship to action memory. First, we consider repetition effects, both in posture choice and in response time measures. Our analysis is that these effects can be explained by simply assuming that the context includes the history of immediately preceding actions and that such history is generally predictive of future actions. Second, we consider dynamic effects in which a movement parameter varies over the course of an action. Our interpretation of such results is that the current context includes information derived from the current ongoing action as well as static information available prior to movement onset. Third, we consider semantic effects on action. In this case, the explanation lies in the assumption that context includes the current contents of consciousness and that movement selection will be affected by the range of concepts being attended and rehearsed. Finally, we turn to situations in which the informativeness of the preceding history of movements is deliberately manipulated. These results similarly follow from the view that the selection of movement parameters depends on memory for action and context.

A. Repetition Effects in Posture Choice

1. *Evidence*

The simplest evidence that action depends on memory consists of intertrial dependencies. There are many possible ways to demonstrate such dependencies. For example, Glover and Dixon (2001a) had righthanded subjects reach out and pick up a small bar on a tabletop; the orientation of the bar varied from 5–35° clockwise from the sagittal plane. Subjects grasped the bar with the thumb and forefinger of their right hand in either a wrist-abducted (thumb-right) posture or a wrist-adducted (thumb-left) posture. Not surprisingly, we found that the hand posture used to grasp the bar varied systematically with the orientation of the bar. For example, when the bar was oriented relatively far in the clockwise direction, subjects were much more likely to grasp the bar with the wrist abducted (that is, with the thumb on the right). However, in a post hoc analysis of these data, there was also a repetition effect: Subjects tended to use the same posture as they had on the previous trial, independent of the bar orientation. These data are shown in Fig. 1. As the orientation of the bar increases in a clockwise direction from sagittal, the probability of selecting the wrist-abducted posture increases. However, if one has just completed a wrist-abducted grasp on the previous trial, the entire function is shifted so that that posture is more likely to be repeated. We interpret this to mean that the recent use of a posture primes that action and increases the likelihood of that action on the subsequent trial.

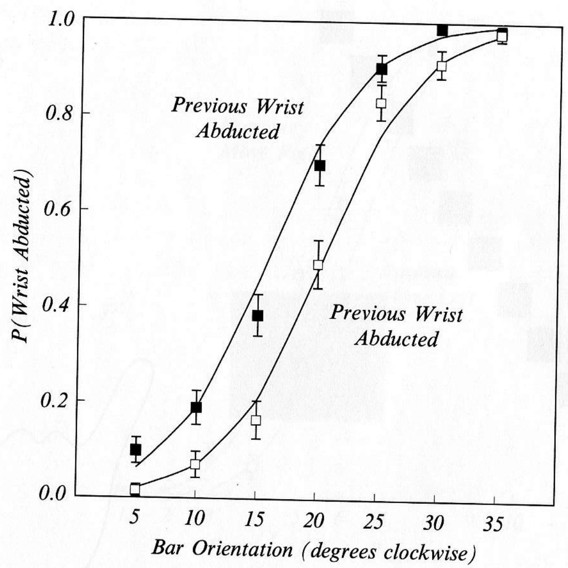

Fig. 1. Repetition effects on posture choice in the data of Glover and Dixon (2001a). Smooth curves depict the model simulation described in the text.

Comparable repetition effects were observed by Dixon (2002). In this case, subjects were asked to reach and touch a target location while avoiding an obstacle (a vertical rod) that interposed the initial position of the hand and the target location. The arrangements of the obstacle and the possible target locations are shown in Fig. 2. When the target was to the far right of the obstacle, subjects almost always moved around the right side of the obstacle; when the target was to the far left of the obstacle, subjects almost always moved around the left side. However, central target positions were more ambiguous, and subjects moved to either the left or right on different trials. The choice of posture for these central positions, though, depended on what action was performed on the previous trial, as shown in Fig. 3: Following a move to the right, for example, subjects were more likely to move to the right, even when the target position was relatively far to the left. Crucially, this result only occurred when the target on the previous trial was similar to the target on the present trial. As shown in Fig. 4, the choice of posture for central target trials was affected by the previous action only when the previous action was also to a central target.

Even more compelling evidence for the mediating role of similarity was obtained by Dixon (2003). The experimental task was the same as in Dixon (2002): Subjects reached around an obstacle to touch a target location. In

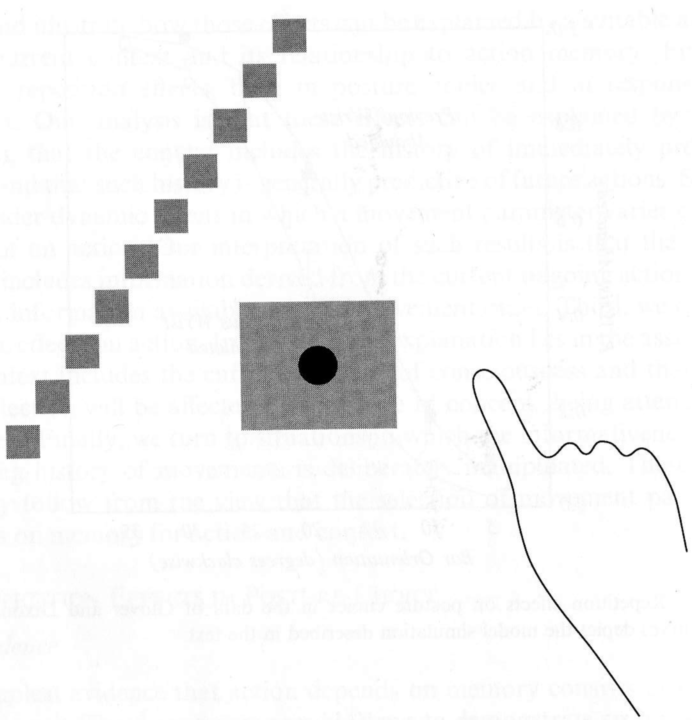

Fig. 2. Stimulus arrangement in Dixon (2002). Subjects reach around a vertical pole to touch a gray square target; the figure depicts the 10 possible locations for the target.

this case, though, two different types of backgrounds and targets were used: The target was either a gray square against a dark background or a blue cross against a red striped background. Even though this stimulus manipulation was completely independent of the required action, it still had an effect on posture choice: Movements to the central targets were likely to resemble the action on the preceding trial when either that action also involved a central target or the target and background were of the same form.

Comparable stereotypy in movements has also been observed in other contexts. For example, Diedrich, Thelen, Smith, and Corbetta (2000) found that infants who were likely to persevere in a reaching task also showed more consistency in movement trajectory across successive trials. Similarly, Jax and Rosenbaum (2003) found that movements designed to avoid an obstacle tended to be repeated on subsequent trials even when the obstacle was no longer present. These results seem to clearly implicate the role of memory for previous actions in the selection and control of current actions.

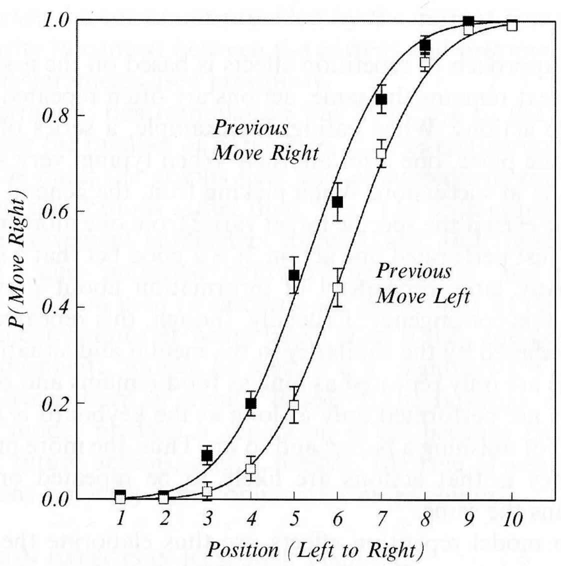

Fig. 3. Repetition effects on posture choice in Dixon (2002). Smooth curves depict the model simulation described in the text.

