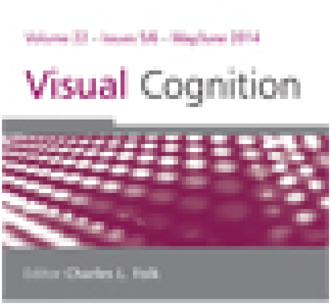

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Time course of planning for object and action parameters in visually guided manipulation

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Under visual guidance, subjects reached for and manipulated an object that varied in weight and surface texture (slipperiness). The manipulatory action was either grasping, lifting, or posting in a slot. The task was constrained or unconstrained with respect to speed, grasp pattern, and contact force. Initiation time (pre-reach), movement time (reach), and post-contact errors were measured, to examine planning for task performance at three points in time. Results indicate that in the constrained task, the manipulatory action was planned during the initiation time, but planning for object parameters was deferred until the reach interval. With relaxed task constraints, initiation times increased, and texture and manipulatory action had independent effects on premovement planning. Errors were affected interactively by all variables. The results suggest a planning process that unfolds over time, incorporating in turn the manipulatory action, object texture, and object weight. This unfolding accommodates variables proximate to the time where they will affect physical action.

People act on the world of objects for functional purposes. Functional acts are generally planned in advance, using sensory guidance along with cognitive intention and memory for past actions. Generally, we know what action we intend to perform with an object well before we reach for it—whether we want to push it or lift it, for example. Vision provides us with immediate and ongoing

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information about the geometry of action space: Where the object is and how its points of contact are oriented with respect to our body. Vision may indicate attributes of the object such as its weight and texture—although these can also be specified from memory, and some attributes may be available only after contact. If we are surprised by any of these parameters, the result can be an action slip: The milk spills; the plate is dropped.

Purposive interactions with objects require that parameters relating to functional action, spatial geometry, and object properties, like those listed earlier, be converted into motor parameters, such as arm velocity, reach direction and extent, hand shape, wrist orientation, grip force, and lift force. When they are planned in advance (cf., reflexive actions), these motor parameters constitute a *forward model* of the action, designating how it will unfold over time. The present paper is concerned with the construction of such a forward model after visual exposure to an object, in response to various action and object constraints. The general issue is how the model is influenced by these constraints at different points in time.

The concept of a forward model has been used extensively in the domain of motor control. Recently, it has been articulated by Wolpert and Ghahramani (2000) as an internalized system that predicts the consequences of action. The model arises from sensorimotor knowledge to predict particular motor events. During such an event, the model predicts values for a set of parameters that describe the continuously changing *state* of the sensorimotor system, for example, the active muscles, the positions of limbs, and so on. The event also takes place in a *context* consisting of parameters that change more slowly, if at all—for example, the identity of the target object or task constraints. Although the context constrains the predicted states, its parameters are not directly incorporated into the forward model.

During the course of any one movement, multiple models are formulated: A forward dynamic model predicts how the state of the system will change as a consequence of a motor command, given the context. A forward sensory model specifies the sensory feedback that will result from the change in state. Feedback from the sensory system can be used to update the models on-line, improving their prediction. For example, the trajectory of a ball can be estimated from its changing retinal position and used to update predictions about its future path. Feedback can also produce long-term sensorimotor learning that changes the predictive models that are formed.

The essence, then, of a forward model is that it predicts the consequences of motor commands for the unfolding states of the sensorimotor system, given motor commands and context. Here, we address the issue of which contextual parameters influence the model, and at what points in time. This issue has received attention in previous research on action planning and execution. Our general approach is to vary contextual parameters that should strongly constrain how an object is manipulated, and hence should alter the states predicted by the forward models. We examine the time course of movement prior to object contact, to determine whether variations in levels of the parameter affect performance. If so, it indicates that the parameter influenced the preparation for the ultimate manipulatory act at that point in time.

Several time periods that might be the locus of action planning and preparation have generally been distinguished. One period is prior to initiating movement. Another is during the reach. Yet another is after contact. The first two of these periods have frequently been differentiated in response-time studies, by partitioning the total pre-contact time into initiation time (from go signal to start of reach) and movement (reaching) time. Although it has sometimes been assumed that movement preparation and planning occur entirely within the initiation time (e.g., Pratt & Abrams, 1994; Rosenbaum, 1980), this assumption is unlikely to hold in general. People may begin reaching before they have entirely planned the action, especially when there is an imperative go signal and no penalty is associated with the action, and some actions must be adjusted while ongoing, in response to sensory input (e.g., Bootsma & Van Wieringen, 1990). Planning seems more likely to be completed prior to movement when there are discrete response alternatives, and less likely to be completed when there is target uncertainty (see Meegan & Tipper, 1998, regarding location uncertainty). Without necessarily assuming that planning is generally completed before movement, research on simple arm movements reveals contexts in which the separation of initiation and movement times provides insights into the planning process.

Klatzky, Fikes, and Pellegrino (1995) found effects of two variables on initiation time in a reach-to-contact task. They had subjects reach for and make contact with an object, using a hand shape (e.g., poking or grasping) that was cued by the object's colour. Movement of the object was to be avoided. The time prior to reaching was affected both by the stimulus–response compatibility—the perceptual affordance of the object for the colour-cued hand shape—and the stability of the object's support, as manipulated by whether the base of the object was on a sliding or stable surface. These effects were attributed to planning for two components of the action, respectively: The hand configuration used at contact, and the reach. Evidence for parallel, independent planning of these components was obtained. In other studies, another variable that has been found to affect pre-movement initiation time is the required spatial precision of an aimed movement (Sidaway, 1991; Spijkers, 1987).

Planning for an action can also occur during the reaching movement itself, prior to contact. Purdy, Lederman, and Klatzky (1999) compared performance in a peg-in-hole task with and without visual guidance. Although vision led to faster movement initiation, grasping, and manipulation, subjects were actually faster to reach when denied vision, indicating that the movement interval was used to plan visually guided action. In particular, the late acceleration phase of reaching has been implicated as a point when people accommodate the force precision required by the action. Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987) found that the fragility of the object (ball vs light bulb) and the target movement (place vs throw) affected the movement time, particularly the later stages. Klatzky et al. (1995) found that in addition to affecting initiation time, the stability of the object's support plane also affected movement time.

Fikes, Klatzky, and Lederman (1994) found that object texture, in the form of coefficient of friction, affected movement time when subjects grasped and lifted a dowel. (This was in contrast to a null finding of Weir, MacKenzie, Marteniuk, & Cargoe, 1991; however, that study did not have a contact sensor to differentiate between pre-contact and post-contact effects, and those observed were attributed to the post-contact phase.) Based on a model of Fearing (1986), Fikes et al. showed that object slipperiness determines the tolerance for placement of the fingers so as to prevent the object from slipping. Presumably, people were anticipating the greater precision demands of a slippery object while they reached for it, slowing their reaching time. This slowness with the slippery dowel was not observed with the initiation time, indicating that consideration of these constraints was delayed until the hand approached the dowel.

