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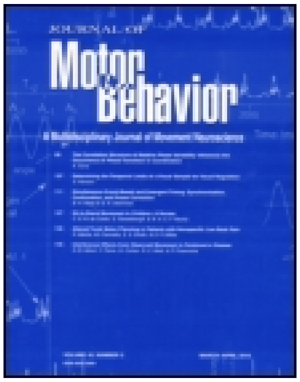

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Variations of Tool and Task Characteristics Reveal That Tool-Use Postures Are Anticipated

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Variations of Tool and Task Characteristics Reveal That Tool-Use Postures Are Anticipated

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ABSTRACT. The authors examined anticipation in tool use, focusing on tool length and tool-use posture. Adults (9 women and 9 men in each experiment) held a rod (length 0.4–0.8 m), with the tip upward; walked toward a cube; chose a place to stop; and displaced the cube with the rod's tip. In 2 experiments, rod length, mass, and mass distribution, and the size of the cube were manipulated. Chosen distance depended on rod length and cube size. Because effects of cube size on distance resulted only from postural changes related to required control, distance anticipated displacement posture. A postural synergy comprising legs and trunk provided a stable platform for the displacement. An arm synergy was less extended for small cubes, longer rods, and handle-weighted rods. Selected distance anticipated those postures.

Key words: anticipation, movement control, postural synergies, precision requirements, tool use

For an act to be coordinated, various details of its execution must be anticipated. For instance, one must open a hand in time and to the right size to grasp an object. Anticipation is also required in tool use, and it is anticipation in tool use that is the topic in this article. Not only must tools be grasped appropriately for the to-be-performed action, various aspects of the unfolding act must also be anticipated. For instance, using a long rod to displace an object requires one to select a larger distance to the object than would be required if a short rod was used. The nature of the task may also put demands on anticipation; using a rod for displacing a small object may require a different action than would be needed for displacing a large object. In two experiments, we examined how participants used a rod to reach for and displace an object, and we measured whether they anticipated the properties of the rod and the accuracy demands. We manipulated rod length, rod mass, mass distribution, and the size of the cube that was displaced.

In our approach (e.g., Bongers, Smitsman, & Michaels, 2003, in press; Smitsman & Bongers, 2003), we concentrated on action aspects in tool use, in contrast with the focus in most studies of tool use, which was on cognitive processes (Bates, Carlson-Luden, & Bretherton, 1980; Brown, 1990; Connolly & Galgleish, 1989; Kohler, 1925; McCarty, Clifton, & Collard, 1999). In the latter studies, the investigators assumed that tool use manifests a certain degree of cognitive complexity, in that it is an indirect means of goal attainment. From that viewpoint, aspects related to the control and coordination of actions with tools have generally been neglected. In the current study, we focused on how actions with tools are controlled; that is, we examined whether tooling actions anticipate characteristics of tool and task. If the effects of tool and task on an action are anticipated, then action characteristics affect the planning of actions with tools. Such a finding would strengthen the view that a full understanding of tool use entails action characteristics and not just cognitive processes.

How do we study anticipation in tool use? As in our earlier study (Bongers, et al., 2003), participants approached an object while carrying a rod pointing upward; they stopped, lowered the rod, and displaced the object with the rod's tip. We measured the selected distance and the posture at the start of the displacement. Ideally, the distance that is selected should accommodate not only the rod's length but also the posture that is required to control the rod during the displacement. For instance, a very heavy rod might require one to lean back to maintain balance, so one should select a shorter distance to the object in that situation than if the posture is more upright. Selected distance is

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the dependent variable by which we assessed anticipation: The distance that is chosen with the rod pointing upward should provide room for the posture with which the object will be displaced. By manipulating geometrical (i.e., rod length) and postural aspects, we attempted to determine which aspects are reflected in the chosen distance and, thus, are anticipated.

In our earlier work, in which we varied only properties of the rod, we showed that participants' choices of distance and arm posture did indeed vary as a function of both geometric and kinetic properties of the rod (Bongers et al., 2003). Most of the variances in distance and posture were attributable to rod length; a larger distance was selected with longer rods. The mass of the rod also affected distance: First, a smaller distance was selected with heavier rods than with lighter rods. Second, a larger distance was selected for rods weighted at the tip than for rods weighted at the handle.

To extend our earlier findings, we varied not only rod kinetics (i.e., mass and mass distribution) but also task requirements in the current experiments. To manipulate task requirements, we changed the needed precision at the rod's tip by varying the size of the cube that had to be displaced. An examination of the effects of precision constraints should help us find the variables relevant to the guidance of actions in which tools are used, in two ways. First, and most important, manipulation of accuracy demands offers a special window into anticipation that is not offered by manipulation of rod properties. It is possible that manipulation of rod properties directly affects the distance the individual chooses and that posture then has to bridge the remaining gap. For example, a rod perceived to be longer than it is might lead one to select a distance too far from the object; the posture would then have to compensate for the extra distance. The combinations of postural changes and distance adaptations in response to manipulations of rod characteristics will always be ambiguous; however, that is not the case for manipulations of precision requirements. In any observed changes in distance, postures must be anticipated, because nothing else differs other than the posture required to control the rod. Hence, the effect of cube size on distance can be regarded as a test case for whether upcoming postures are anticipated. Second, pitting the effects of rod properties against the effects of accuracy constraints might enable us to reveal the range of variables relevant in anticipating actions with tools. For instance, if not much accuracy at the tip is required, then there is no need to control the rod dexterously, implying that there is no need for the posture to counteract the rod's kinetics—the forces and torques it creates—in a systematic way. However, when a precise action is required, one needs to control the tip of the rod with dexterity. Examining how rod properties affect actions when accuracy demands are high might reveal the set of variables that are anticipated in tool use.

