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An action perspective on tool use and its development

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The research presented in this dissertation was conducted at the Department of Developmental Psychology, University of Nijmegen, under the auspices of the Rutten Institute for Research in Psychology.

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An action perspective on tool use and its development

een wetenschappelijke proeve op het gebied van de Sociale Wetenschappen

Proefschrift

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### Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prelude</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>Chapter 1</td>
<td>General Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>Do young children prospectively adapt their actions to properties of rods that are used for displacing a toy?</td>
<td>19</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Properties of tool and task determine young children’s adaptations in actions</td>
<td>63</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Geometrics and dynamics of a rod determine how it is used for reaching</td>
<td>97</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Variations of tool and task characteristics reveal that tool use postures are anticipated</td>
<td>135</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Epilogue</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>Summary</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td>Samenvatting</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Dankwoord</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>Curriculum Vitae</td>
<td>199</td>
</tr>
</tbody>
</table>
“The embryos stood in front of God, with their feeble hands clasped politely over their stomachs and their heavy heads hanging down respectfully, and God addressed them.

“He said: ‘Now you embryos, here you are, all looking exactly the same, and We are going to give you the choice of what you want to be. When you grow up, you will get bigger anyway, but We are pleased to grant you another gift as well. You may alter any parts of yourselves into anything which you think would be useful to your later life. For instance, at the moment you cannot dig. Anybody who would like to turn his hands into a pair of spades or garden forks is allowed to do so. Or, to put it another way, at present you can only use your mouth for eating. Anybody who would like to use his mouth as an offensive weapon, can change it by asking, and be a corkindrill or a sabre-toothed tiger. Now, step up and choose your tools, but remember that what you choose you will grow into, and will have to stick to.’

“All the embryos thought the matter over politely, and then, one by one, they stepped up before the eternal throne. They were allowed two or three specializations, so that some chose to use their arms as flying machines and their mouth as weapons, or crackers, or drillers, or spoons, while others selected to use their bodies at boats and their hands as oars. We badgers thought very hard and decided to ask three bones. We wanted to change our skins for shields, our mouth for weapons, and our arms for garden forks. These bones were granted. Everybody specialized in one way or another, and some of us in very queer ones. For instance, one of the desert lizards decided to swap his whole body for blotting-paper, and one of the toads who lived in the drouthy antipodes decided simply to be a water-bottle.
“The asking and granting took up two long days—they were the fifth and the sixth, so far as I remember—and at the very end of the sixth day, just before it was time to knock off for Sunday, they had got through all the little embryos except one. This embryo was Man.

“‘Well, Our little man,’ said God. ‘You have waited till the last, and slept on your decision, and We are sure you have been thinking hard all the time. What can We do for you?’

“‘Please God,’ said the embryo, ‘I think that You made me in the shape which I now have for reasons best known to Yourselves, and that it would be rude to change. If I am to have my choice I will stay as I am. I will not alter any of the parts You gave me, for other and doubtless inferior tools, and I will stay a defenceless embryo all my life, doing my best to make myself a few feeble implements out of the wood, iron and other materials which You have seen fit to put before me. If I want a boat I will try to construct it out of trees, and I want to fly, I will put together a chariot to do it for me. Probably I have been very silly in refusing to take advantage of Your kind offer, but I have done my very best to think it over carefully, and now hope that the feeble decision of this small innocent will find favour with Yourselves.’

“‘Well done,” exclaimed the Creator in delighted tones. ‘Here, all you embryos, come here with your beaks and whatnots to look upon Our first Man. He is the only one who has guessed Our riddle, out of all you, and We have great pleasure in conferring upon him the Order of Dominion over the Fowls of the Air, and the Beasts of the Earth, and the Fishes of the Sea. Now let the rest of you get along, and love and multiply, for it is time to knock off for the week-end. As for you, Man, you will be a naked tool all your life, though a user of tools. You will look like an embryo till they bury you, but all the others will be embryos before you might, Eternally undeveloped, you will always remain potential in Our image, able to see some of Our sorrows and to feel some of Our joys. We are partly sorry for you, Man, but partly hopeful. Run along then, and do your best. And listen, Man, before you go …’

“‘Well?’ asked Adam, turning back from his dismissal.

“‘We were only going to say,’ said God shyly, twisting Their hands together. ‘Well, We were just going to say God bless you.’”