A third point in time at which action and object parameters can affect motor planning and preparation is after contact, but prior to manipulation. Johansson and Westling (1984) found that subjects who were grasping and lifting an object without vision adjusted their grip force according to the coefficient of friction and weight, after the object was contacted. Heavier or slippery objects require greater grip forces than do lighter or less slippery objects. However, the time required to attain a suitable grip force remained invariant across surface textures. This constancy was maintained by increasing the rate of grip force adjustment when the object was slippery.

Weir, MacKenzie, Marteniuk, Cargoe, and Frazer (1991) also found that an object's weight affected the contact time prior to lifting, but not the reaching time. Four visibly distinct dowels, ranging in weight from 20 to 410 g, were reached for, grasped, and lifted in a sequence of either blocked or random trials. The kinematics of movement were measured with a tracking system, and contact was sensed (in Experiment 2 only) with an electrical sensor. This allowed the authors to parse the response interval into two components, pre-contact arm movement and pre-lift contact. The second of these intervals, between initial contact and lift, was greater for the 410 g dowel than for those ranging from 20 to 150 g; however, the free phase of movement was unaffected by weight.

Planning and preparation do not stop, of course, once a manipulatory action—even a simple ballistic action like lifting—has begun. People adjust their grip force on an object that is perturbed during the act of lifting, whether from adding an external force (e.g., Johansson & Westling, 1988) or from changes in the movement itself (e.g., Flanagan & Wing, 1995; Witney, Goodbody, & Wolpert, 1999). Witney, Goodbody, and Wolpert (2000) suggested that the latency to adjust the grip given a change in movement (e.g., one hand pushes on an object being lifted with the other) is so short that it points to predictive adjustment using a forward model (feedforward), rather than a closed-loop correction (feedback).

In the present experiments, variations in object parameters—texture, as used by Fikes et al. (1994), and weight, as investigated by Weir, MacKenzie, Marteniuk, Cargoe, and Frazer (1991) and Johannson and Westling (1984)—was incorporated into multiple task contexts involving grasping and/or lifting an object. One was a highly constrained context, in which the task was speeded, terminal contact force was required to be low so that the object did not slide on a slippery support plane, and the object was to be grasped in a difficult-to-maintain posture (side to side). This was compared to an unconstrained context, in which the task was performed at a comfortable rate, sliding of the object on the support plane was tolerated, and a natural, front-to-back grasp was allowed. Moreover, these contraints were introduced or relaxed in the context of three actions, which varied in the movement trajectory imposed subsequent to object contact: The object was grasped without lifting, lifted above the table, or lifted so as to contact a slot in an upper surface. These actions are ordered in increasing complexity with respect to the movement required.

Our general interest was in how contextual parameters related to object and action would influence the forward model, by their effects on the states that the model predicts. The scope of the forward model is, in these experiments, equivalent to motor planning that takes place prior to object manipulation. As was noted previously, one should not assume that planning is exhausted prior to arm movement; on the contrary, the process extends in time into the reach and even after contact with an object has been made. We examined the planning process at three points in time, using temporal and error measures. Two temporal measures were used: Pre-movement initiation time and pre-contact movement time. Differences between levels of a variable with respect to these measures were taken as evidence that the impact of the variable was incorporated into the forward model at that time. Although we recognize that the locus of planning is to some extent under the subject's control, potentially muddying the initiation/movement time distinction, premature initiation of reaching was discouraged both by instruction and by the inclusion of catch trials, in which no object appeared. Moreover, rather than assuming discrete planning intervals prior and subsequent to movement, we treat the two temporal measures as accessing, at different points in time, a more continuous process of constructing and modifying a forward model.

In addition to the temporal measures, we examined effects of manipulated parameters on post-contact errors. Such errors can be taken as failures of planning, either because the process was incomplete by volition before the manipulation was attempted, or because some motor demands simply cannot be fully assimilated prior to or during initial contact. In either case, to the extent that errors are affected by characteristics of the object or by the action complexity, they indicate that accommodation of these variables is deferred, in whole or part, until the action itself.

Given these assumptions, the following questions were pursued: (1) Would object parameters of weight and texture influence the forward model, that is, would variations in the object affect initiation and/or movement time? Previously these effects were elusive. Texture has been found not to affect initiation time (Fikes et al., 1994), and weight has been found only to affect post-movement, contact time (Weir, MacKenzie, Marteniuk, Cargoe, & Frazer, 1991). However, such effects may be found when different levels of task constraints and action complexity are considered. (2) Would action parameters influence the forward model? Whereas effects of object parameters on initiation time have proved elusive, and effects on movement time have been mixed, complexity of the ultimately required action might be more powerful in affecting temporal planning measures. (3) Would task constraints and object parameters interact? In particular, would object parameters such as texture be incorporated earlier into the forward model when the task was highly constrained (with respect to speed, grasp, and force), or would task constraints dominate motor preparation, precluding object-related planning? (4) Would action complexity and object parameters interact? That is, would more complex actions introduce more or less planning for object parameters? (5) Would the object parameters of weight and texture have equivalent effects on the forward model? These parameters act together to influence the grip force that must be imposed to lift an object. Accordingly, it seems plausible to assume that they would either jointly be included or excluded from the planning process. On other hand, texture has been found to affect movement time, and weight has not. (6) Would some combinations of object, action, and task constraint prove sufficiently demanding that action errors would ensue, and how would these conditions relate to the planning process as revealed by temporal measures?

The experiments addressing these issues proceeded as follows. Experiment 1 manipulated object weight and texture, along with the required manipulatory action, in a highly constrained task (speeded, with grasp and contact-force constraints). Subjects appeared to plan the action during the initiation time, but to defer or fail to consider planning for object parameters. Experiment 2 addressed the same variables, but in an unconstrained environment. Initiation times increased relative to the constrained task, and pre-movement planning for object texture was evidenced as well as for manipulatory action. Experiment 3 examined the effects of texture and action when both varied randomly from trial to trial, placing greater load on the early planning process.

EXPERIMENT 1

Method

Subjects. Thirty-nine right-handed University students participated as part of an optional course requirement. Twenty-four took part with the light dowel, and fifteen with the heavy dowel. An additional eleven subjects were excluded because they could not maintain the required grasp (two subjects in the light group, nine in the heavy); this could potentially bias the heavy condition toward stronger individuals and reduce effects of weight. All subjects had normal vision without glasses. Wearing glasses was not permitted because of potential reflections of the glass lenses onto the Plato spectacle lenses described below.

Stimuli. The stimuli were two wooden dowels, each weighing 127 g, and two steel dowels, each weighing 681 g. Each dowel was 2.9 cm diameter × 15.2 cm long and was mounted to the centre of a 6.4 cm × 6.4 cm wood base. The dowels were painted red. A green slippery coating, consisting of water-soluble lubricating jelly and a few drops of washable green finger-paint, was thinly applied to the entire surface of one wood and one steel dowel. Each coated dowel was recoated immediately following a trial in which it was grasped.