We hypothesized that distance anticipates the posture required to control the rod during displacement. In what ways might posture be affected by our independent variables? First, we assume that there is some kind of functional organization of posture. The results of previous research have suggested that joint–muscle systems are coordinated into synergies so that similar tasks can be performed. The concept of synergy, as currently understood, is that muscles can cooperate in a flexible way, depending on task conditions (cf. Bernstein, 1967; Hepp-Reymond, Huesler, & Maier, 1996; Kelso, 1995)—as opposed to Sherrington's (1906/1947) original suggestion that reflexes are laid down in the spinal cord. The notion of flexible synergies is particularly suited to an understanding of how the action system deals with the large variety of tools that are handled in everyday life. Thus, in our study, we had a corollary interest in the synergies that underlie reaching with rods.

Researchers who have focused on postural adjustments during reaching and grasping without a tool have postulated two postural synergies: (a) one synergy coordinating the relation between trunk and arm, in which trunk movement is functionally separate from the hand action; and (b) a synergy in the arm, which brings the hand to the target (Ma & Feldman, 1995; Wang & Stelmach, 1998). It appears that those two synergies also underlie reaching with a tool (Bongers et al., 2003). We were especially interested in the functionality of the two synergies for tool use. For instance, one of the synergies may be important in counteracting the forces created by the rod, whereas the other synergy may provide stability when precision demands are higher (cf. Kaminiski, Bock, & Gentile, 1995; cf. Martin, Teasdale, Simoneau, Corbeil, & Bourdin, 2000, cf. Saling, Stelmach, Mescheriakov, & Berger, 1996). For the present study, it is particularly relevant that a given synergy provides a *postural length*. By that term, we mean that the arrangement of joint angles results in a certain distance. For instance, one can reach objects farther away when the elbow is extended than when one flexes the elbow. Therefore, we addressed our goal of determining whether posture is anticipated by ascertaining whether postural length is anticipated in the selected foot distance.

To summarize, in the present study we examined how geometric and kinetic properties of the body + rod system and a task property (needed precision, operationalized as the size of a to-be-displaced object) affected distance and posture in our displacement task. We aimed to reveal whether tool-use postures were anticipated in the distance.

EXPERIMENT 1

Participants had to approach a cube while holding a rod pointing upward. They selected a distance to the cube, lowered the rod's tip, and displaced the cube sideward. In this experiment, we varied the rod's length, its homogeneous mass, and cube size. Obviously, we expected an effect of rod length; a larger distance should be selected with longer rods. However, our more important expectation was that changes in distances should also reflect changes in posture that follow from the synergistic organization of arm and trunk. Those synergies, in turn, should also depend on kinetics of the rod and, thus, on homogeneous mass. Kinetic variables that might be relevant to the posture are the torque created by the rod and how easily the rod can be wielded. As to the torque, longer and heavier rods produce more torque in the joints and, thus, would require a posture that could counteract large torques. Wieldability of a rod depends on its resistance to rotational acceleration. A held rod rotates around axes through some joint (e.g., the wrist), and the resistance to rotational acceleration depends not only on the rod's constituent masses but also on how far they are from the axis of rotation. A rod's moment of inertia is the sum of all of its masses multiplied by their squared distances from the axis. Rods with less rotational inertia might be noisier—show more movement—at the tip because small variations in muscle-produced torque would yield a bigger effect. Lighter rods have less rotational inertia and thus would be noisier than heavier rods. The noisiness would be particularly important when accuracy is needed. Therefore, changes in behavior that have the same direction for small cubes and lighter rods would favor the noisiness hypothesis. Hence, we expected the manipulation of cube size to be helpful in revealing the variables determining the behavior.

Method

Participants

Participants (9 women and 9 men) ranged in age from 22 to 39 years. All participants were right-handed and either volunteered to participate in partial fulfillment of a course requirement or were paid a fee for their participation.

Apparatus

We used 25 rods, five mass densities by five lengths: 0.4–0.8 m, in 0.1-m steps. The rods were made of aluminum tubing (outer diameter = 2.2 cm, inner diameter = 1.9 cm). To manipulate the mass of the rods, we inserted steel rods into the tubing; the rods differed in diameter, and their lengths corresponded to the aluminum tubing. The inner steel rods were kept in place with small plastic discs. We constructed five rod types for each of the five lengths: In each type of rod, the inner rod had a diameter of 0.2, 0.4, 0.6, 0.8, or 1.0 cm. A handle was added to each rod, extending the tubing and steel by 11.5 cm. A small disc separated the handle from the rod.

The mass of the rods ranged from 104 g for the shortest rod with the smallest diameter of inserted steel to 724 g for the longest and heaviest rod. The static moment ranged from 0.264 Nm to 3.247 Nm, and moment of inertia ranged from 0.0096 kgm^2 to 0.2045 kgm^2.

The to-be-displaced object was a cube that could be slid along a slot in a small panel. The slot was adjusted to the participant's wrist height as measured with the arm at the side. Behind the slot was a carriage to which a small cube (of 1.5 cm) or a large cube (of 5.5 cm) could be attached. A hanging weight of 87 g resisted the movement of the cube with a force of approximately 0.04 N. The back of the cubes just touched the panel; that placement ensured that participants used the tip of the rod to displace the cube.