Introduction

Humans extensively rely on tools to alter the capacity for action when performing the diversity of tasks required in everyday lives. For example, think of the wide range of instruments helping us in our daily routine of getting up; the day usually starts with lying in a bed under sheets, an alarm-clock wakes us up, we take a shower to wash, we use a toothbrush, etc. When we consider the whole day the number of tools that we use increases explosively. Note that the kind of implements individuals use varies from a small hand-held object (i.e., a tooth-brush) to a different surface of support (i.e., a bed), or a whole system of waterworks (i.e., the shower). All of those instances illustrate the different ways in which humans create objects and surfaces to adapt the capacity for action when action systems fall short or action goals can be achieved more easily. Although most researchers would agree that implements change action possibilities, this tended not to be the focus in most of the studies. The present thesis concentrates on how hand-held tools can affect the capacity for action, and how the capability to use tools may develop.
The change in possibilities for action engendered by tools is most salient when one holds a tool; a tool in the hand feels as a part of the body. One seems to feel the point of contact between tool and environment as if a body part makes contact with the world instead of an attached object (see also J.J. Gibson, 1979, and Loomis & Lederman, 1986). For example, when writing with a fountain pen one can feel the tip scratching over the paper as if the pen and the hand are one. Holding an implement makes one feel as if the body is actually expanded, which might be the basis of the changes in action possibilities with a tool.

One of the simplest forms of change that a hand-held tool can bring about is “lengthening” of a body segment, which affects that segment’s reaching range. Note that the new reaching range depends not only on the implement’s length but also on the actors’ posture to control the implement. The posture changes when forces and torques in joints and muscles change under variations of tool properties. The present thesis reports experiments of how young children and adults adapt actions to displace an object using a rod. Using a rod lengthens the arm and thus should extend the range for manual actions. The current’s thesis major concern is with the variables that determine the reaching range in using a rod and changes with respect to those variables with age. To help reveal those variables, we varied properties of the rod, such as its length, mass, and mass distribution, as well as precision requirements of the task. In all the experiments reported here children or adults had to choose a distance from which to displace an object using the rod’s tip. To perform the task the distance to the object the reacher must select is based not only on the rod’s length, but also on postural adaptations required in controlling the rod. For example, when a rod (of a certain mass) necessitates handling with a relatively less extended arm, then the chosen distance should anticipate this difference in arm posture. Therefore, the distance should reflect whether participants prospectively adapt their actions to changes in action possibilities due to rod and task.

In this introductory chapter, I will explain some of the thesis’ background. Based on a survey of studies into tool use over the last decades, I will argue that the change in action possibilities brought about by tools deserves more attention. The current thesis adopts a combined perspective of Ecological Psychology and Dynamic Systems Theory on the development of action (see also Smitsman, 1997; Smitsman & Bongers, 2000) to study the changes in action possibilities engendered by tools. A
key feature of this perspective is the view that tools change the dynamics of the action system and that on the basis of those changed dynamics new possibilities for action develop. Following from this, a further key assumption is that the changes in the dynamics of the action system brought about by bodily growth are similar to the changes brought about by a tool, albeit on a different time scale. In this vein, tool use may offer a special view on one of the main challenges of development—adapting to bodily changes.

**Perspectives on tool use**

A generally accepted definition of tools is as objects that can be attached to the body to alter the capacity for action (Beck, 1980; Connolly & Dalgleish, 1989; Steenbergen, Van der Kamp, Smitsman, & Carson, 1997). Even though most researchers would agree on this definition, the overview presented in this section shows that the changes in the capacity for action with a tool tended not to be the main issue in the majority of studies. This overview is not meant to be exhaustive, its purpose is to show that the central point of most earlier studies was related to cognitive capabilities required to use a tool. A focus on cognitive abilities makes it easy to overlook the alterations in action possibilities due to tools. At the end of this section I will show how attention has been drawn back to focus on action possibilities with tools. The present thesis picks up on those alternative views and sketches how tool use can be studied from an action perspective, grounded in theories of motor development and perception (Smitsman & Bongers, 2000).