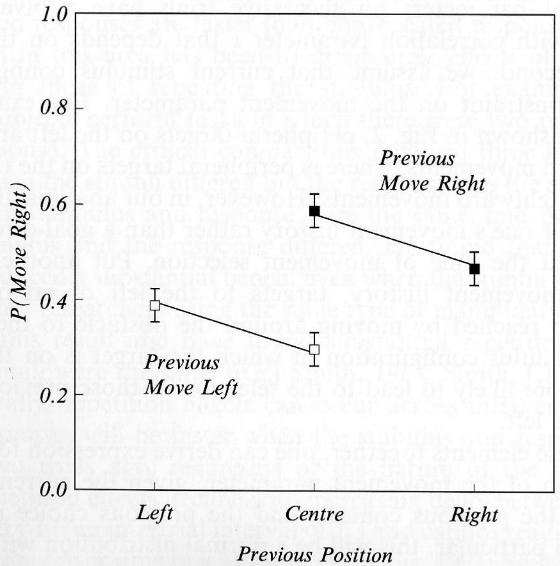

Fig. 4. Repetition effects for central targets in Dixon (2002) as a function of target position on the previous trial. Smooth curves depict the model simulation described in the text.

2. Model

The memory approach to repetition effects is based on the assumption that when the context remains the same, actions are often repeated. Life is filled with repetitive actions: When eating, for example, a series of very similar actions will take place, one after another. When typing, very similar movements are made in succession. When picking fruit, the general form of each reach is similar even if the specific target varies from one moment to the next. Thus, having just performed one action, it is a good bet that a similar action will follow. Any large repository of information about previous actions would reflect this contingency. Crucially, though, this repeated-action contingency is mediated by the similarity in the mental and situational context. Eating actions are only repeated as long as food remains and one is hungry; typing actions are performed only as long as the keyboard is available and one has a goal of finishing a paper; and so on. Thus, the more precise form of the contingency is that actions are likely to be repeated only when the context remains the same.

In order to model repetition effects, we thus elaborate the context c in Eq. (1) in several ways. First, we assume that there is a correlation in memory between the movement parameter used on one trial with the movement parameter used on the next. However, this correlation depends on the similarity in the context between the two trials. In particular, we assume that the movement parameters on successive trials have a bivariate normal distribution with correlation parameter s that depends on the contextual similarity. Second, we assume that current stimulus configuration also provides a constraint on the movement parameter. For example, in the configuration shown in Fig. 2, peripheral targets on the left are more likely to cue leftward movements, whereas peripheral targets on the right are more likely to cue rightward movements. However, in our analysis, this constraint is a product of one's movement history rather than a goal-directed computation done at the time of movement selection. Put another way, in an individual's movement history, targets to the left of an obstacle have typically been reached by moving around the obstacle to the left. Consequently, a stimulus configuration in which the target is on the left of the obstacle is more likely to lead to the selection of those previous actions of moving to the left.

Putting these elements together, one can derive expression for the posterior distribution of the movement parameter, given the current context, its similarity to the previous context, and the previous choice of movement parameter. In particular, this will be a normal distribution with mean

$$\mu_{m|p,c,s} = (1 - s - \rho_c)\mu_m + sp + \rho_c m_c \qquad (2)$$

where ρ_c indexes the constraint provided by the current context, s depends on the similarity in context between the current and previous trial, and p is the movement parameter used previously.

As an illustration, this formulation was fit by eye to the data in Fig. 1 and 3. (Because the number of parameters is large relative to the degrees of freedom in the data, the graphs here and in subsequent simulations must be regarded as illustrations rather than "fits.") In both graphs, we assumed that negative movement parameters corresponded to leftward movements, that positive values indicated rightward movements, and that $\mu_m = 0$. Equation (2) was then used to calculate the probability of the best estimate of the movement parameter being larger than 0 (i.e., the probability of a rightward movement). As can be seen, it is straightforward to recover the same qualitative pattern of results. Based on the Bayesian estimation mechanics, the model predicts a repetition effect because past actions are predictive of future actions, and it predicts the role of similarity because such repetitions generally occur only with similar contexts.

B. Repetition Effects in Response Time

1. Evidence

There is an extensive history of research on repetition effects using response time as a dependent variable. It has long been known that in choice reaction tasks, repeated responses are faster than nonrepeated responses. An important problem in this area has been to disentangle effects of repeating the response from those of repeating the stimulus. For example, Bertelson (1965) had subjects perform tasks in which there were two possible stimuli for each response. The critical comparisons involved three kinds of trials: Those on which the stimuli differed but the response was the same; those on which both the stimulus and response were the same; and those on which both the stimulus and the response differed. He found that repeating the response produced a substantial benefit even when the stimuli were different. However, other researchers using the same type of manipulation have failed to replicate this result and have found substantial repetition effects only when the stimuli were the same (e.g., Smith, 1968; Smith, Chase, & Smith, 1973). Generally, repetition effects can occur across intervening trials; for example, responses will be faster when the stimulus and response matches that from two trials ago, regardless of the nature of the previous trial. Although repetition effects decline with increasing delay between trials, they are still found with an intertrial interval of 1 s and cannot readily be ascribed to a simple decay over time (e.g., Pashler & Baylis, 1991; Smith et al., 1973).

Pashler and Baylis (1991) argued that the similarity of the stimuli on repeated-response trials is a critical variable in determining whether the repeated responses are fast. In their results, different-stimulus/same-response trials were about as fast as same-stimulus trials when the stimuli on successive trials differed in a superficial and irrelevant manner (e.g., letter color when responses must be made on the basis of letter identity). But when the stimuli differed more significantly (e.g., upper and lower case letters), the advantage for different-stimulus/same-response trials was more modest, and when the stimuli mapped to the same response shared only stimulus category (letters vs. digits), the trials were almost as slow as different-response trials. Similar conclusions can be drawn from repetition effects observed in other paradigms. For example, Huettel and Lockhead (1999) found that in dimensional filtering tasks, responses were fast when both the irrelevant dimension and the correct response matched that on the previous trial. Gratton, Coles, and Donchin (1992) found comparable results in a letter-flanker task: Repetition effects on response time and error rates were specific to cases in which the irrelevant noise characters matched those on the previous trial.

Several authors have proposed what might be termed shortcut accounts of these repetition effects. In this form of explanation, there is an explicit or implicit comparison of the current stimulus with the stimulus presented on a previous trial. When the match is sufficiently close, the response from the previous trial can be produced; otherwise, a more time-consuming computation must be undertaken to identify the appropriate response. This general approach has been elaborated to incorporate a variety of different kinds of factors known to modulate repetition effects. For example, Schvaneveldt and Chase (1969) investigated the notion that the comparison process depends on a memory trace of the previous stimulus that decays over time. Huettel and Lockhead (1999) accounted for effects of stimulus similarity in terms of an explicit comparison process. Pashler and Baylis (1991) explained effects of alternating response hand by assuming that shortcut links could exist between relatively abstract descriptions of the required response. However, all of these mechanisms share the assumption that repetition effects arise because of the involvement of mechanisms that do not come into play with nonrepeated-response trials.