Procedure

The rods stood in a rack about 3 m from the target. The participants grasped the rod designated by the experimenter and, with the rod at an angle of about 45° upward from the horizontal, walked toward the stand (see Bongers et al., 2003, Figure 1, for a pictorial depiction of the task—note that the stand in that experiment differed from the one used in the current experiment). The participants' task was to stop at a place from which they could displace the cube

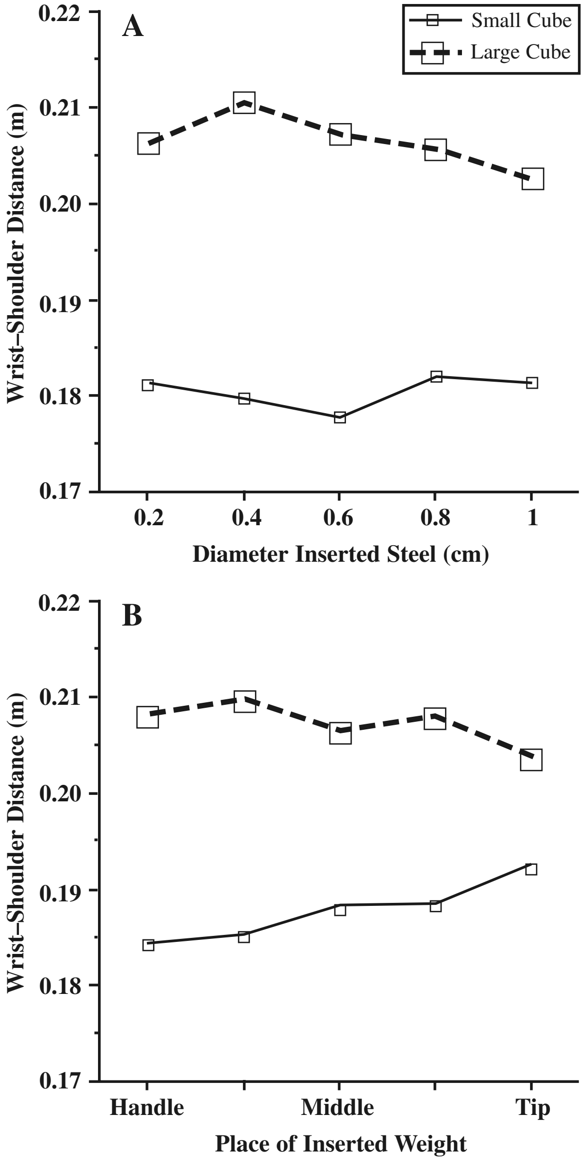

FIGURE 1. The interaction between cube size and rod type on wrist–shoulder distance for (**A**) Experiment 1 and (**B**) Experiment 2.

most comfortably; they then displaced the cube approximately 14 cm to the left with the tip of a rod (the cube returned automatically to its original position because of the weight). We videotaped the approach, reach, and displacement. We used a video digitizing system to determine the positions of the handle and the tip of the rod and various anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, and wrist) in a two-dimensional plane at the moment the displacement of the object started. We measured foot distance as the distance between the stand and the foot nearer to the stand.[1] We computed postural angles from the positions of the joints.

Design

Each participant was tested in one session. There were 50 conditions: 25 rods (i.e., five rod types and five rod lengths) and two cubes that had to be displaced. Each cube was tested in four successive blocks consisting of 25 trials, one for each rod, presented in random order. That gave a total of 200 trials for each participant. For each cube, the first block was considered as practice and was not further analyzed.[2] The order of cube sizes was balanced over participants.

Results and Discussion

We begin this section by examining the selected distance, which, we hypothesized, would reflect anticipation. We then turn to the extent to which joint angles are organized in synergies and how posture depends on tool and task characteristics, respectively.

Foot Distance

Recall that participants selected the distance while they held the rod pointing upward, whereas they displaced the object while holding the rod horizontal—distance indicated whether postural aspects were anticipated. We analyzed foot distance by means of a three-way multivariate analysis of variance (ANOVA), with cube size (small [1.5 cm] and large [5.5 cm]), rod type (steel, diameter of 0.2, 0.4, 0.6, 0.8, and 1.0 cm), and rod length (0.4, 0.5, 0.6, 0.7, and 0.8 m) as within-participant factors. The analyses were performed on the averages for each participant over the three repetitions. To increase the power of the tests, we did not look at the omnibus test but only at the linear and quadratic contrasts.[3]

Participants chose to stop 5 cm closer to the stand when the cube was smaller (0.780 m vs. 0.831 m), $F(1, 17) = 39.36$, $p < .001$. Rod length, as expected, also showed a significant effect, $F(1, 17) = 1{,}091.09$, $p < .001$; participants selected a larger distance from the stand when they were to reach with longer rods (see Table 1). The linear contrast of rod type was marginally significant, $F(1, 17) = 4.15$, $p < .06$; the means showed that participants tended to select a larger distance to the stand when they held more massive rods (0.2-cm rod, 0.903-m distance [*SD* = 0.153 m]; 0.4-cm rod, 0.904-m distance [*SD* = 0.151 m]; 0.6-cm rod, 0.904-m distance [*SD* = 0.152 m]; 0.8-cm rod, 0.908-m distance [*SD* = 0.147 m]; and 1.0-cm rod, 0.908-m distance [*SD* = 0.152 m]). None of the interaction effects were significant.

First and foremost, the 5-cm effect that cube size had on the selected distance led us to believe that accuracy constraints prospectively affected the action. Arguably, the need for precision could affect only the posture with which the object is displaced; cube size has no effect on the information about length of the rod. Therefore, an effect of cube size on distance seems to demonstrate that the upcoming posture is anticipated in the chosen distance.