**Tool use as indicator of intelligence**

A great deal of interest in tool use stemmed from an evolutionary perspective (Beck, 1980; Berthelet & Chavaillon, 1993; Hall, 1963; Köhler, 1925; Tomasello & Call, 1997). The interest was in the evolution of the cognitive capacity required to use a tool. Therefore, different types and levels of tool use in anthropoids, lower species, and young children, were studied. From the assumption that a tool served as a means to act on an other object it was supposed that insight into means-end relationships formed the core for tool use to evolve (cf. Smitsman & Bongers, 2000). Tool use was thereby considered as problem-solving behavior because it
was held to be a case of indirect goal attainment. The occurrence of problem-solving behavior in a species, or at a given age, was seen as an indication of intelligence (cf. Berthelet & Chavaillon, 1993; cf. Tomasello & Call, 1997). The thought underlying this perspective is nicely illustrated by a quote from Fyssen, cited in Berthelet and Chavaillon:

Once man had managed to hold the first rock in his hand, and started to examine it by handling it between the thumb, the index, and the middle finger, he thus inaugurated the era of experiments and of observations, and consequently, hypotheses... (Fyssen in Berthelet & Chavaillon, 1993, p. xvii)

One of the firsts to furnish a systematic account in the studies of intelligent behavior of anthropoids was Köhler (1925) who studied whether chimpanzees could apply insight to the solutions of problems. Köhler performed his studies at the time the Gestalt psychology began to develop and he was interested in whether the animals could “see” the potential connection between tool and goal object. He presented apes with a problem (i.e., food positioned beyond reach) and asked whether they used objects present in their cage to solve the problem. For example, in one of Köhler’s studies, fruit was placed outside the cage, beyond arm length. One stick or a set of sticks was placed in the cage and the question was whether the ape would use a stick to reach for the fruit.

Following up on the experiments of Köhler, Richardson (1932) investigated the age at which infants used a string attached to an object placed beyond arm length to pull the object. The focus in the experiments was on the age at which infants could solve the problem. Again, tool use was considered as problem-solving behavior that could illuminate in the development of intelligence.

However, the occurrence of tool use in the animal world is not restricted to anthropoids and humans; also lower mammals, fish, and birds (cf. nest building) show capacity to use tools (cf. Beck, 1980). Because those animals were assumed not to have intelligence, the appropriateness of tool use to study intelligence was called into question and such experimentation waned.
Tools as objects

Tool use often involves holding and wielding an object in the hand. Hence, one of the first thoughts that may come to mind when thinking about tool use is that it is a kind of object manipulation. Parker and K.R. Gibson (1977) proposed a classification of five categories of object manipulation that applied directly to tool use, they distinguished: simple prehension, simple object manipulation, object-substrate manipulation (e.g., banging an object on the floor), complex object manipulation, and social-object manipulation. Parker and K.R. Gibson used criteria of Piaget’s model of sensorimotor intelligence to differentiate between intelligent and unintelligent tool use. Object-substrate manipulation was considered proto-tool use whereas true tool use is a complex form of object manipulation. In the case of tool use, both the goal-object and the implement are separated from the environment and manipulated while in proto-tool use only the goal-object is separated and manipulated. So, an example of proto-tool use is banging a nut on a hard surface and an example of tool use is banging two objects to produce noise (Parker & K.R. Gibson). Although Parker and K.R. Gibson focussed on classifying different forms of object manipulation, they assumed different levels of cognition to make those behaviors possible. Note that Parker and K.R. Gibson’s classification concentrates solely on the object manipulation that took place independent from the goal achieved with the manipulation. This may limit the usefulness of their classification. For example, banging a nut into another nut (which is also held in the hand) or into the floor is similar in terms of the goal that is achieved; in both cases the shell is to be broken. Parker and K.R. Gibson classify one case as tool use and the other as proto-tool use but based on the goal-directness of the behavior there is no reason to assume that one behavior is more intelligent than the other. The limitations of Parker and K.R. Gibson’s approach originate from their neglecting the goal that is achieved with a certain type of object manipulation.

To achieve a certain goal when using a tool, the relation between tool and goal-object needs to be regulated. For example, when using a spoon for eating, the bowl of the spoon needs to be properly oriented to scoop the food. Several investigations have shown that the relation between tool and goal-object is important to whether infants perceive the potentialities of the tool (Bates, Carlson-Luden, & Bretherton, 1980; Brown, 1990; cf.
Van Leeuwen, Smitsman, & Van Leeuwen, 1994). In the cited experiments, properties of a tool, such as its shape (for instance, a hook, a rake, or a rod), and the orientation between tool and goal-object were varied (cf. Bates et al., 1980). The perceived spatial contact between tool and goal object is important for tool use to emerge (Bates et al., 1980; Brown, 1990; cf. Van Leeuwen et al., 1994). It was contended that the visible link between tool and object facilitates the problem-solving required to use the tool; younger children found it easier to use the tool if the configuration between tool and goal object suggested a direct relation. The results were interpreted in terms of new levels of symbolic thinking and its accompanying representational skills. Despite the focus on perceptual aspects of the tools in the experiments, the explanation was sought in terms of underlying cognitive abilities of the child.