2. *Model*

Rather than assuming that repeated trials are somehow a special case, in our approach we assume that the responses for repeated stimuli are generated by the same process that generates responses on nonrepeated trials. The difference is that repeated stimuli provide a greater degree of constraint on the nature of the response to be performed and, by virtue of that constraint, produce more rapid responding. In order to model response time, we assume that the perceptual information that determines the nature of the current

context is not available instantaneously but rather develops over time. In other words, the stimulus has to be recognized and interpreted in the context of the current goals and intentions—a time-consuming process. Without this stimulus information, both the similarity of the current context to the previous trial (i.e., s in Eq. [2]) as well as the relevance of the history of previous actions (i.e., ρ_c) would revert to a default value of 0. However, both should increase as the stimulus is processed. In particular, we assume that the mean of the posterior is:

$$\mu_{m|p,c,s}(t) = [1 - u(t)s - u(t)\rho_c]\mu_m + u(t)sp + u(t)\rho_c m_c \quad (3)$$

where $u(t)$ increases monotonically from 0–1 over time.

Clearly, when the context is similar to that on the previous trial, the best estimate of the movement parameter will change more quickly from the default based on the prior distribution, μ_m. An illustration is provided in Fig. 5. If we arbitrarily assume that in this simulation response time effects reflect the time to cross a threshold of 1, the figure suggests a repetition effect of about 70 ms (relative to a different stimulus and response). The dependence of the repetition effect in this formulation on stimulus similarity is also

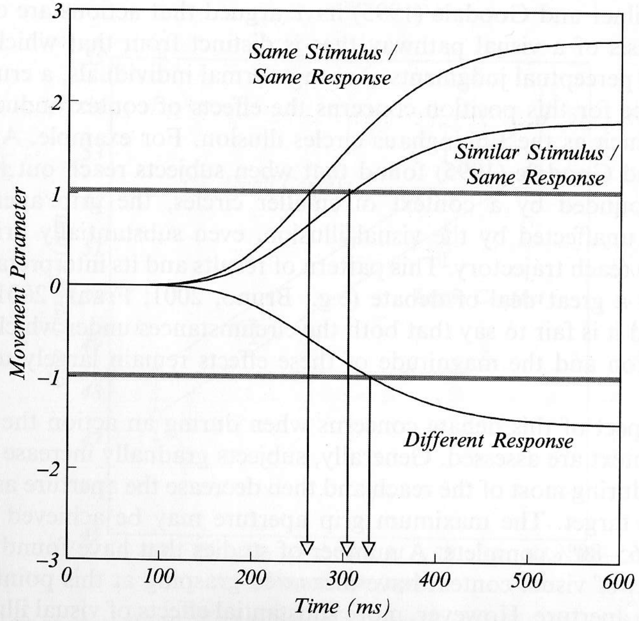

Fig. 5. Simulation of repetition effects on response time as a function of stimulus similarity across trials.

shown in Fig. 5. In this case, when the current stimulus is less similar to the previous (i.e., s is smaller), the repetition effect reduces to about 30 ms.

Related assumptions suffice to account for several other findings related to repetition effects. For example, it seems plausible to suppose not only that actions are likely to repeat immediately, but also with some frequency after a short delay. However, as the temporal gap increases, the likelihood that an action will be repeated becomes progressively less. For example, short pauses are common in the train of repeated actions involved in eating. However, after a significant delay it becomes much more likely that the meal is finished and that the associated actions will not reoccur for some time. As a consequence of this temporal relationship, the predictive value of a previous action for the upcoming trial can be expected to fall off with delay, and the parameter s in Eq. (3) would decline monotonically with the delay between actions. A similar analysis can also be used to explain the effects of intervening trials.

C. Visual Context Effects in Posture Choice

1. *Evidence*

An important problem in the control of movements concerns the role of vision. Milner and Goodale (1995) have argued that actions are controlled on the basis of a visual pathway that is distinct from that which informs conscious perceptual judgments. Among normal individuals, a crucial piece of evidence for this position concerns the effects of context-induced visual illusions such as the Ebbinghaus circles illusion. For example, Aglioti, De Souza, and Goodale (1995) found that when subjects reach out to grasp a disk surrounded by a context of smaller circles, the grip aperture was relatively unaffected by the visual illusion, even substantially prior to the end of the reach trajectory. This pattern of results and its interpretation have generated a great deal of debate (e.g., Bruno, 2001; Franz, 2001; Glover, 2002), and it is fair to say that both the circumstances under which illusions affect action and the magnitude of these effects remain largely unresolved issues.

One aspect of this debate concerns when during an action the effects of visual context are assessed. Generally, subjects gradually increase their grip aperture during most of the reach and then decrease the aperture as the hand nears the target. The maximum grip aperture may be achieved when the action is 65–80% complete. A number of studies that have found relatively little effect of visual context have measured grasping at this point of maximum grip aperture. However, more substantial effects of visual illusions can be found when grip aperture is measured somewhat earlier in the reach trajectory. For example, Glover and Dixon (2002a) examined the effect of

the Ebbinghaus circles illusion. Subjects were asked to reach out and grasp a target disk lying on a tabletop, surrounded by drawings of either larger or smaller circles. In perceptual judgments, the larger surrounding circles cause the target to be judged as smaller, and the smaller surrounding circles cause the target to be judged as larger. An effect of context can also be found on grip aperture 50% through the reach, as shown in Fig. 6. Clearly, the grip aperture is affected by the size of the target, so that a larger grip is used for larger disks. However, grip is also affected by the context: Larger grip aperture is found with a small surrounding context than with a large surrounding context.

Clear effects of visual context can also be found when there is relatively little opportunity to correct the choice of posture in the course of the movement. In the task used by Glover and Dixon (2001a), subjects reached out and grasped a short wooden dowel with their thumb and forefinger with either a wrist-abducted (thumb-right) posture or a wrist-adducted (thumb-left) posture. An important aspect of the task was that it was awkward or costly in terms of time and effort to change grip posture after the movement was under way. In order to examine effects of visual context, the bar was placed on a background grating that was oriented either 10° clockwise or 10°

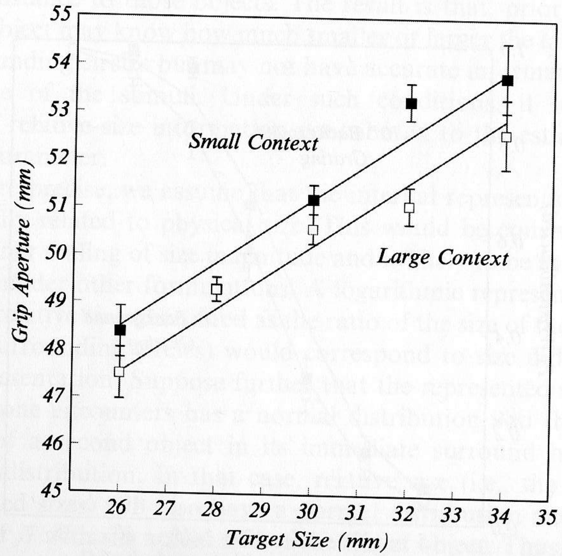

Fig. 6. Grip aperture at 50% of reach in the data of Glover and Dixon (2002a) as a function of object size and visual context. Smooth curves depict the model simulation described in the text.

counterclockwise from the sagittal plane. When the background was oriented counterclockwise from sagittal, the bar appeared slightly more clockwise than when the background was oriented clockwise from sagittal, and vice versa. That is, the orientation of the bar relative to the background had an effect on the perceived orientation of the bar. As shown in Fig. 7, this effect was also reflected in the choice of posture: Wrist-abducted postures were more likely with the counterclockwise background, and wrist-adducted postures were more likely with the clockwise background.