Friction coefficients for the dowels were estimated by having a subject rest the right forearm and hand (cleaned of dirt or oils) on a horizontal platform, palm up with the index and middle fingers extended. The dowel was positioned on its side, perpendicularly across the middle and distal phalanges of the fingers. The base of the dowel did not contact the hand and was suspended over the edge of the platform. The experimenter then slowly tilted the platform until the dowel began to slip across the surface of the fingers. The angle at which the slip occurred was recorded, and the tangent of this slip angle was taken as the friction coefficient. Five observations were taken from each of four participants with each dowel. The average coefficients were as follows: uncoated wooden dowel, .50; coated wooden dowel, .19; uncoated steel dowel, .32; coated steel dowel, .12.

Apparatus and procedure. The apparatus is illustrated in Figure 1. Prior to the start of each trial, the base of one of the two dowels was fitted onto a square with the same dimensions, which had a wood upper surface contacting the dowel's base, bonded to an underside made of plexiglass. Two pegs at opposite corners of the upper surface of the square were aligned with matching holes in the base of the dowel, in order to secure their attachment. The dowel and fitted square were then positioned on the centre of a wooden platform with raised edges that rested on the table, so that there was a distance of 1.9 cm from each edge of the dowel's base to each inner edge of the platform. A plexiglass sheet

Figure 1. The experimental apparatus. The start key is immediately in front of the subject. The dowel is shown as having been lifted from the home platform through the slot for the posting action.

(10.2 cm × 10.2 cm) was centred on the floor of the platform in order to create a slippery interface between the dowel base and the platform. Using a similar technique as for the dowels, the coefficient of friction between the plexiglass square attached to the dowel and the plexiglass sheet on the platform was found to be 0.42 (averaged over heavy and light dowels).

Finally, a black circular disk was suspended directly above the platform. There was a circular slot (7.3 cm in diameter) in the centre of the disk, and a black, light-weight plastic hinged flap covered the slot from the top. The entire assembly (disk + flap) was supported by a spring-loaded adjustable arm mounted to the back edge of the table. This arm, and thus the disk height, was adjusted relative to the height of each subject while seated at the table, so that the disk could be reached at a distance of 80–90% of the total length of the subject's fully extended arm as measured from the shoulder.

To control the onset of visual input and to prevent vision between trials, subjects wore glasses with liquid-crystal shutters (Translucent Technologies). Under computer control, the shutters change from translucent to transparent within 10 ms and return to translucent in 2 ms. Cardboard barriers were placed on the sides and bottom of the lenses to prevent visual cues from those angles. The subject was seated with the sagittal mid-line of the body aligned with the dowel. A start key was located 9.5 cm from the proximal edge of the table, aligned with the subject's sagittal mid-line.

The spectacles were programmed to occlude the subject's vision between trials. While waiting for the start of each trial, each subject was instructed to gently rest the index, middle finger, and thumb of the right hand on the start key. A radio played between trials, to mask any potential auditory cues that could indicate which of the two dowels (uncoated or coated) was being positioned on the platform.

The start of each trial was indicated by the radio being turned off. After a random interval, ranging approximately from 1 to 3 s, the spectacles became transparent so that the subject could see the dowel. Immediately upon seeing the dowel, the subject was to reach out and perform the correct action with it. To prevent premature lift-off from the start key, instructions were to make the entire movement as smooth and as continuous as possible, without hesitation after lift-off or during the course of the movement.

Subjects performed three manipulatory actions, called grasping, lifting, and posting. In all three actions, the following three contraints were introduced. (1) The reach constraint was to reach as quickly as possible without making errors (described later). (2) The grasp constraint was to grasp the vertical centre of the dowel using a side-to-side pinch grasp involving the index, middle finger, and thumb. Subjects were to grasp the dowel so that the fingers and thumb either contacted or wrapped around the sides of the dowel, rather than simply pinching the front and back surfaces of it. (3) The contact force constraint was to contact the dowel with sufficiently low force that its base did not move and hit the surrounding edges of the platform.

During the grasping action, subjects simply had to observe these constraints and grasp the dowel firmly enough so that it could be lifted—even though it was not to be moved physically. The spectacles were programmed to become translucent to prevent vision 3 s after the initial contact of the hand with the dowel, and subjects were required to maintain the grasp until vision was occluded. This requirement was introduced to approximately equate the total time during which the hand was in contact with the dowel across the three actions.

For the lifting action, subjects were required to reach out, grasp the dowel, lift it and place it on the table to the right of the platform, while following each of the general constraints listed earlier. Importantly, the trajectory of the lift was not specified, and thus subjects usually combined the vertical lift and lateral trajectory to place it on the table into one continuous smooth movement.

For the posting action, subjects were to reach out, grasp the dowel, lift it, "post" it through a slot suspended directly above the dowel, and then put it down to the right of the platform on the table. Since the action required only a vertical post-contact movement, and the ratio of slot diameter to dowel diameter was was 2.5:1, the posting movement could presumably be performed ballistically and with minimal if any visual guidance. However, subjects had to maintain post-contact control by keeping the dowel in a vertical orientation and by preventing it from slipping from the hand during posting.

After receiving the instructions for the first action, subjects practised lifting the dowels. They practised the requisite side-to-side grasp with the uncoated dowel three times, then the coated dowel three times. Subjects were initially instructed to use only the distal phalanges of the index and middle fingers. However, because holding the heavy dowel in this way proved difficult, we allowed subjects in the heavy condition to grip with the middle as well as the distal phalanges of the fingers, if the practice grasps showed they could not lift the dowel with the distal phalanges alone. Seven subjects used only the distal phalanges and eight added the middle phalanges.

Dependent measures. The *initiation time* was recorded as the time from when the spectacles switched to a transparent state to the time when the hand was released from the start key. To record the *movement time*, the platform for the dowel rested on a piezoelectric force-sensitive plate. The movement time was the interval between release of the start key and triggering of this plate when the dowel was touched. Errors were of two types: *Base move errors* (the base of the dowel slid and contacted an edge of the platform) and *grasp slip errors* (the dowel slipped from the hand either prior to, during, or after lift-off). All errors were recorded by experimenter observation.

Design. The experiment combined the within-subject factors of surface texture (coated and uncoated) and action (grasping, lifting, and posting), and the between-subjects factor of dowel weight. It lasted approximately 1 h. Each action was performed over a single block of 22–38 trials—as many as permitted in the time allotted for the block (variations in trial N reflected differences across subjects in the time required for instructions and practice lifting, and the time to clean hands after trials with the coated dowel). The order with which each action was performed was counter-balanced across subjects. The texture of the dowel varied randomly within each block, with the constraint that each texture was sampled with approximately equal frequency (with slight departures from equal N due to truncation of blocks). In addition to the texture conditions, 10% of the trials within each block consisted of catch trials in which the dowel was absent, and the subject was instructed not to release the start key. These trials were included to motivate the subjects to wait until they viewed the dowel before initiating movement.