Not only postural aspects were anticipated, however, because distance was also well accommodated to length of the rod, indicating that participants stopped at a place that left room for the rod to be lowered. To determine the nature of the relation between stopping distance and rod length, we regressed foot distance on rod length. The results—foot distance = 0.38 + 0.87 × rod length, $F(1, 2698) = 5{,}459$, $p < .001$, $r^2 = .67$—showed that length explained the majority of the variance in the selected distance.

What can we learn from the direction of the effects? Displacing a smaller cube implies more dexterous control of the rod than does displacing a large cube. Remember that, according to the noisiness hypothesis—small muscle-produced torque has more effect on lighter rods than on heavier rods—lighter rods also require relatively more control. We found that for a smaller cube and a rod with less mass, a smaller distance was selected, implying that

TABLE 1. Means and Standard Deviations for the Rod Length Effects of Experiment 1

Rod length (m)	Foot distance (m)		Wrist–shoulder distance (m)		Shoulder–ankle distance (m)	
	M	*SD*	*M*	*SD*	*M*	*SD*
0.4	0.729	0.087	0.202	0.065	0.120	0.038
0.5	0.820	0.088	0.201	0.066	0.113	0.038
0.6	0.905	0.087	0.195	0.067	0.107	0.035
0.7	0.995	0.086	0.189	0.068	0.104	0.035
0.8	1.078	0.086	0.180	0.068	0.097	0.035

the smaller distance is selected when more control of the rod is required. That conclusion was corroborated by the effect of length, which showed that a relatively shorter distance was selected with longer rods—the slope of the regression line was less than one, suggesting that longer rods require more control. That increased control for longer rods could follow from the fact that a small movement at the wrist results in a larger movement at the rod's tip when the rod is long than when it is short. Hence, more control, and thus a relatively shorter distance, is required for longer rods.

In sum, a closer distance to the object is selected when more control of the rod is required, implying that selected distance anticipates not only the length of the rod but also the posture with which one must control the rod during displacements. We turn now to the postural basis that underlies those prospective changes in the distance.

Postural Synergies

Our first step was to determine the way the posture was organized. On the basis of earlier research, we believe that the limb segments are linked into synergies so that functional units that can perform a task are formed. Hence, we set out by establishing whether such functional units were also used in the present task.

Ideally, to examine whether the posture is organized into synergies, one should analyze electromyographs of active muscles (cf. Hepp-Reymond et al., 1996) or cross-correlations of kinematic patterns over different joints (cf. Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; e.g., Newell & Van Emmerik, 1989). Because we had joint-angle data only at the moment of displacement, however, we concentrated on how different postural angles covaried over trials in our examination of whether postural synergies were underlying the current tooling behavior. We reasoned that if a stable synergy was underlying the postural organization, a gradual change in one postural angle would be paralleled by a gradual change in another postural angle involved in that synergy. If the postural angles covary over trials, it is reasonable to conclude that those postural angles are linked in the same synergy. Two assumptions were important to our reasoning: We assumed that (a) the same synergies are used over trials and (b) postural measures at one moment in the trial are representative of kinematic joint patterns. In short, to determine whether the posture was organized into synergies, we measured whether postural angles covaried over trials by performing regression analyses on the angles.

We expected the posture to be organized in two synergies: one synergy organizing the arm and the other organizing the trunk and legs (Ma & Feldman, 1995; Wang & Stelmach, 1998). To examine whether there was a synergy in the arm, we analyzed the relationship between shoulder angle and elbow angle. A regression analysis on all the raw data showed a strong relationship between those two angles: shoulder angle = 0.76 × elbow angle – 96.69, $F(1, 2698) = 5{,}443$, $p < .001$, $r^2 = .67$. That finding suggested that the joints in the arm were indeed organized as a synergy. The slope of the regression line showed that the shoulder was more anteflexed (i.e., upper arm put forward) when the elbow was more stretched.

To evaluate whether the adjustments in the arm were related to organization of the trunk and leg, we regressed hip angle on shoulder and elbow angles. The analysis showed that the changes in the hip angle were only weakly related to the changes in the arm posture: hip angle = 5.40 – 0.05 × elbow angle + 0.25 × shoulder angle, $F(2, 2697) = 308$, $p < .001$, $R^2 = .19$.

To determine whether the trunk and leg were organized as a synergy, we performed a regression analysis with hip angle as the dependent variable and with ankle angle and knee angle as independent variables. The overall regression analysis—hip angle = 179.15 – 1.90 × ankle angle – 1.45 × knee angle, $F(2, 2697) = 2{,}532$, $p < .001$, $R^2 = .65$—showed a relatively strong relation between those angles. The analyses showed that the trunk was bent more forward when the knee was extended and the shank was more upright; that is, the trunk was bent forward when the leg was more extended.

In short, separate synergies were formed in the trunk–leg and in the arm. Those postural synergies should be the basis for the changes in posture that are anticipated in the distance. In the next section, we examine how the lengths that the postural synergies provide depend on the independent variables.

Postural Distances

Regarding the posture, our concern was not so much with the changes in the angles per se but with how different experimental manipulations affected the lengths produced by different synergies. The length of a synergy results from the combination of joint angles making up the synergy; for example, the shoulder–elbow synergy produces a horizontal arm length. As we noted earlier, only when synergy lengths are anticipated can the displacement be performed with an optimal posture—foot distance should accommodate both rod length and synergy length.

We defined the lengths produced by the arm and body synergies as the horizontal distances between the extreme joints of each synergy. We used the horizontal distance because the selected distance to the stand could vary only in the horizontal direction. The wrist–shoulder distance, which reflects contributions of the arm synergy, is larger when the arm is more extended. The shoulder–ankle distance, which reflects the body synergy, is positive when the shoulder is in front of the ankle; so larger positive values represent the body's leaning more forward. To examine whether and how the posture was adapted to our manipulations, we analyzed the wrist–shoulder distance and the shoulder–ankle distance in separate three-way multivariate ANOVAs with cube size, rod type, and rod length as within-participant variables. The analyses were performed on the averages over three trials. Again, we looked only at the linear and quadratic contrasts.