Other evidence that illusions can affect action planning was obtained by Glover and Dixon (2004). In this case, subjects were asked to jump from one end to the other of a Müller–Lyer illusion laid out on the floor. As in Glover and Dixon (2001a), it was difficult to adjust one's trajectory in the course of the movement, and, similarly, the visual context had an effect on performance: Subjects jumped farther for the "wings out" version of the illusion figure than for the "wings in" version.

2. *Model*

The role of many context-induced visual illusions in motor control is straightforward to explain in the present framework. Indeed, Bayesian accounts of perceptual phenomena have some precedent (e.g., Knill &

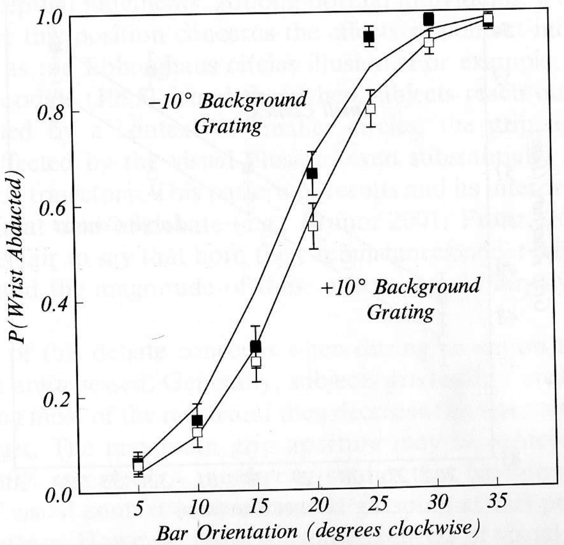

Fig. 7. Posture choice in Glover and Dixon (2001a) as a function of visual context and bar orientation. Smooth curves depict the model simulation described in the text.

Richards, 1996). For example, Richards, Jepson, and Feldman (1996) discussed the role of context in the interpretation of line drawing elements; Weiss, Siomcelli, and Adelson (2002) used Bayesian estimation to account for some visual motion illusions; and Mather (2000) suggested that some geometric illusions could be explained by Bayesian integration mechanisms. In the present application, we assume that, in the world, visual context is correlated with other aspects of the visual array. As a consequence, context is predictive of the posture required to grasp the target. Consider the Ebbinghaus circles illusion. In this effect, for example, adjacent larger circles make the central target circle appear smaller. However, from a Bayesian perspective, this is perfectly sensible because in the world, small objects are, on average, smaller than surrounding objects. Thus, the size of an object relative to its surround will be predictive of its absolute size. Moreover, there is some reason to suspect that under a range of circumstances, perceptual information about relative size will be more readily available than information about absolute size. For example, if the stimuli are viewed without head movements and without other surrounding visual context, the perceptual cues to distance may be minimal, and, consequently, estimates of absolute size based on the retinal image would have a degree of uncertainty. However, estimates of relative size would be unaffected by variation in distance: An object that is 10% larger than nearby objects will remain 10% larger regardless of the distance to those objects. The result is that, prior to the movement, the subject may know how much smaller or larger the target is relative to the surrounding circles but may not have accurate information about the absolute size of the stimuli. Under such conditions, it would not be surprising if relative-size information contributed to the estimation of the movement parameter.

To be more precise, we assume that the internal representation of size is logarithmically related to physical size. This would be consistent with the Weber–Fechner scaling of size magnitude and is likely to be at least approximately true under other formulations. A logarithmic representation of size implies that relative size (measured as the ratio of the size of the target to the size of the surrounding circles) would correspond to size difference in the internal representation. Suppose further that the represented size of graspable objects one encounters has a normal distribution and that the represented size of a second object in its immediate surround has a similar, independent distribution. In that case, relative size (i.e., the difference in the represented sizes) will also have a normal distribution and will have a correlation of .7 with the actual size of the target object. Thus, in principle, relative size should be predictive of the absolute size. The extent to which relative size should influence grip aperture will depend on how reliable the relative size and absolute size information is in the environment in which the grip aperture has to be selected. However, if the absolute size information is at least partially fallible, one would expect to see some effect of independent information concerning relative size. Indeed, as we previously argued, in many contexts relative-size information could be much more robust and precise than information about absolute size.

To apply these considerations to the choice of movement parameters, we assume that estimates of the movement parameter can be generated based on both relative size information, r, and absolute size information, a. In each case, a parameter value is selected based on prior movements associated with that information, namely, m_r and m_a. In general, the movement parameter based on absolute size and that based on relative size will be correlated. However, we may write the estimate of the movement by calculating the unique contribution of each:

$$\mu_{m|a,r} = (1 - \rho_{ma.r} - \rho_{mr.a})\mu_m + \rho_{ma.r}m_a + \rho_{mr.a}m_r \quad (4)$$

where $\rho_{ma.r}$ and $\rho_{mr.a}$ are partial correlations that index the unique contribution of a and r. This result is formally similar to that in Eq. (2), and it produces similar patterns of predictions. The match of this formulation to the grip aperture data of Glover and Dixon (2001a) is shown in Fig. 6. As can be seen, the approach readily accounts for the effect of visual context on grip aperture early in the reach.

The same approach suffices for the orientation illusion investigated by Glover and Dixon (2001a). In this case, we assume that the orientation of the bar relative to the background is mildly predictive of the absolute orientation of the bar. Consequently, if the absolute orientation of the bar is not immediately apparent, the relative orientation would provide some information about the appropriate movement parameter. As before, we argue that the predictive value of relative orientation accrues from an individual's history of actions in the world. For example, it seems plausible to suppose that there are commonly visual elements in one's work space that are aligned roughly with the sagittal plane. Such elements might include the edges of a desk or table, pieces of paper or tools, and so on. These elements in effect generate a frame of reference against which the orientation of other objects might be judged. As argued with respect to relative size, information concerning the orientation of objects relative to that frame of reference might be much more precise than information concerning egocentric orientation. Moreover, relative orientation will be predictive of egocentric orientation even when the frame of reference is not precisely aligned with sagittal. On average, for example, objects that are oriented somewhat clockwise from sagittal will also tend to be clockwise of other elements in the work space. Given this analysis, Eq. (4) applies just as readily to the use of relative orientation as it does to relative size. In Fig. 7, we assume that positive values of the movement parameter indicate a wrist-abducted posture, and Eq. (4) is used to predict the probability that the parameter is greater than 0. As with the size illusion, the approach provides a good account for the obtained results.

D. Dynamic Visual Context Effects

1. Evidence

A critical result for understanding effects of visual context is that those effects vary over the course of the reach trajectory. Early in the reach, the visual context has a fairly large effect on grip aperture, and this effect gradually declines as the hand approaches the target. This pattern of results has been obtained with the Ebbinghaus circles illusion (Glover & Dixon, 2002a), with the background-induced orientation illusion (Glover & Dixon, 2001a,b,c), with the Muller–Lyer illusion (Heath, Rival, & Binsted, 2004), with visual feedback (Glover & Dixon, 2001a,c, 2002a; Heath et al., 2004), and without visual feedback (Glover & Dixon, 2001a,c, 2002a; Heath et al., 2004).