Results

The principal dependent measures were initiation time, movement time, and the two categories of error. Pairwise comparisons between texture and weight levels were performed, where appropriate, as a priori contrasts. Because action effects were not as predicted, we treated comparisons among action levels as post hoc, using a Bonferroni correction with alpha set at 0.05. Figure 2 shows the mean initiation time and movement time across conditions for all experiments, with standard errors of the mean.

To summarize the results, texture and weight affected movement time interactively, but initiation time was affected only by the required action. The coated dowel led to slower movements, particularly when it was heavier. Somewhat surprisingly, the posting action led to the fastest initiation and movement times.

Initiation time. The ANOVA showed only effects of action, $F(2, 74) = 3.94$, $p = .0237$. Post hoc tests revealed that grasping and lifting were significantly slower than posting, but did not differ from each other. The texture effect did not reach significance ($.15 > p > .10$), although the trend was toward a longer initiation time (by 11 ms) for the coated dowel. Also, the effect of weight was not significant ($.15 > p > .10$), although the trend was toward a longer initiation time (by 48 ms) for the heavier dowel.

Movement time. The ANOVA showed effects of action similar to those found in initiation time, $F(2, 74) = 4.86$, $p = .0104$. In contrast to the null effect of texture on initiation time, texture significantly affected movement time, $F(1, 37) = 34.78$, $p < .0001$. Both of these variables interacted with weight: for action by weight, $F(2, 74) = 8.19$, $p = .0006$; for texture by weight, $F(1, 37) = 4.88$, $p = .0334$. The movement time was significantly greater for the coated dowel than the uncoated dowel at both levels of weight, but this difference was enhanced when the dowels were heavy (33 ms for the light object vs 73 ms for the heavy). Conversely, the heavier object led to longer movement time, more so when it was coated (56 ms difference, contrast marginally significant, $p = .0705$) than when it was not (16 ms, non-significant difference). For the heavy objects, the lifting action produced significantly slower reaches than grasping and posting, which did not differ, whereas for the light objects, all means differed significantly, with grasping slowest and posting fastest.

Errors. Figure 3 shows the mean base-move and grasp-slip outcomes for all experiments reported here, along with standard errors of the mean. As all the error data tended to show higher-order interactions as well as main effects, the ANOVAs are summarized in the Appendix. In this and subsequent experiments, errors with the grasping action were low. In the lifting and posting actions, errors were substantial when the dowel was coated; slips rarely

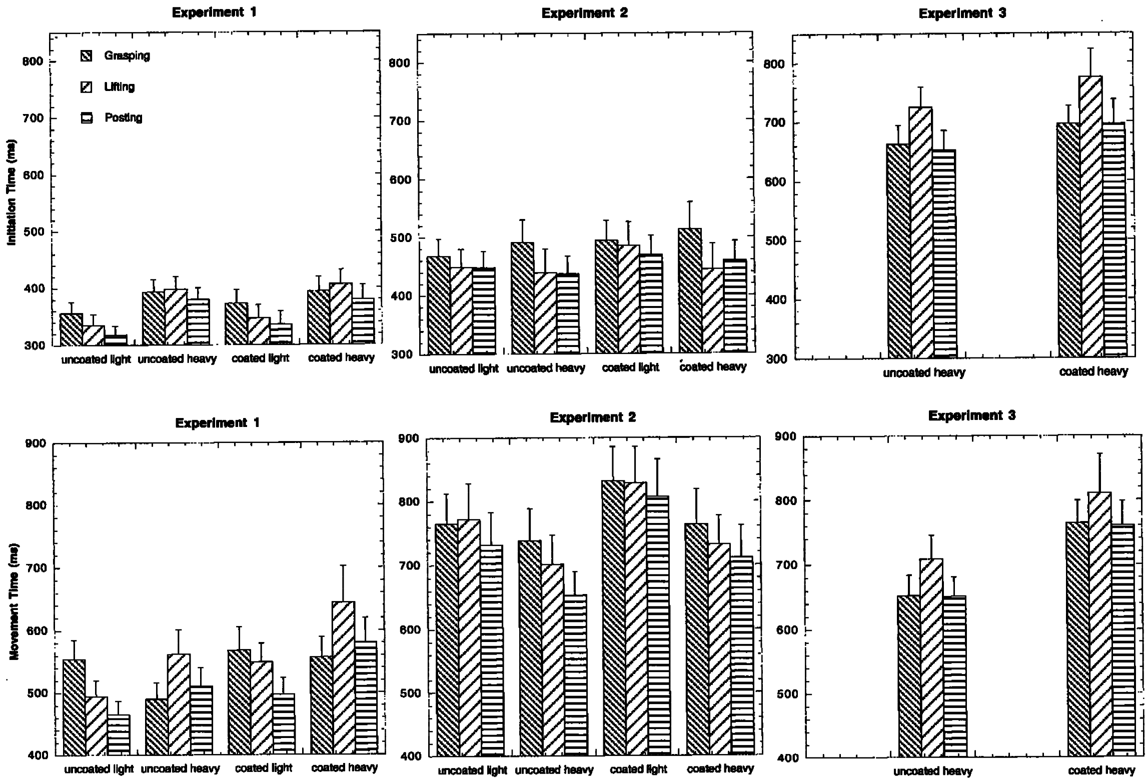

Figure 2. Average initiation time (top row) and movement time (bottom row) for each experiment, by combination of object texture and weight. Bars show standard error of the mean.