The wrist–shoulder distance was smaller for the small cube than for the large cube (0.180 m vs. 0.206 m), $F(1, 17) = 14.90$, $p = .001$. The linear contrast of rod length was significant, $F(1, 17) = 9.00$, $p < .01$, showing that the wrist–shoulder distance was shorter for longer rods (see Table 1). In addition, one interaction was significant: Cube Size × Rod Type, $F(1, 17) = 4.51$, $p = .05$, which showed that the wrist–shoulder distance was relatively constant over rod weights for the small cube, whereas that distance tended to decrease over weight for the large cubes (see Figure 1A).

Did the significant effects on wrist–shoulder distance yield a consistent picture with respect to accuracy demands? Accuracy demands associated with the small cube decreased the arm extension, suggesting that a smaller wrist–shoulder distance is more dexterous. Longer rods had an effect in the same direction and of approximately the same magnitude (2 cm): the longer the rod, the smaller the wrist–shoulder distance. Even though both of those effects imply better control with a shorter arm, the small effect of rod mass, which was seen only for the large cubes, was the opposite: Heavy rods yielded a shorter arm distance. A dexterity interpretation of shorter arm distance would lead to the expectation of a shorter arm distance when noisier (i.e., lighter) rods are used.

The shoulder–ankle distance depended, linearly, on the length of the rod, $F(1, 17) = 20.98$, $p < .001$. The means showed that that distance was smaller for longer rods (see Table 1). None of the other effects were significant. The relatively upright body posture seen with longer rods likely stems from a compensation in the displacement of the center of mass (CM) of the body + rod system. As the CM of the rod is displaced farther outward (as happens with longer rods), the displacement of the CM of the body + rod system becomes greater. The postural adaptation in the body might reflect a compensation for that shift. Note that adjustments of the legs and trunk have a larger effect on the shift in CM than do adjustments of the arm. An upright body posture such as that has also been found when individuals lift the arm to a horizontal position in front of the shoulder (cf. Massion, 1992; Van der Fits, Klip, Eykern, & Hadders-Algra, 1999). The fact that the body compensates would be in agreement with the claim that the body synergy provides for a stable platform on the basis of which the arm can be controlled (cf. Kaminiski et al., 1995).[4] Note that the body synergy was not affected by either cube size or rod mass; hence, our findings are not in agreement with the claim that the trunk participates in the focal movement, as has sometimes been found in other tasks (cf. Martin et al., 2000).

In sum, the body synergy was adapted only to rod length, whereas the synergy in the arm was affected by length, mass, and cube size. In other words, body posture depends on length in the body + rod system, whereas the arm also depends on kinetics of that system as well as on precision requirements.

Conclusion

The effect of cube size on foot distance showed clearly that posture was anticipated in the distance: Changes in distance as a function of cube size could follow only from the posture with which the object has to be displaced. When a smaller cube had to be displaced, a smaller distance to the cube was selected; in that condition, more control of the rod was required and the arm distance was smaller. The effects of rod length corroborated that finding; the changes in distance and posture were also in agreement under variations of length. The effect of both cube size and rod length showed that under conditions in which more control of the rod was required—small cube and long rod—a posture with a smaller arm distance was anticipated in the foot distance. However, the anticipation was not found when rod mass was manipulated. Rod mass did have the hypothesized effect, albeit statistically marginal, on distance—a shorter distance when more control was required—but because rod mass had an opposite effect on posture, there can be no appeal to (postural) anticipation in that case.

The findings with respect to length and cube size could be explained in terms of required control, which, we hypothesized, is related to how easily the rod could be wielded. However, the effect of mass on posture hints at minimization of the torque in the arm. Before we further address the underlying basis of that finding, we present an experiment in which we changed the mass distribution of the rods. Variations of mass distribution change the dynamics of the body + rod system in slightly different ways than does variation in homogeneous mass. Varying mass distribution increases the range in which the rotational inertia (i.e., the wieldability) and the torque of the rod can be manipulated. We expected that manipulations of mass distributions would provide further insight into how the adaptations in foot distance and posture were related.

EXPERIMENT 2

The results of Experiment 1 showed that foot distance and posture both depended strongly on cube size and rod length. Rod mass had some minor effects, but its effects on posture and foot distance conflicted. We had expected that mass would have stronger effects on posture, either because of differences in the loads that had to be borne or because of the differences in wieldability. In Experiment 2, we attempted to exaggerate the differences in loads (torques) and wieldability by inserting lead weights at different places in the rods, thereby changing their mass distributions. Note that rods with mass at the tip would affect behavior in the same way as our heavier rods, because both produce relatively larger torques and have more resistance to rotational acceleration. However, the varying of mass distribution enabled us to extend the range of the rotational inertia of the rods (and concomitantly improve the stability of the tip) while keeping the torque range similar to that used in Experiment 1. Disentangling the effects of torque and wieldability may help reveal the basis of the postural changes. Moreover, increasing the range of rotational inertia allowed us to examine the relation between stability of the rod's tip and the precision requirements in more detail.