A central consideration in evaluating such results is what counts as a "fairly large" effect. Glover and Dixon assessed the magnitude of the illusion effects by comparing them to the effects of the physical stimulus at the same point in the movement trajectory. For example, early in a reach, there is only a small effect of the physical size of a target disk on grip aperture, and consequently one would expect effects of visual illusion to be similarly small. As the reach progresses, the effect of disk size on grip aperture become more pronounced, and one would expect visual illusion effects to be more apparent as well. Thus, one technique used to assess the magnitude of the visual illusion is to scale those illusion effects by the size of the effect of the physical stimulus.

This pattern of results can be seen in the results of Dixon and Glover (2001). In these experiments, subjects grasped a target disk that was either 28, 30, or 32 mm in diameter; adjacent to the target was a context disk that was either smaller (26 mm) or larger (34 mm). The context disk generates a contrast effect comparable to that obtained with the Ebbinghaus circles illusion, so that in perceptual judgment tasks, the target is judged as smaller alongside a large context disk and larger alongside a small disk. Figure 8 shows the effects of the physical disk size and the visual illusion over the course of the reach. In the upper curve, the effect of disk size is expressed as the slope of the grip aperture × disk function; the lower curve indicates the size of the context effect (i.e., the difference in grip aperture between small and large contexts). Clearly, the effect of disk size increases over time; the

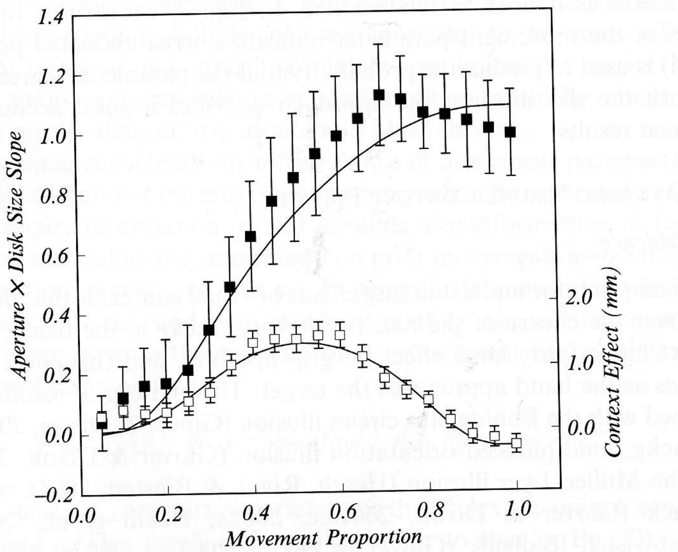

Fig. 8. Effect of context and disk size in Dixon and Glover (2001) as a function of movement proportion. Smooth curves depict the model simulation described in the text.

effect of context initially increases as well, but then it declines as the hand nears the target. Figure 9 shows the scaled context effect, that is, the effect of the context divided by the magnitude of the disk size effect. Based on the scaled context effect, our analysis is that the effect of the context is large initially and decreases monotonically over time. Concurrently, the effect of the represented disk size increases over time as the grip comes to be adapted to the size of the disk. These two trends combine to generate the nonmonotonic trend shown for the "raw" context effect shown in Fig. 8. The raw effect of the illusion is largest at about halfway through the reach. At this point, there are fairly substantial effects of disk size on grip aperture, but the hand is still far enough from the target that the effect of the illusion has not been reduced completely.

Glover (2002; see also Glover & Dixon, 2001a) interpreted these and similar results as supporting a distinction between action planning and action control, rather than a distinction between perception and action as argued by Milner and Goodale (1995). He suggested that the initial planning of the action depended heavily on contextual information in the stimulus environment and, as a consequence, was influenced by the context-induced visual illusions such as the Ebbinghaus circles display. Subsequently, though, different visual information is used in the course of the online

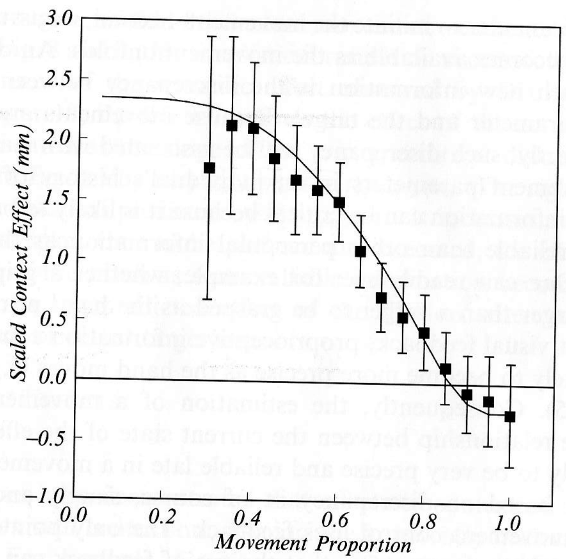

Fig. 9. Effect of context scaled by the effect of disk size in Dixon and Glover (2001) as a function of movement proportion. Smooth curves depict the model simulation described in the text.

control of the action. This control information is tuned to the discrepancy between the hand posture in the course of the reach and the final target contours. Consequently, the information used during the control of the action is much less affected by the visual illusions, and the magnitude of the illusion effects decreases as the movement trajectory unfolds.

2. *Model*

In order to explain dynamic effects, we build on the formulation of Eq. (4) to account for how movement parameters change over time rather than simply the choice of a movement parameter. However, we assume that the mechanism used to control action is mediated by memory in precisely the same way as the selection of movement parameters at the outset. We argue that there are two dynamic components: First, movements are not initiated instantaneously but rather develop over time as an internal representation of the intention to move is formed. Such an intention forms part of the context that allows suitable movement parameters to be retrieved from memory. Depending on the experimental paradigm, the intention to move may develop as a function of the stimulus onset (as was assumed, for example, in our discussion of repetition effects on response time), or as a function of a signal from the experimenter to initiate the movement. Second, we assume that new information becomes available as the movement unfolds. An obvious component of such new information is the discrepancy between the current movement parameter and the target. Because movements are usually not planned perfectly, such discrepancy will be associated with suitable corrections of movement parameters in an individual's history of movements. Discrepancy information can be critical because it is likely to be much more precise and reliable than other perceptual information as the movement progresses. One can readily see, for example, whether a grip aperture is smaller or larger than a target to be grasped as the hand nears the target. Even without visual feedback, proprioceptive information concerning hand posture is likely to become more precise as the hand moves (e.g., Pagano & Turvey, 1995). Consequently, the estimation of a movement parameter based on the relationship between the current state of the effector and the target is likely to be very precise and reliable late in a movement.