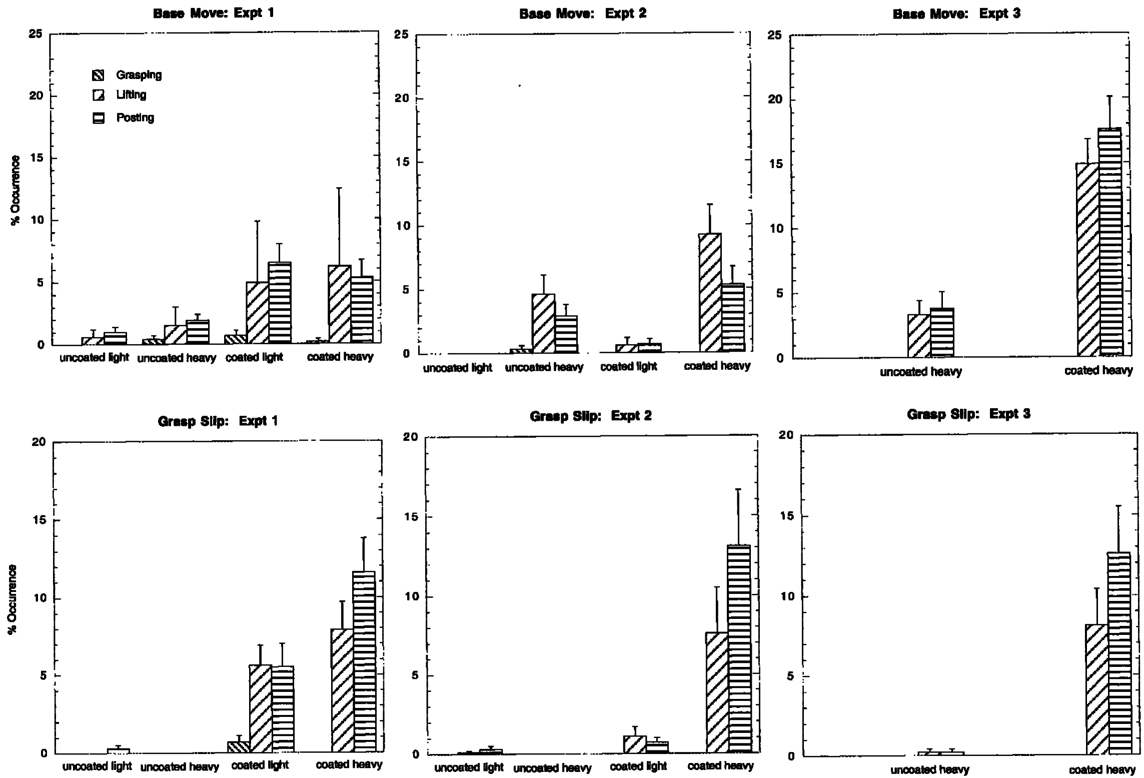

Figure 3. Percentage of trials in each experiment on which base moves (top row) and grasp slips (bottom row) occurred, by combination of object texture and weight. Bars show standard error of the mean.

occurred with the uncoated dowel. In addition, grasp-slip errors, but not base moves, showed an effect of weight. Subjects clearly had difficulty complying fully with the task constraints when the dowels were coated. Grasp slips occurred on a substantial percentage of trials when the coated dowel had to be lifted, principally when it was heavy, but to a lesser extent when it was light.

Discussion

The failure to find effects of texture and weight on initiation time is consistent with previous findings, described in the introduction. The fast initiation and movement times for posting are not what would be expected from movement complexity, and we have no explanation.

A principal finding of this experiment is that texture and weight interacted to affect movement time. The interaction can be understood from the joint effects of these variables on the required grip force. More grip force must be used with a heavier object and with a slippery object. Accordingly, the movement time was slower for the slippery dowel, particularly when it was heavy. Thus the data replicate previous findings indicating that movement time is affected by the force demands of grasping and lifting an object.

The action by weight interaction on movement time is also predicted by the action constraints and their implications for grip force. In the lifting and posting actions, lifting a heavier object requires more grip force, anticipation of which could produce increased movement time. The data show, accordingly, that the heavy dowels led to significantly longer movement times in the lifting and posting action, but not in the grasping action. Since the grasp terminates before the object is lifted, a greater mass could actually be beneficial, if the contact-force constraint (do not move the base upon contact) was easier to satisfy. (However, the trend in this direction was not significant.)

EXPERIMENT 2

The finding that initiation time was unaffected by either weight or texture is consistent with data of Fikes et al. (1994). It suggests that early in its progress, the forward model does not take into account the constraints on action that arise from properties of the object. The model does, however, take into account differences in the actions required, though not as ordered by complexity.

It may be that object-based constraints are not being considered early in planning because task constraints are being given a higher priority. In particular, in Experiment 1 subjects were asked to reach as quickly and as accurately as possible. This instruction may have led subjects to initiate the reach quickly and delay the considerations of object properties until movement onset. Moreover, subjects were required to plan for a somewhat awkward grasp posture and a low terminal force at contact, to avoid sliding the base of the object.

Experiment 2 tested the hypothesis that the consideration of object properties such as texture and weight, which would primarily affect the forces required at lifting, was given a low priority in the context of the multiple pre-lift constraints on performance. The experiment paralleled Experiment 1, but it differed in that the overall task constraints were relaxed: Subjects self-controlled the movement speed, they adopted a more natural, front-to-back grasp, and they were allowed to move the base of the dowel within the frame of the platform. These relaxed constraints may open up the window for subjects to consider action and object properties in the initiation period, anticipating post-contact forces and movement complexity. In support of this prediction, a pilot study with the heavy dowel, in which subjects were told to move at a comfortable rate, showed a significant (61 ms) effect of texture on initiation time, with more rapid initiation for the uncoated dowel.

Method

This experiment was identical to Experiment 1, except that the constraints of reach, grasp, and contact force were relaxed: Subjects were instructed to reach comfortably and naturally rather than as quickly as possible, they were asked to grasp the dowel in a more natural three-finger posture—front-to-back rather than side-to-side, without restriction as to which phalanges contacted the object, and the base of the dowel was allowed to make contact with the inner edges of the platform. Thirty-eight right-handed subjects from the same pool as before participated, twenty-four in a light-dowel group and fourteen in a heavy-dowel group. Four others were excluded by the accuracy constraints described above, and ten others in the heavy condition were excluded because they could not maintain a three-finger grasp, even with the more natural posture allowed; presumably even this posture did not uniformly generate sufficient grip force to counteract the load of the heavy dowel. Again, this could have skewed the pool toward stronger subjects in the heavy condition, but robust weight effects in Experiment 1 indicate this is not critical.

Results

To summarize the findings, the effect of texture now was apparent in both initiation time and movement time. Weight did not affect either temporal measure, but heavier objects produced substantially greater errors.

Initiation time. The effect of action was again significant, $F(2, 2) = 6.02$, $p = .0038$. The grasping time was greater than lifting and posting, which did not differ significantly. More importantly, the effect of texture was now significant, $F(1, 36) = 5.39$, $p = .0260$, with the coated dowel leading to slower responses by an average of 24 ms. The texture by action interaction did not approach significance ($F < 1$). The main effect of weight and the interaction between texture and weight did not approach significance, $p > .90$ and $p > .50$, respectively. The effect of weight was only 1 ms in the uncoated-dowel condition and a non-significant −11 ms (faster initiation for the heavy object) in the coated condition.

Movement time. The effect of action was only marginal ($.10 > p > .05$), although the trend was again for the posting action to be relatively fast. The effect of texture was significant, $F(1, 36) = 18.55$, $p = .0001$. Somewhat surprisingly, no main effect of weight or interactions involving weight approached significance (all ps > .25). Indeed, in direct contrast to Experiment 1, the trend was for the difference between coated and uncoated dowels to be greater for the light dowels (65 ms vs 38 ms), and the heavier dowels led to shorter movement times (by 74 ms overall). However, the error pattern suggests that the failure to take weight into account while reaching led to errors.

Errors. As before, the grasping action showed negligible errors. With the other actions, the heavy dowels led to both more base moves and grasp slips, and the combination of heavy weight and a slippery coating particularly increased errors—grasp slips rarely occurred when the dowels were uncoated or light. Note that base-move outcomes were not errors, strictly speaking, given the relaxation of the contact-force constraint.

Comparison of Experiments 1 and 2. The two experiments were compared in ANOVAs that added the factor of constraint level (Experiment 1: High; Experiment 2: Low) to those of texture, weight, and action. Here we consider only main effects and interactions involving the constraint factor.