Method

The setup used in this experiment was similar to the setup of Experiment 1. The experiments differed only in the participants and in the types of rods that were used. Participants (9 women and 9 men) ranged in age from 20 to 26 years. The rods used in this experiment had the same range of lengths as those used in Experiment 1. To manipulate the mass distribution, we inserted a lead cylinder (diameter = 1.9 cm, length = 10 cm, with a mass of 345 g) inside the tube. For each of the five lengths, we constructed five rod types by inserting a weight at one of five evenly distributed rod positions from (just distal to) the handle to the tip. The mass of the rods ranged from 448 g to 520 g, the static moment ranged from 0.809 Nm for the shortest rod with weight near the handle to 3.757 Nm for the longest rod with weight at the tip. Moments of inertia ranged from 0.0197 kgm^2 to 0.3145 kgm^2.

Results and Discussion

As in Experiment 1, we first examine the distance that participants selected. Then we address the synergies into which the posture was organized and the lengths provided for by the synergies.

Foot Distance

We analyzed the foot distance by means of a three-way multivariate ANOVA with cube size (small and large), rod type (five levels, from weight inserted near the handle, Place 1, to weight inserted at the tip, Place 5), and rod length (0.4, 0.5, 0.6, 0.7, and 0.8 m) as within-participant variables. The analyses were performed on the averages for each participant for each condition. Again, to increase the power, we looked only at the linear and quadratic contrasts.

Participants selected a considerably smaller distance to the stand with the small cube than they did with the large cube (0.796 m vs. 0.833 m), $F(1, 17) = 18.61$, $p < .001$. As usual, the linear trend of rod length was significant, $F(1, 17) = 852.33$, $p < .001$, showing that participants selected larger distances to the stand when using longer rods (see Table 2). The linear trend of rod type was significant, $F(1, 17) = 12.65$, $p < .005$. As the means in Table 2 show, participants selected a larger distance to the stand when the weight was placed at the tip than when it was placed at the handle.

Two interaction effects were significant. The first, we argue, is one of the most important effects in this study: The interaction between cube size and the linear trend of rod type, $F(1, 17) = 12.65$, $p < .005$, indicated that for the large cube, participants selected roughly the same distance to the stand for all rod types; for the small cube, however, the distance to the stand tended to be larger for rods weighted at the tip (see Figure 2). Second, the interaction between the quadratic trends of rod type and rod length was significant, $F(1, 17) = 10.64$, $p = .005$. That significant effect seemed to result from a single condition—the longest rod with weight at the tip, in which the foot distance was slightly larger than it was with other rod types.

Those results confirmed a key finding of Experiment 1: A shorter distance to the stand was selected with a smaller cube. Again we argue that changes in foot distance as a function of cube size could be a result only of upcoming postures that are anticipated. Thus, our finding of anticipation was bolstered in this experiment. Furthermore, in the present experiment, the combined effect of a rod with weight at the handle and a small cube size led to an especially short distance. We had expected rods weighted at the handle to be noisier at the tip than rods weighted at the tip. Thus, in the condition in which the task required most control of the rod

TABLE 2. Means and Standard Deviations for the Rod Length Effects of Experiment 2

	Foot distance (m)		Wrist–shoulder distance (m)		Shoulder–ankle distance (m)	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*
Rod length (m)						
0.4	0.729	0.081	0.202	0.057	0.115	0.047
0.5	0.830	0.079	0.205	0.056	0.115	0.044
0.6	0.915	0.084	0.199	0.064	0.108	0.043
0.7	1.004	0.092	0.193	0.067	0.104	0.044
0.8	1.095	0.095	0.188	0.069	0.104	0.042
Rod type						
Place 1 (handle)	0.910	0.154			0.108	0.044
Place 2	0.912	0.154			0.108	0.044
Place 3	0.913	0.155			0.108	0.043
Place 4	0.917	0.155			0.109	0.044
Place 5 (tip)	0.921	0.156			0.112	0.045

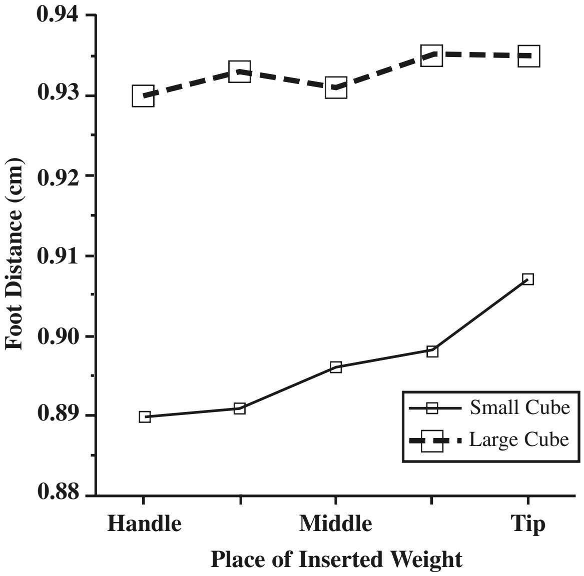

FIGURE 2. The interaction between cube size and rod type on foot distance for Experiment 2.

(i.e., small cube size), and when the noisiest rod was used (i.e., weight at the handle), participants selected the shortest distance. That finding indicates that the upcoming posture—as affected by both mass distribution and cube size—was anticipated in the distance.

That conclusion was strengthened by the effect of rod length. As expected, rod length explained most of the variance in the distance. We computed the regression line for the raw data pooled over participants and found the following: Foot distance = 0.37 + 0.91 × rod length, $F(1, 2698) = 5{,}943$, $p < .001$, $r^2 = .69$, which was comparable to the regression line in Experiment 1 (which showed a slope of 0.87 and an r^2 of .67). The slope of the regression line showed that a relatively shorter distance was selected for longer rods; that is, with rods that require more control, a relatively smaller distance is selected.

In sum, foot distance depended on length, mass distribution, and cube size. With a smaller cube and rods weighted at the handle, participants selected a shorter distance. All in all, those effects indicated that closer distances were selected when better control was required; hence, changes in posture are anticipated in the distance.