Prediction based on discrepancy is, of course, simply another way of saying that movement control uses feedback. The only point of putting it in these terms is to demonstrate that the use of feedback can be conceived as another way of estimating movement parameters based on memory. In particular, feedback can be included in the estimate of the movement parameter as follows:

$$\mu_{m|a,r,d} = (1 - \rho_{ma.rd} - \rho_{mr.ad} - \rho_{md.ar})\mu_m + \rho_{ma.rd}m_a + \rho_{mr.ad}m_r + \rho_{md.ar}m_d \quad (5)$$

As before, the ρ parameters are partial correlations that index the contributions of each source of information, independent of the others, and the *ms* indicate the corresponding movement parameter values. The dynamic effects of context arise in this approach because the availability of the discrepancy information follows a different time course than the relative and absolute size information. Thus, to be more precise, the formulation should be:

$$\mu_{m|a,r,d}(t) = [1 - u(t)\rho_{ma.rd} - u(t)\rho_{mr.ad} - v(t)\rho_{md.ar}]\mu_m + u(t)\rho_{ma.rd}m_a + u(t)\rho_{mr.ad}m_r + v(t)\rho_{md.ar}m_d \quad (6)$$

Here, $u(t)$ increases after the onset of the stimulus or movement signal, and $v(t)$ increases as the movement unfolds. Thus, although both u and v increase monotonically over time, u is assumed to increase relatively early in the movement trajectory as stimulus information is processed and the goal of moving to target is formed, whereas v increases more slowly as discrepancy information is acquired over the course of the movement. The predictions represented by Eq. (6) concern the estimated value of relatively high-level movement parameter, rather than the kinematics of the physical movements themselves, and in a more complete account these predictions would have to

be filtered through a model of the actual movement mechanics. Nevertheless, as shown in Fig. 8 and 9, this simplistic formulation successfully captures the essential features of the dynamic effect observed by Dixon and Glover (2001). In Figure 8, the left axis shows the effect of the actual size of the object (represented as the slope of the grip aperture × disk size relation), represented in Eq. (6) by $u(t)\rho_{ma.rd}m_a + v(t)\rho_{md.ar}m_d$. The right axis shows the effect of context as predicted by $u(t)\rho_{mr.ad}m_r$. It increases at first because the movement takes time to be planned and executed; the effect decreases near the end of the reach as more reliable information becomes available. Figure 9 shows the predicted effect of the illusion when scaled by the predicted effect of actual target size.

E. Semantic Effects

1. *Evidence*

Several authors have demonstrated that effects of context on reaching are not limited to visual context but also include apparently irrelevant semantic information. For example, Gentilucci and Gangitano (1998) printed the words *long* and *short* on objects and observed movement kinematics comparable to that which would be expected if the objects were actually a long or short distance away. Specifically, higher peak velocities were observed when reaching to objects labeled "long" than to objects labeled "short," similar to that observed for objects that are actually farther away (Jeannerod, 1984). Similar observations were made for several other word pairs (Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; see also Glover & Dixon, 2002b). Glover, Rosenbaum, Graham, and Dixon (2004) extended these findings to word pairs that were only implicitly related to object features. For example, reading the word *apple* led to larger grip apertures in a subsequent reaching and grasping movement than the word *grape*, even though the words were not predictive of actual object size.

In many ways, these semantic effects are similar to the effects of visual illusions. For example, they are found near the middle of the reach trajectory, and they tend to be minimal by the time the hand reaches the target. Figure 10 shows representative results from Glover et al. (2004). As with visual illusions, there is relatively little semantic effect either early in the reach or near the end, and the effect is clearest in the middle of the reach. Our interpretation of these dynamic effects is comparable to that proposed for effects of visual illusions: The effect increases initially as the system responds to the target and the signal to move, and then decreases as discrepancy information becomes available over the course of the movement.

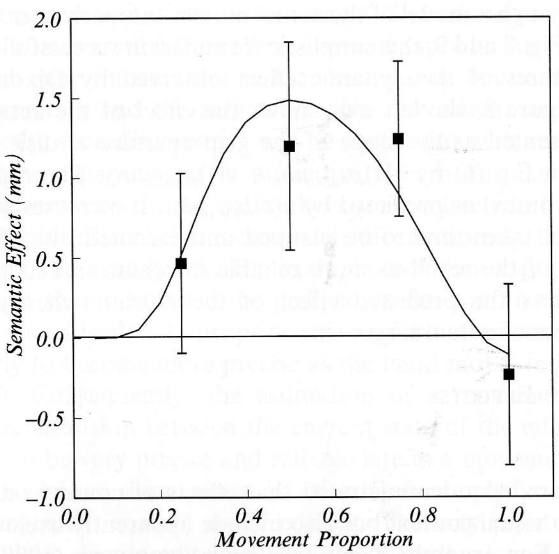

Fig. 10. Effect of semantic context in Glover et al. (2004) as a function of movement proportion. Smooth curves depict the model simulation described in the text.

Another, quite different source of evidence concerning semantic effects comes from experiments by Bargh (e.g., Bargh, Chen, & Burrows, 1996). When subjects were primed with the concept "elderly," they subsequently walked more slowly when leaving the lab. On our analysis, this result may occur because the activation of an "elderly" stereotype primes related actions, including slow walking, and these are more likely to be retrieved during the subsequent planning and control of actions. We suspect that this priming may be comparable to the priming of grasping posture observed by Glover et al. (2004; Glover & Dixon, 2002b) and Gentilucci and Gangitano (1998; Gentilucci et al., 2000).

2. *Model*

Because of the similarity to the visual illusion effects, it is not surprising that the same computational framework suffices for semantic effects as well. The critical step is to note that semantic context is predictive of motor actions just as the visual context is. For example, when picking up an apple, one is typically thinking about the concept of apple in one way or another; when picking up a grape, one is typically thinking about grapes, and so on. Thus, the activation of the apple concept is predictive of the posture needed to grasp an apple, and the activation of the grape concept is predictive of a grape-grasping posture. Of course, the predictive value of such activations is not very high since there are many circumstances in which the one may think about these concepts without grasping the objects. Nevertheless, as in the previous development, these weakly predictive effects can contribute to the estimation of the movement parameter when other sources of information are not perfectly reliable. Formally, the prediction is precisely the same as that for the effects of relative size context:

$$\begin{aligned}\mu_{m|a,e,d}(t) \;=\;& [1 - u(t)\rho_{ma.ed} - u(t)\rho_{me.ad} - v(t)\rho_{md.ae}]\mu_m \\ & + u(t)\rho_{ma.ed}m_a + u(t)\rho_{me.ad}m_e + v(t)\rho_{md.ae}m_d \end{aligned} \tag{7}$$

except that here, the prediction is based on the semantic context, e, rather than relative size. The model predicts the same form of dynamic effect, and, as can be seen in Fig. 9, it provides a reasonable match to the obtained results.

F. Summary

We have outlined a variety of results pertaining to the influences of visual, experiential, and experimental context on action and have demonstrated how each can be explained by assuming that movement parameters are estimated on the basis of previous experience. The core idea in this framework is simply that people have a great deal of available information about previous actions and that this information is used in an optimal (i.e., Bayesian) fashion to estimate movement parameters in the current context. Because it is reasonable to suppose that actions are often repeated, these assumptions predict repetition effects in posture choice and speeded response tasks; because a target's visual context is often predictive of the appropriate posture, we can predict effects of context-induced visual illusions on action; because feedback and other sources of information become available in the course of an action, we can explain the dynamic time course of illusion effects; and because semantic context is predictive of actions, we can account for semantic effects on movement trajectories as well. Thus, the approach integrates a wide range of different kinds of effects under a single conceptual and computational framework.