The initiation time ANOVA showed a main effect of constraint, $F(1, 73) = 11.94$, $p = .0009$, reflecting the slower times in Experiment 2. There was also an Action × Weight × Constraint interaction, $F(2, 146) = 33.29$, $p = .0402$, which was unexpected given that neither experiment showed any effect involving weight. It appeared to reflect a slightly elevated initiation time in Experiment 2 for the grasp/heavy combination, whether or not the dowel was coated. It is unclear why the grasp should be singled out for slower initiation, since the object need not be lifted.

The movement time analysis again showed a main effect of constraint, $F(1, 73) = 25.30$, $p = .0001$, an Action × Weight × Constraint interaction, $F(2, 146) = 5.33$, $p = .0058$, and a Texture × Weight × Constraint interaction, $F(2, 146) = 5.09$, $p = .0270$. These interactions reflect the fact that Experiment

1 produced interactions between weight and action, and between weight and texture, whereas Experiment 2 did not.

The ANOVA on base move errors produced interactions between constraint and weight, $F(1, 73) = 15.98$, $p = .0002$; constraint and texture, $F(1, 73) = 6.14$, $p = .0156$; and Constraint × Action × Weight, $F(2, 146) = 6.53$, $p = .0019$. The rate of base moves in Experiment 2 was not systematically higher than in Experiment 1, but the pattern differed: There was a drop in base moves with the light, coated dowel, particularly with the lifting and posting actions, but there was an increase in errors with the heavy, coated dowel. The ANOVA on grasp slip errors produced interactions between constraint and weight, $F(1, 73) = 4.27$, $p = .0424$, and Constraint × Weight × Texture, $F(1, 73) = 4.35$, $p = .0405$. Grasp slips with the light, coated dowel appear to have been reduced by replacing the side-to-side grasp of Experiment 1 with a more natural grasp configuration; on the other hand, errors with the coated, heavy dowel increased somewhat.

Discussion

With the greater tolerance for reaching speed, grasping, and contact force in Experiment 2, initiation time reflected the demands on load force imposed by slipperiness. This is in contrast to the null effect of Experiment 1. However, Experiments 1 and 2 agreed with respect to the null effect of weight on initiation time. In another departure from Experiment 1, the movement time in Experiment 2 was unaffected by weight. However, there was apparently a speed/accuracy tradeoff, since errors in the most difficult condition—lifting a coated, heavy dowel—increased. In the absence of a tradeoff, one would expect errors to *decrease* given a more relaxed speed constraint, as was found for the light, coated dowel.

The initial hypothesis for Experiment 2 was that more relaxed constraints might increase the set of variables incorporated into the forward model during the initiation time. Indeed, the finding that texture had an effect here, but not previously, confirms that hypothesis. It is then particularly interesting that weight still remained without a systematic effect (although there was an elevated initiation time for one condition with the heavy dowel). One possible explanation for the difference between texture and weight is that the latter is more perceptually salient. Our between-subject design, which gave subjects experience with only one weight, should have motivated them to consider it, because they could retain a memory trace of the previous trial and did not have to discern weight perceptually. Nonetheless, they largely did not. The null result agrees with others' findings that weight takes effect late in the course of manipulation (see introduction). Below, we consider a more general hypothesis, namely, that perceptual salience influences the stage at which variables are incorporated into the forward model.

EXPERIMENT 3

In Experiments 1 and 2, the actions were not ordered as predicted, in terms of motor complexity, with respect to initiation or movement time. However, the actions were performed in blocks of trials. Thus, after a few trials of practice, subjects may have no longer needed to consider action constraints on a trial-by-trial basis. Fikes et al. (1994) found stronger effects of texture on movement time in a randomized than in a blocked texture condition, supporting the idea that blocking reduces the effects of variables that enter the planning process. Hence, the main goal of this experiment was to investigate whether action-complexity effects would be observed in initiation and/or movement time if subjects were required to consider action parameters with the onset of each trial. Accordingly, action as well as texture was manipulated randomly rather than blocked.

An additional interest was in whether texture and action would interact in their temporal effects. The observed independence of these variables in the first two studies indicates separate planning processes.

Method

Twenty-two right-handed subjects from the same pool as before participated. Another five subjects were excluded from the analyses due to errors, and two were eliminated because they could not maintain a three-finger grasp. The stimuli and procedures were identical to the heavy-dowel condition of Experiment 2, with the exception that both the action and the texture were randomly varied from trial to trial, within the constraint of approximately equal Ns for each level of the variables. In order to vary the action from trial to trial, subjects had a training session prior to the start of the experiment, during which they learned a correspondence between a tone and each action. Subjects listened to a tape of three 500 ms tones (low 250 Hz, middle 650 Hz, and high 1050 Hz). The ascending sequence of tones was presented three times, while the experimenter indicated which action corresponded to each tone. Then the tones were presented four times in random order, and upon hearing each tone, the subject had to verbally indicate which action to perform while simultaneously mimicking that action. The experiment proceeded once the subject had learned the tone/action correspondence, which was counterbalanced across subjects.

The experimental procedure was identical to those of the previous experiments, except that one of the three tones sounded at the same time as the spectacles cleared. At that point, the subject had to decide which action needed to be performed and to assimilate the surface texture of the dowel.

Results and discusion

Experiment 3 is a parallel experiment to the heavy-dowel condition of Experiment 2. Accordingly, we report an ANOVA that treats the Experiment 3 (random) and Experiment 2 (blocked), heavy-dowel data as two levels of a new factor: Action expectancy. Note that ANOVAs on Experiment 3 alone revealed significant effects of action and texture on both initiation and movement time, and no interactions ($Fs < 1$). To summarize the results of the combined analyses, the blocked actions of Experiment 2 led to shorter initiation times than the randomized actions of Experiment 3, but yielded no overall advantage in movement time. Most importantly, the study replicated the finding that texture could affect pre-movement planning time, and the texture effect (32 ms overall) was not significantly altered by action expectancy. Texture also affected movement time, more so with randomized than blocked actions. Although action effects were obtained with respect to both initiation and movement times, the actions were again not ordered as predicted by movement complexity.

Initiation time. There were main effects of action expectancy, $F(1, 34) = 22.05$, $p < .0001$, action, $F(2, 68) = 3.20$, $p = .0469$, and texture, $F(1, 34) = 5.82$, $p = .0213$. There was also an action by action-expectancy interaction, $F(2, 68) = 10.28$, $p < .0001$. No other effects approached significance.

The action-expectancy effect reflects the finding that subjects were 237 ms slower to initiate the movement when the action was not known beforehand. Moreover, the order of action initiation times was quite different between the two conditions. In the blocked condition, as described previously, the grasping action was significantly slower than lifting and posting, which did not differ, whereas in the random condition, the lifting action was slower than grasping and posting, which did not differ. The slowing of the lifting action indicates that in a randomized condition, some aspect of this action requires planning that is not present with the other actions. One possibility is that there is uncertainty from trial to trial as to what constitutes an adequate lift distance. Whereas the target movements in the grasping and place actions are fully constrained (i.e., requiring no movement and movement up to the slot, respectively), the lift can be to an arbitrary height. Possibly, the lift must be replanned from trial to trial when the action is random, and memory for immediately prior movement cannot be relied on.