Postural Synergies

In Experiment 1, we found two postural synergies. One—the body synergy comprising the ankle, knee, and hip—provided a stable platform. The shoulder and elbow formed the other synergy. To determine whether the posture was organized according to similar synergies in Experiment 2, we again performed regression analyses between the various angles.

A regression analysis on all the raw data showed a relationship between the shoulder and elbow angles: shoulder angle = 0.85 × elbow angle – 109.71, $F(1, 2698) = 3{,}906.66$, $p < .001$, $r^2 = .59$. That finding again suggested that the joints in the arm were indeed organized as a synergy: The shoulder was more anteflexed when the elbow was more extended.

To reveal whether the hip was part of a body synergy, we examined hip, knee, and ankle angles. We found a moderate correspondence among those angles: hip angle = 157.49 – 1.67 × ankle angle – 1.48 × knee angle, $F(1, 2698) = 1{,}564.64$, $p < .001$, $R^2 = .54$. Body posture was organized as a synergy: The hip bent more forward when the knee extended more and the shank was more upright.

Overall, the analyses on the postural synergies suggested that separate synergies were formed in the body and in the arm. Although the synergy in the arm was not as stable as it was in Experiment 1, we conclude that the discovered synergies were the same as we had found there. To examine the functionality of the synergies, we tested how the length of each synergy was affected by properties of rod and cube.

Postural Distances

As in Experiment 1, we determined wrist–shoulder distance, which reflected contributions of the arm synergy, and the shoulder–ankle distance, which reflected contributions of the body synergy. To test whether one or both of the postural synergies created different distances in different experimental conditions, we analyzed the wrist–shoulder distance and the shoulder–ankle distance in separate three-way multivariate ANOVAs with cube size, rod type, and rod length as within-participant variables. The analyses were performed on the averages for each participant for each condition. Again, we looked only at the linear and quadratic contrasts.

The wrist–shoulder distance was adapted to size of the cube, $F(1, 17) = 7.99$, $p = .01$, and was smaller for the small cube (0.188 m) than for the large one (0.207 m). That effect shows again that precision requirements affect the arm posture. The linear contrast of rod length was significant, $F(1, 17) = 4.96$, $p < .05$, showing again that the wrist–shoulder distance was shorter for longer rods (see Table 2). The only significant interaction was between cube size and rod type, $F(1, 17) = 13.04$, $p < .005$. The effect seemed to show that for the small cube, the wrist–shoulder distance was smaller when weight was placed nearer the handle, whereas for the large cube, that distance was larger (see Figure 1B).

We had expected that both longer rods and small cubes would require better control. Because both conditions yielded a smaller wrist–shoulder distance, one can conclude that a shorter distance provides for better rod control. The other manipulation that was expected to increase the need for control—a rod with a less stable tip (i.e., more mass at the handle)—also led to a less extended arm when that arm had to displace a small cube.

For the shoulder–ankle distance, the main effect of rod length was significant, $F(1, 17) = 5.02$, $p < .05$. The means showed again that the shoulder–ankle distance was smaller for longer rods (see Table 2). Moreover, the quadratic contrast for the main effect of rod type was significant, $F(1, 17) = 5.05$, $p < .05$, showing that the shoulder–ankle distance was small for rods weighted near the handle but larger for the rods with weight closer to the tip. None of the other effects were significant. In short, in conditions in which the rod required better control, the body did not lean as far forward as it did when less control was required. That finding suggests that a more upright body provided for more stability. However, the body was affected only by variations of the rod, not by variations in object size.

Conclusion

The finding that foot distance was affected by cube size was already strong evidence that posture was anticipated in the distance. That evidence was corroborated by the direction of the effects: Foot distance was shortest when arm distance was smallest—that is, when a small cube had to be displaced with a rod weighted at the handle (cf. Figures 1B and 2). In the condition in which the rod required most control, it was most important for the change in distance to be in agreement with the change in posture. Moreover, the body leaned less forward when the rod was weighted in the handle. In sum, those effects showed that the changes in the chosen distance anticipated the adjustments in the postural synergies.

GENERAL DISCUSSION

In the present study, we addressed anticipation in tool use. We examined whether rod length and tool-use posture were anticipated when participants chose a distance from which to displace an object with a rod. The selected distance should accommodate the length of the rod and the posture during displacement; hence, we used that distance as an indication of anticipation. In two experiments, we varied length, mass, and mass distribution of the rod, and the size of the to-be-displaced cube. As expected, a larger distance was selected with longer rods. In addition, a strong effect of cube size on selected distance was found in both experiments. Because cube size could affect the distance only through posture—cube size was not related to information about rod properties that could affect chosen distance directly—that finding was strong evidence that posture was anticipated in the distance. The effect of cube size showed that a shorter distance was selected with the small cube, that is, when more control of the rod was required. The effect of rod length on distance pointed to the same conclusion: For a long rod, a small movement at the wrist yielded large effects on the tip, and we found that long rods led to a relatively smaller selected distance (i.e., the increase in distance was smaller with longer rods). In short, the effects of both cube size and rod length indicated that the controllability of the rod is the variable that is anticipated in the distance.