Alternative explanations have previously been proposed for some of these results. For example, repetition effects in response time have been explained by "shortcut" processes that curtail computation of a response when the stimuli on successive trials match, and the dynamic illusion effects have been explained on the assumption that different visual pathways subserve action planning and action control. Our argument, though, is that the memory and action framework is more general and parsimonious because it subsumes these other explanations. For example, the use of a distinct visual pathway during action control can be thought of as simply another source of information that can be used as a memory retrieval cue to make dynamic predictions of movement parameters. However, in Section IV we review several other results that would seem to implicate specifically the ability of the motor control system to make Bayesian-like predictions based on previous experience. These results provide evidence for something akin to the present approach over and above any gain in parsimony or comprehensiveness.

IV. Other Evidence on Memory and Action

A. Predictiveness of Relative Size

One result that seems to implicate the use of memory in action derives from the manipulation of the predictiveness of visual context in an experimental session. The usual manner in which one would vary visual context in an experiment would be to factorially manipulate the contextual information and the physical nature of the target. For example, in Dixon and Glover (2001), 28-, 30-, and 32-mm target disks were paired with either a 26-mm context disk or a 34-mm context disk. Although this design ensures that the size of the context disk does not predict the size of the target, *relative* size in fact does predict the target. For example, if relative size is defined as the size of the target divided by the size of the context, there is a modest correlation of .38 between relative and absolute size. Thus, irrespective of the movement history with large and small objects, one should expect an effect of relative size simply on the basis of the experience subjects have with the stimuli in the experiment.

A straightforward test of this interpretation is to alter the design of the stimuli so that relative size is no longer predictive of grip aperture. Dixon, Glover, and Schneider (2003) used context disks that were either a fixed percentage larger or a fixed percentage smaller than the target. The results of this manipulation are compared to the usual, orthogonal manipulation of context size in Fig. 11. The results demonstrate that in the crucial middle portion of the reach trajectory, the orthogonal manipulation of context produces a greater effect of context on grip aperture than when relative size is fixed and provides no information. This result strongly suggests that the dynamic effect of visual context depends on the predictive value of that context.

B. Reliability of Perceptual Information

Another manipulation that should produce related effects pertains to the reliability of perceptual information. In general, the magnitude of the context effect (i.e., $\rho_{mr.ad}$ in Eq. [6]) will depend in a complex way on the

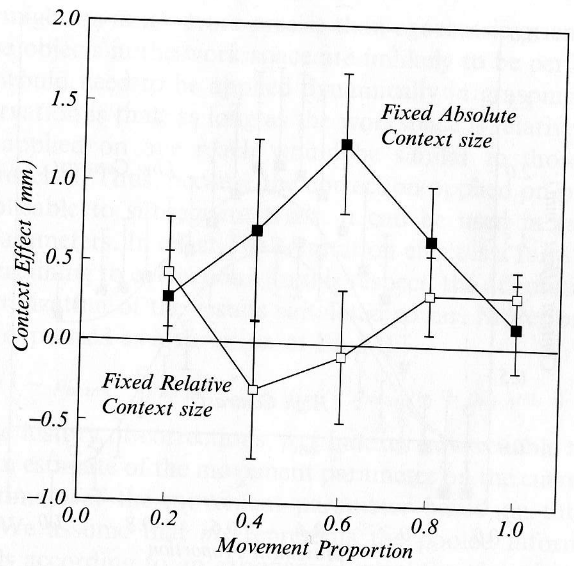

Fig. 11. Effect of context in Dixon et al. (2003) as a function of experimental context and movement proportion.

relationship among the different predictors. However, in a broad set of plausible circumstances, $\rho_{mr.ad}$ will decrease as ρ_{ma} increases. In other words, the unique contribution of relative size information will vary inversely with the reliability of the absolute size information. Relative size information will be most helpful if the absolute size information is noisy or unreliable, and, in the limit, relative size information will add nothing if absolute size information is perfect. The net implication then is that any manipulation that decreases the reliability of the perceptual absolute size information should increase the effect of relative size information.

Dixon and Glover (2001) found such a result when target contrast was manipulated. Subjects reached out and grasped a target disk in the presence of a context disk that was either larger or smaller than the target. The disks were white with a black edge and could be placed either on a black background or a white background. Absolute size information was difficult to discern when the disks were against a black background because the dark edge tended to blend in with the background; the contours of the disks were much easier to see when the disks were placed against a white background. Consistent with the prediction, the context effect was larger and longer lasting when the target was presented under low-contrast conditions (see Fig. 12). The predictions of the model were fit by eye to these results and

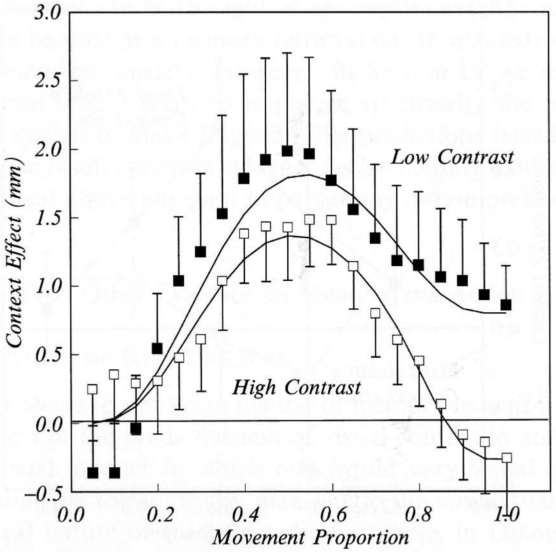

Fig. 12. Effect of context in Dixon and Glover (2001) as a function of stimulus contrast and movement proportion. Smooth curves depict the model simulation described in the text.

shown in the figure as well; the differing results for the two conditions was generated simply by varying the reliability of information about absolute size.

C. Adaptation to Experimental Context

A third source of evidence pertaining to the informativeness of the context comes from adaptation effects. Glover and Dixon (2001b) used the orientation illusion previously used by Glover and Dixon (2001a): Subjects reached out and picked up a bar resting on a grating oriented either 10° clockwise or 10° counterclockwise from sagittal. However, rather than changing randomly from trial to trial, the orientation of the background grating remained fixed for a block of 14 trials. While a clear effect of context was observed in the first half of each block, it disappeared by the second half. In a sense, subjects had become "adapted" to the illusory orientation of the bar. (We use the term *experimental context* to refer to such effects of the composition of blocks of trials, and reserve the term *visual context* for effects of the visual array on any given trial.)

These results are precisely what one would expect if the use of relative orientation information was mediated by memory for recent movements. As previously argued, the orientation of objects relative to other elements in the

work space might be much more precise than egocentric orientation. However, because objects in the work space are unlikely to be perfectly aligned, corrections would need to be applied dynamically in grasping targets. The crucial observation is that, as long as the workspace is relatively stable, the corrections applied on one reach would be similar to those applied on subsequent reaches. Thus, because the correction applied on previous trials is likely applicable to subsequent trials, it can be used in estimating the movement parameters. In effect, the adaptation effect is a form of repetition effect, but pertaining to corrections. In this respect, the adaptation effect is a natural generalization of the results simulated so far. More formally, these ideas can be expressed as a variation of Eq. (4):

$$\mu_{m|a,r,k} = (1 - \rho_{ma.rk} - \rho_{mr.ak} - \rho_{mk})\mu_m + \rho_{ma.r}m_a + \rho_{mr.a}m_r + \rho_{mk}m_k \quad (8)$$

where k is the history of corrections, ρ_{mk} indexes how reliable those corrections are as an estimate of the movement parameter on the current trial, and m_k is the estimate of the movement parameter based on those previous corrections. We assume that m_k represents the pooled information from previous trials according to an exponential weighting function, so that the most recent trials are most likely to be predictive of the current trial and more distant trials less likely. This would seem to capture the notion that the elements of the workspace that comprise the frame of reference are only likely to be stable in the short term (cf. Scheidt, Dingwall, & Mussa-Ivaldi, 2001).