Movement time. The effects of action and action by action-expectancy interaction were marginal, $.10 > ps > .05$; as with the initiation time, the tendency was for the lifting action to be slowest in the randomized condition. There were significant effects of texture (81 ms overall), $F(1, 34) = 18.46$,

$p < .0001$, and a texture by expectancy interaction, $F(1, 34) = 4.21$, $p = .0479$. Subjects moved more slowly toward the coated dowel, significantly so at both levels of expectancy, but the difference was substantially greater when the action was random than when it was blocked.

Errors. Again, only the lifting and posting actions produced base moves and grasp slips. The pattern was much like that observed with the heavy objects in Experiment 2: Grasp slips were found primarily with the coated objects, and base moves were far more common with the coated dowel than the uncoated. The Appendix shows the ANOVA combining Experiment 3 with the heavy-dowel group of Experiment 2; note that ANOVAS on Experiment 3 alone showed significant effects of texture, action, and the interaction, for both base-move and grasp-slip errors.

GENERAL DISCUSSION

The present studies provide a view of the temporal unfolding of a plan for visually guided action on an object, or in other words, they indicate the construction of a forward model. The studies do so by partitioning the response into pre-movement initiation time, movement time, and post-contact errors. In the introduction, we raised a number of questions in regard to the construction of the model. Addressing those questions in turn, we found: (1) With respect to planning for object attributes, texture, but not weight, was incorporated early into the forward model. Weight appeared to enter the planning process only under the most constrained conditions, and then it affected movement time rather than initiation time. (2) Parameters differentiating the action to be performed on the object were incorporated into the model at the earliest stage, and had less effect later, during the reach. The reverse was true for object parameters. (3) When the task was highly constrained with respect to speed, hand posture, and force, planning for object parameters was reduced, suggesting competition between accommodating general task constraints and planning for object contact. (4) Action complexity and object parameters had independent effects when both were present, suggesting that planning based on the object does not change according to the complexity of the act to be performed. (5) The object parameters were themselves prioritized rather than equated in planning; an effect of texture did not guarantee an effect of weight. (6) Error data indicated that action and object parameters, as well as task constraints, interacted during physical contact and action, and certain combinations of those variables led to substantial levels of error.

We draw these conclusions by examining the effects of the various manipulations on our three dependent measures. Consider first the effects on initiation time. The nature of the action that was demanded after contact—grasping, posting, or lifting—affected initiation time across all studies. However, the ordering among actions was not constant: When actions were blocked, the posting initiation was relatively fast, especially in relation to initiation for grasping, with lifting initiation more variable relative to the others. When actions were randomized, lifting became the slowest action to be initiated, possibly because it is the least constrained with respect to final position of the limbs. In a blocked sequence of lifting trials, subjects may have relied on memory for the previous terminal position to determine the current one, which would not be possible in the randomized condition.

Whereas initiation time was consistently affected by action, it was not invariably affected by object texture. Across the studies, and within each weight category, there was a tendency for the slipperiness of the object to affect initiation time more, the longer the baseline initiation time (i.e., the time for the uncoated object). This pattern is shown in Table 1, along with comparable data for movement time. The slowing of initation time reflected two different causes. Initiation time increased from Experiment 1 to Experiment 2 because the speed constraint was relaxed, whereas it increased from Experiment 2 to Experiment 3 because the action variable was randomized. Notwithstanding these variations in the causal manipulation, the increased allocation for pre-movement planning appears to have allowed the texture of the object to be incorporated into the plan. Moreover, the independence of the texture and action variables on initiation time suggests that the nature of the action that is to be performed does not alter the preparation for the object's surface and weight.

Finally, the task parameter of weight failed to show a systematic effect on initiation time in any experiment. This null effect, in contrast to that of texture, indicates that object attributes enter into the planning process differentially.

Next consider the effects of the experimental manipulations on movement time. The action effect on movement time was relatively strong in Experiment 1, but it weakened and became non-significant in Experiments 2 and 3, when the speed constraint was relaxed. In contrast, texture effects were found in all three experiments. Thus the relative importance of these two variables seems to

TABLE 1
Relation of texture effects (coated minus uncoated dowel) to the baseline initiation time (IT) and movement time (MT) with the uncoated dowel

Dowel	*Uncoated IT (ms)*	*Texture effect IT (ms)*	*% increase IT*	*Uncoated MT (ms)*	*Texture effect MT (ms)*	*% increase MT*
Light:						
Experiment 1	336	16	4.76%	505	33	6.53%
Experiment 2	455	28	6.15%	757	65	8.59%
Heavy:						
Experiment 1	390	3	0.77%	521	73	14.01%
Experiment 2	456	16	3.51%	697	38	5.45%
Experiment 3	680	42	6.18%	671	107	15.95%

have shifted between the initiation and movement periods, action being more consequential prior to movement, and texture being more important after the reach onset. When speed was not imposed as a constraint, subjects appeared to have given sufficient time to pre-planning the actions, that additional planning (at least, differential planning across the three actions) during the movement period was not needed. Those action effects that were obtained in movement time mimicked the trends in initiation time, suggesting that the differential planning demands were carried over to the movement phase, if planning was not completed beforehand. This was most likely in the speeded condition of Experiment 1.

It should also be noted that there is some ambiguity about the effects of action on movement time that were obtained. The pattern of base moves, described later, suggests that the actions of grasping, lifting, or posting may actually have led to differential reaching trajectories. In this case, action effects on movement time could be interpreted as arising during movement execution rather than planning. Kinematic data are needed to settle this issue, which we discuss in a more general context later.

Weight effects on movement time were found only with the most constrained condition: The coated object in Experiment 1, where there were task constraints of speed, side-to-side grasp, and low contact force. In this case, the heavy dowel slowed movement time relative to the light object, for those actions where the dowel had to be lifted. This contrasts with the findings of Weir, MacKenzie, Marteniuk, Cargoe, and Frazer (1991) that there were no weight effects in the free movement phase of reaching. However, that study used lighter dowels and did not have the present constraints. It appears that weight affects movement time only under particularly demanding conditions for action.

Finally, considering the error data, which refer to post-contact effects, there were strong and interactive effects of task and object properties. The general error pattern was to find few errors with the grasping action. With the other actions, grasp slips occurred only with coated objects, and far more when they were heavy. Base moves were found with coated objects in Experiment 1 regardless of weight, whereas in subsequent studies, the pattern was to find base moves with heavy objects, more so when they were coated.