Several changes in posture were associated with increased control of the rod. The results showed that posture was organized in two synergies: one synergy in the arm, comprising shoulder and elbow, and the other synergy in the body, comprising ankle, knee, and hip. The body synergy was adapted mainly to rod length, whereas the arm synergy was adapted to rod length and mass and cube size. The body effect was a more upright posture for longer rods. The general effect on the arm synergy was less extension when rods required more control; that is, increased control was associated with smaller cube size and longer rods. Of critical interest was whether changes in synergy length would be reflected in the chosen distance. We found that they were: The selected distance was relatively shorter for the smaller cube and the longer rods. However, the mass effects were more complicated: When weight of the rod was manipulated, the changes in posture did not coincide with changes in foot distance, whereas under variations of mass distribution, postural changes were in agreement with changes in distance. Lighter rods and rods with mass at the handle have less rotational inertia, and thus less net muscle torque is required to make the tip move; so, they must be controlled with less noise. Variations in mass distribution made it possible to manipulate the controllability of the rod over a larger range, and under that manipulation we found the most telling effect: Participants anticipated the shorter arm distance, which was used to displace a small cube with a rod weighted at the tip, by using a very short foot distance (see Figures 1B and 2). That result showed that in a situation in which the most control of the rod was required, the smaller arm distance was anticipated in the foot distance. In sum, our results showed that controllability of the rod is the variable that determines the posture and is anticipated together with rod length.

Note that controllability seems to be more important for handling the rod than is torque, because torque in the joints was not minimized. Minimizing torques in the joints would entail less extension of the arm (i.e., wrist closer to the shoulder), which would have been especially important for rods that produce more torque. We found that the wrist was in front of the shoulder and the arm was more extended both with the heavier rods in Experiment 1 and with the rods weighted at the tip in Experiment 2—rod types that produce greater torques than do lighter rods and rods weighted at the handle. From those findings, we inferred that the participants did not adapt the posture to minimize the torque in the arm joints, a conclusion similar to that reached in Bongers et al. (2003). The perhaps obvious finding that the load a tool produces is not always the limiting factor can be seen as a first step in the search for the set of variables that do determine the control over a tool and would have to be anticipated in an action with a tool.

Our finding that distance anticipated posture may be helpful in understanding the postural basis of tool use. We hypothesized that synergies were underlying the postural organization in our task; to measure synergies, we examined whether postural angles changed in a systematic way over trials. We are aware that that is a crude measure for establishing the underlying synergies, but our experimental setup was not up to the task of a more detailed examination of synergies. Therefore, our results are mute on the issue of whether muscle synergies are flexible (cf. Bernstein, 1967; Hepp-Reymond et al., 1996; Lee, 1984; Macpherson, 1991) instead of anatomically based reflexes (cf. Sherrington, 1906/1947).

In the literature, several functionalities for synergies have been distinguished. In some tasks—for example, reaching with the hand to a target in front—one synergy has been found to control the trunk, independent of the motion of the hand, whereas the other synergy coordinates the motion around the arm joints to bring the hand to the target (cf. Kaminiski, 1995; Ma & Feldman, 1995; Saling et al., 1996; Wang & Stelmach, 1998). In other tasks—such as manipulation of accuracy constraints—the trunk was also shown to contribute to the focal movement (cf. Martin et al., 2000). In the present experiments, the synergy in the arm was affected by rod length and mass and by precision requirements; the arm was organized to control the rod, whereas the synergy in the body, comprising leg and trunk, functioned as a postural stabilizer that made it possible for the arm to control the rod. Our findings show similarities between actions with a tool and actions without a tool, but also dissimilarities, that is, no contribution of the trunk under variations of accuracy constraints. Therefore, we argue that the organization of the synergies is flexible, depending on constraints of tool and task.

Actions have been shown to reflect differences in tool properties in other experimental setups. Dean, Brüwer, and their colleagues (Cruse, Brüwer, & Dean, 1993; Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990; Dean & Brüwer, 1994; 1997) investigated how the kinematics of actions was adapted to the length of a hand-held pointer. In a series of experiments, they asked participants to make pointing movements with and without a pointer in a two-dimensional plane at approximately shoulder height. In some experiments, the pointer varied in length. The tip of the end-effector had to successively touch two points, and an obstacle placed between those points had to be avoided (Dean & Brüwer, 1997). Joint angles and end-effector trajectories depended on the size of the obstacle and the length of the pointer; hence, their study showed that actions with tools change according to properties of the tool (i.e., length) and properties of the task (i.e., obstacle size). In our study, we went a step further and showed that the changes in posture, which follow from changes in the properties of tool and task, are anticipated. Furthermore, we showed that it is not only arm posture but also whole-body posture that is anticipated. However, note that our implementation of task properties differed considerably from that of Dean and colleagues: We varied accuracy constraints.

To conclude, in the present study we have shown that characteristics of tool and task are anticipated in tooling actions. Our interest in this study was to show that action aspects are important for understanding tool use. The finding that properties of tool and task prospectively affect actions supports the idea that tool use entails not only cognitive processes but also action characteristics, and extends the conclusions of earlier studies of tool use in which the focus was mainly on cognitive processes (cf. Bates et al., 1980; cf. Köhler, 1925).

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NOTES

1. On most trials, the feet were closely aligned, but we always measured foot distance from the foot closest to the table.

2. A pilot study revealed that, particularly for the small cube, participants needed about five trials before they could perform the task comfortably. However, our interest was not in how participants learned to select the distance but in properties of tools and object that affected actions prospectively once participants had mastered the task. Therefore, we let participants practice with all the rods for each cube before the experimental trials.

3. Because the rod types and lengths were varied in a gradual fashion, we expected a gradual adaptation in the dependent variables. In the linear and quadratic contrasts, we tested a linear and a quadratic relation between the independent and the dependent variables. Specifying those contrasts a priori increases the power of the tests because only specific relations between the independent and the dependent variables are tested.

4. One might expect a similar effect as a function of mass because the CM of the body + rod system also shifts outward when mass of the rod increases. However, we did not find such an effect.

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