Van Leeuwen et al. (1994) extended this paradigm by arguing that the relation between user and tool was as important as the relation between tool and goal-object. According to their reasoning, which had its roots in an ecological approach to perception, one should ask whether the relation tool and goal-object was functional, that is, does it indicate how the child could grasp the tool to maintain an orientation between tool and goal-object. The importance of the relation between tool and child for tool use to emerge in a situation was confirmed by their results: in experiments in which a cookie had to be obtained with a hook, young children’s rate of success depended on the configurations between hook and cookie but also on the orientation of the hook to the child. The study by Van Leeuwen et al. presented a first step in appreciating the full set of relations in which a tool is embedded. I will return to this point later when explaining the action perspective on tool use (cf. Smitsman & Bongers, 2000).

**Tool use and language**

Greenfield (1991) and Paillard (1993) sought similarities between the development of language and the development of tool use, and how they relate to brain development. In this line of research, tool use is studied as a particular instance of object combination, which has its match in other forms of object combination, such as occurs when speaking. More specifically, those investigators search for similarities between linguistic grammars and grammars for action and, related to this, their interest was
in the relative importance of specific parts of the brain for the capacity of tool use and language to develop. However, Vygotsky (1978) points to the active role of speech to structure actions when a child learns to use tools. He gives several examples of how children use speech to discover how a tool can be used. From this could be concluded that language and tool use were more related than their shared brain organizations.

There is much more that could be said about the relation between language and tool use (see, for instance, K.R. Gibson & Ingold, 1993). However, such a discussion is beyond the scope of the present thesis.

**Motor aspects of tool use**

Most of the studies discussed so far concentrated primarily on cognitive abilities to use a tool. However, using a tool implies grasping and controlling it, and thus studying tool requires the consideration of both postures and movements. For instance, grip patterns will vary dependent on the size of the tool; a needle is grasped with a precision grip whereas a shovel is grasped with a power grip. Connolly and Elliot (1972) made a detailed study of the grip patterns children employed when holding a tool. Thus, they focussed on the postures and movements with which tools were controlled.

In later studies, Connolly and colleagues (Connolly & Dalgleish, 1989; 1993) extended their earlier research and concentrated on how grip pattern changed as the skill of tool use developed. However, the focus in those later studies shifted towards a more cognitive level and concentrated on how the components of an action make up the skill. Within this so-called “skill-integration” approach, the focus is on how the cognitive construction of an action plan develops (Connolly & Dalgleish, 1989; 1993; Koslowski & Bruner, 1972; McCarty, Clifton, & Collard, 1999). The focus was on units of an action plan (i.e., the different movements that made up the total action) and how children adapted their action plan to incorporate the tool. Connolly and Dalgleish (1989) followed mealtime sessions of two groups of infants at monthly intervals during a half-year. They described the successive stages in actions when children learned to use a spoon. On the basis of their results, Connolly and Dalgleish presented the principal stages in the development of the spoon using skill. I find it striking that although the actions of the children were studied and analyzed, the findings were interpreted at the cognitive level.
A new perspective on tool use

The studies cited so far provide insight in several important aspects of human tool using behavior. Focussing on cognitive abilities, they revealed important constraints on the development of tool use. Nevertheless, the emphasis on cognitive abilities arguably ignores other important aspects of tool use, for instance, the alterations in capacities for action brought about by tools. Inspired by and in line with recent approaches to tool use, the present thesis argues that the change in action possibilities engendered by tools deserves more attention. This new perspective on tool use may be labeled an *action perspective* on tool use and is grounded in new approaches to study the development of perception and action that originate from Ecological psychology and Dynamical Systems Theory (Lockman, 2000; Smitsman, 1997; Smitsman & Bongers, 2000). Before this standpoint is further expounded some limitations of primarily focussing on cognitive abilities related to tool use are addressed.

From several studies, one may conclude that the cognitive abilities of an actor cannot be the sole determining factor for tool use to emerge. The occurrence of tool use in different anthropoids has shown that whether or not tool use evolved in a species depended to a large extend on local circumstances (McGrew, 1993; Sugiyama, 1993; Tomasello & Call, 1997). Hence, it is not just the brain capacity or cognitive abilities that determine the level of tool use displayed, but the animal’s environment also seems important.