It appears that when the base move was no longer treated as an error (i.e., Experiments 2 and 3), the subjects treated the reach, grasp, and lift more as a unit. They tolerated more contact force with the heavy object, moving it within the frame of the base as they grasped and lifted it. When the heavy object was also slippery, the push would last longer, and be more likely to move the dowel within the frame of the base, before it could be adequately grasped for lifting—as is indicated by the prevalence of grasp slips with coated, heavy dowels.

On the whole, these trends suggest that instructions to grasp, lift, or post are incorporated early into the forward model. Object texture is planned for during the reach, and prior to reach onset only if the action is unspeeded and initiation time is relatively slow. In contrast, the accommodation for weight is largely left to the post-contact phase of the action.

This temporal pattern of planning may reflect the point during action at which the planned-for variable takes effect. That is, planning for a parameter may tend to occur in temporal proximity to the point where the parameter directly affects motor output. The action variable may be assimilated earliest, texture next, and weight last, because the points in the action that they influence unfold in this order. Different actions, for example, lifting versus posting, require different post-contact trajectories. As was noted earlier, these different terminal acts may produce variations in the spatial position of the arm throughout reaching, especially when the action is unitized (i.e., the reach does not come to a stop before the grasp and lift). In contrast, manipulations that increase requirements for force precision—which is one effect of slipperiness—have been shown to slow the late acceleration phase of reaching. The principal effect of weight appears to be to alter the rate of grip force increase only once the object is grasped (Johansson & Westling, 1984). Thus the order in which a variable is incorporated into action appears to recapitulate the order in which it is incorporated into planning.

An alternative influence on the time course of planning is the perceptual salience of the variable that is planned for. In particular, in the present studies (and likely in general), texture was more salient than weight, and it appeared to enter the forward model earlier. Weight was manipulated between subjects in part to compensate for the difficulty of discriminating different levels. Subjects could then rely on memory for the experienced weight level; however, the retrieval of memory information about weight may be slower than the perception of texture from obvious surface cues. It would be useful to conduct experiments in which the perceptual salience of a variable was specifically manipulated, in order to determine its influence on the time course of motor preparation. However, it is worth noting that the required action (grasp, post, or lift) took effect as early as initiation time, whether it was blocked—i.e., retrieved from memory—or randomized—signalled by an arbitrarily associated auditory cue. In neither case would the required action be signalled by a perceptually salient cue, which argues against the idea that perceptual salience is necessary in order for a variable to have an impact early in the preparation process.

In terms of the framework of Wolpert and Ghahramani (2000), the action constraints and object attributes that were manipulated here are enduring contextual variables that alter predictions of the forward dynamic model about the more continuously changing states of the system. They also should alter predictions of the forward sensory model about the sensory consequences of action, for example, the anticipated pressure on the skin from contact with a heavy vs light object or the visual and kinesthetic inputs resulting from pre-shaping the hand for the required grasp. Context alone does not govern movement; ongoing sensory feedback is used to revise the predictive models and adjust performance as the movement unfolds. Nonetheless, context plays a critical role in specifying the predicted states.

Our data indicate how pre-contact initiation and movement time, along with postcontact errors, respond to different levels of a contextual parameter. How are we to interpret these effects? An effect on initiation time can be attributed to the differential demands on planning for the different levels of a variable, for example, longer time to make predictions about a slippery object than an uncoated one. The possibility must be acknowledged that a parameter could be incorporated into the forward models during the initiation period, but fail to have an effect on initiation time, because planning time is constant across the different levels of the parameter. However, we attempted to minimize this possibility, by selecting the different levels of a parameter so that they differed widely in their demands on the eventual manipulatory act and hence should make very different predictions of states within a forward model.

An effect of parameter variation on movement time is more ambiguous, as was noted earlier when discussing the effects of the required action: It could reflect either planning time during the movement or consequences of planning for movement *per se*. For example, a slippery object should slow the movement time not solely because it is slower to plan for, but because its slipperiness means that lower terminal speed is required in order to reduce the force when the object is contacted. When the effect of a variable arises during movement but not initiation time, one can infer that it reflects planning during the movement interval, although alteration of reaching can play a role in the effect as well. When the effect of parameter variation arises exclusively in errors, as occurred for the weight variable in Experiment 2, it suggests that planning was deferred until manipulation itself—with negative consequences.

The present data show that not all contextual variables that ultimately affect a simple action are incorporated into planning prior to movement. They do indicate, however, that the early planning process considerably precedes object contact. The overlapping nature of effects across pre-movement and movement periods suggest that the model unfolds relatively continuously in time, with at least some parameters being incorporated well before motor imperatives assert themselves.

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APPENDIX
F TESTS FOR EFFECTS ON ERRORS WITH $p < .10$, BY EXPERIMENT

	Experiment 1	*Experiment 2*	*Experiment 2 (heavy) vs 3*
Base move effects			
action	$F(2, 74) = 20.97, p < .0001$	$F(2, 72) = 24.33, p < .0001$	$F(2, 68) = 40.45, p \leq .0001$
texture	$F(1, 74) = 29.16, p < .0001$	$F(1, 36) = 10.58, p = .0025$	$F(1, 34) = 30.31, p < .0001$
weight	n.s.	$F(1, 36) = 51.13, p < .0001$	—
action × texture	$F(2, 74) = 9.58, p = .0002$	$F(2, 72) = 3.10, p = .0509$	$F(2, 68) = 13.33, p < .0001$
action × weight	n.s.	$F(2, 72) = 19.97, p < .0001$	—
texture × weight	n.s.	$F(1, 36) = 4.61, p = .0001$	—
action × texture × weight	n.s.	n.s.	—
expectancy	—	—	$F(1, 34) = 6.57, p = .0150$
action × expectancy	—	—	$F(2, 68) = 6.12, p = .0036$
texture × expectancy	—	—	$F(1, 34) = 10.38, p = .0028$
action × text × expectancy	—	—	$F(2, 68) = 4.60, p = .0134$
Grasp slip effects			
action	$F(2, 74) = 19.39, p < .0001$	$F(2, 72) = 14.04, p < .0001$	$F(2, 68) = 20.24, p \leq .0001$
texture	$F(1, 37) = 79.06, p < .0001$	$F(1, 36) = 28.44, p < .0001$	$F(1, 34) = 31.72, p < .0001$
weight	$F(1, 37) = 4.78, p = .0352$	$F(1, 36) = 19.84, p < .0001$	—
action × texture	$F(2, 74) = 18.54, p < .0001$	$F(2, 72) = 12.83, p < .0001$	$F(2, 68) = 19.58, p < .0001$
action × weight	$F(2, 74) = 2.74, p = .0708$	$F(2, 72) = 10.11, p < .0001$	—
texture × weight	$F(1, 37) = 5.26, p = .0275$	$F(1, 36) = 21.60, p < .0001$	—
action × texture × weight	$F(2, 74) = 3.32, p = .0417$	$F(2, 72) = 10.94, p < .0001$	—
expectancy	—	—	n.s.
action × expectancy	—	—	n.s.
texture × expectancy	—	—	n.s.
action × text × expectancy	—	—	n.s.