D. Memory-Contrast Effects

Another type of evidence for the role of memory in action comes from the work of Haffenden and Goodale (2002a,b). Haffenden and Goodale (2002a) used a surface texture as a cue to an object's size. For example, a texture of triangular shapes might be associated with large objects, and a texture of circular shapes with small objects. Subsequent reaches to a medium-sized object were influenced by the texture on its surface, so that, for example, grip aperture was smaller when the surface texture matched the previously viewed large objects. This result suggests a memory-based size-contrast effect. For example, experience with the large objects of a particular texture makes the medium-sized object with the same texture appear smaller by comparison, and this effect was evident in the grip trajectory. Haffenden and Goodale (2002b) examined the consequences of varying a target's position on such cue effects (using color in this case rather than surface texture). Cue effects were observed for movements made to targets presented in a single location but not for movements to targets whose location varied.

These results clearly implicate memory in the selection of movement parameters. On our analysis, the size of an object relative to previous encounters with similar objects can function as a relative-size cue just as does the size of an object relative to other objects in the work space. Thus, we can account for this result using a variant of Eq. (4), except that the information about relative size would be based on memory rather than comparisons to other, simultaneously visible objects. Consistent with our analysis of repetition effects, the use of memory in these circumstances is specific to the details of the action and the situation. Thus, varying target position reduces or eliminates the cue effects because movements of a different type (i.e., to a different location) are relevant to the estimation of the movement parameter.

V. Relation to Other Approaches

Although the present proposal is unique in at least some respects, it is closely allied with a variety of extant theories. Perhaps the most germane is the theory of motor control proposed by Rosenbaum, Loukopoulis, Meulenbroek, Vaughn, and Englebrecht (1995). They proposed that actions were accomplished by evaluating stored postures in terms of their match to a target. The stored postures in turn determine both final joint angles needed to arrive at the target and (implicitly) properties of the movement trajectory. What is different about the present proposal is that we assume that the use of the stored postures is based not on the intended target position but rather on task goals and the stimulus configuration. Further, much of the power in our framework derives from the more general use of context to constrain an extensive memory for previous actions.

Smith et al. (1973) proposed a conceptually related approach to account for repetition effects on response time. They argued that in order to identify a response, the stimulus must be compared to a set of possible stimulus-response pairs in short-term memory. To explain repetition effects, they assumed that the search of short-term memory was ordered by recency, so that the stimulus responded to on a recent trial is more likely to be encountered first. This is comparable to our framework in that contextually appropriate responses are selected from memory based on the match to the current stimulus configuration. Although we would not exclude the possible involvement of short-term memory in our approach, we assume that the selection of a response depends more generally on a long-term memory repository of previous actions. Moreover, the recency effect in our account follows in a straightforward fashion from the principles of optimal estimation rather than requiring ad hoc assumptions concerning the ordering of search.

The present conception is also similar in many respects to the instance theory of automaticity (Logan, 1988). In this account, memory traces of prior episodes with a stimulus and task race independently, and the winner

determines the response on a given trial. Because the number of instances increases over time, the average speed of the winner will increase, in keeping with the pattern of speed increases observed with extended practice. The present proposal is related to Logan's analysis in that both depend on the availability of instances in memory. The mechanics of response selection are quite different, though: In Logan's model, a single instance is selected on the basis of a race process and is used to model the current response; in the present approach, we estimate movement parameters based on a posterior distribution of parameter values. However, there are a variety of conditions in which similar predictions could arise. For example, if the current context is sufficiently specific, the posterior distribution might be largely a function of a specific previous instance. Further, if the internal context develops over time (as was suggested in our discussion of repetition effects on response time), the selection of that previous instance might have some of the same properties as the independent race process envisioned by Logan.

Körding and Wolpert (2004) used precisely the same mechanics as described here to model the control of saccadic eye movements. In particular, they assumed that the selection of a movement parameter involves Bayesian estimation based on previous experience. Similarly, Vetter and Wolpert (2000) developed a related Bayesian account of some aspects of movement dynamics. However, the concern in these studies was with the integration of different sources of sensory information and the calibration of that information over trials; the potentially larger role of memory for action was not a primary focus. The present work builds on these ideas but accounts for a broader range of visual and semantic context effects by assuming that actions are based on a large repository of previous actions in memory.

The Bayesian approach to the use of memory is also related to the ideas of Anderson and Milson (1989). They proposed that the current context provides a set of memory cues, and that based on these cues, the memory system estimates a value termed a need probability for each item in memory. The most important difference between the present approach and that of Anderson and Milson is that we estimate properties of the entire posterior distribution rather than probabilities for individual items or instances. Nevertheless, the natural way in which Anderson and Milson's formulation accounts for various aspects of memory suggests that similar variables might be readily incorporated into the present framework. For example, Anderson and Milson explain effects of practice, spacing, and retention interval in terms of the Bayesian posterior probability calculations. However, related variables have effects on motor learning (e.g., Magill & Hall, 1990; Newell & Rosenbloom, 1981; Young, Cohen, & Husak, 1993), and it is tantalizing to suppose that a Bayesian account of these phenomena could be obtained using the estimation procedures developed here.

VI. Conclusion

We argue that the role of memory in action provides a collection of powerful explanatory principles for understanding a wide range of effects on action and action control. Moreover, the interpretation of action selection as the Bayesian estimation of movement parameters provides a variety of novel and perhaps surprising predictions. For example, as predicted by this approach, repetition effects on posture choice are mediated by contextual similarity; effects of visual illusions and visual context are expected to be larger when other visual information about the target is impoverished; and effects of relative size and orientation cues vary with the experimental context. In the present chapter, we have provided merely an outline for a more comprehensive application of these ideas and have only touched on a few aspects of the conceptual analysis that would ultimately be needed. Nevertheless, we believe that the present demonstrations provide clear evidence of the power of this approach.

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SELF-GENERATION AND MEMORY

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I. Introduction

It is probably regarded as a truism that active or self-initiated encoding produces superior memory than does passive or perceptual encoding. There are any number of research areas that support such a view. In educational research, much is written on the superiority of active as opposed to passive learning strategies (e.g., Kalem & Fer, 2003; Michael & Modell, 2003). Research on persuasion typically shows that self-generated arguments are better remembered than arguments supplied by a speaker (e.g., Petty, Ostrom, & Brock, 1981). Memory research indicates that carrying out an action produces better memory for the act than merely viewing the action or hearing a verbal description of the action (*the enactment effect*; Engelkamp, 1998; Zimmer, Cohen, Guynn, Engelkamp, Kormi-Nouri, & Foley, 2001). Likewise, generating verbal materials leads to better memory than does reading the same materials (*the generation effect*; Slamecka & Graf, 1978). The effects of semantic elaboration may be encompassed in this generalization as well: greater semantic elaboration implies both greater active involvement with the materials and heavier reliance on self-initiated processing (e.g., Tailby & Haslam, 2003). This idea is also implied by theories of cognitive aging that focus on reduced cognitive control, with a concomitant reduction in self-initiated encoding (and retrieval) processes, as the locus of age-related declines in memory (e.g., Anderson & Craik, 2000). These and other findings are quite supportive of the traditional view "that material