That cognitive factors are not the only constraints on the emergence of tool use is also argued from another perspective (Ingold, 1993, but see also, 1996; 1997). Based on ideas developed in social anthropology and the evolution of technology, language, and tool use, Ingold discounts that a disembodied thing called intellect or cognition controls action. Activities such as tool use, he argues, should not be studied as “the behavioural products of the operation of higher intellectual capacities” (Ingold, 1993, p. 433). Instead, Ingold argues that the functions of a tool originate in the use of a tool. For instance, the function of a paper-clip as a tool to eject a diskette from a computer emerged only in the context of Apple computers. In a similar vein, Ingold argues that the possible functions of a tool depend on the user. He gives the example of the Aboriginal people who “have few tools, but use them in whatever way
they come in handy, for manifold purposes that we might never think of when we classify the objects by function” (Ingold, 1997, p. 129). In other words, the use of a tool depends on how it can alter the capabilities for action given a user and the user’s surroundings. Tool use is embodied and also embedded in the environment, which again implies that it does not solely depend on the emergence of new cognitive abilities.

Earlier I discussed the results of Van Leeuwen et al. (1994) that showed that the emergence of tool use depended as much on the relation between tool and goal-object as on the relation between tool and child. This implied that to perform a goal-directed action with a tool, the relation between tool and actor should be adapted to control the relation between tool and goal-object (cf. Smitsman, 1997). Steenbergen et al. (1997) picked up on this; they manipulated properties of a tool and examined how actions were adapted to control the interface between tool and goal-object. More specifically, they manipulated the orientation between bowl and stem of a spoon that was used to scoop rice. They found that children two to four years-old adapted their grip to control the relation between rice and bowl. Similar findings were reported by Lockman (1997; see also, 2000) who showed that different tools for painting or writing were used differently depending on the surface on which to paint or write. Together, the studies of Lockman and Steenbergen et al. showed that grip on the tool was varied to control the interface between tool and target. In the same vein as those studies, the current thesis explores how changes in the effector system due to a tool, affect the actions when the relation between tool and goal-object needs to be controlled.

The action perspective has consequences for how one approaches the development of tool use. Directing attention to how tools augment action possibilities necessitates a developmental perspective directed to the mechanisms that engender new patterns of behavior. Contrary to earlier approaches that assume discontinuous steps because of the presumed cognitive leaps that are involved, in the present thesis a more continuous approach to the development of tool use is proposed (Lockman, 2000; Smitsman, 1997; Smitsman & Bongers, 2000). Grounded in advances in the study of action development during the last two decades, the present thesis starts from the assumption that tools affect the actions in a way that has deep similarities with the changes in actions due to a growing body. In the following sections the theoretical viewpoints from which this proposition originates will be presented.
Affordances and effectivities

Within the framework of Ecological Psychology, a person’s possibilities for action are approached with an emphasis on the reciprocity between a person and the surroundings. This reciprocity implies that action possibilities depend on the individual as well as on the environment. J.J. Gibson (1979) defined *affordances* as the possibilities for behavior provided to a given organism by an environmental layout. For example, a ball on a table affords grasping and throwing given that the ball fits the hand size. Thus the concept of affordance relates body properties to environmental properties. What is the importance of this approach for studying tool use?

The concept of affordances illustrates that the environment is perceived in relation to the actor’s capabilities for action (cf. Reed, 1996). Tools enable an actor to enter into a specific relationship with the environment; once attached to the body, tools alter the end-effector’s properties and, thus, the relation between actor and environment. In this perspective, tools serve a dual role (cf. J.J. Gibson, 1979; Shaw, Flasher & Kadar, 1995); on the one hand a tool is an object in the environment that constitutes affordances, and on the other hand, once an object is grasped, it alters the capacity for action and functions as a tool. For instance, a pole in the ground affords leaning against but once a pole is grasped it affords throwing. This example demonstrates the dual role tools have in the relation between an individual and its environment, clearly expressed in the following quotation from J.J. Gibson:

> When in use, a tool is a sort of extension of the hand, almost an attachment to it or a part of the user’s own body, and thus is no longer a part of the environment of the user. But when not in use, the tool is simply a detached object of the environment ... the boundary between the animal and the environment is not fixed at the surface of the skin but can shift. (J.J. Gibson, 1979, p. 41)

So far, the emphasis has mainly been on how the meaning of environmental properties depends on properties of the action system. In a similar vein, capabilities for action in the organism also can be defined in relation to the environment. Shaw and Turvey (Shaw & Turvey, 1981; Turvey & Shaw, 1979) labeled the possible ways in which the neuromotor
system can be organized into functional units, *effectivities*. The neuromotor system is constituted of body segments and joints that can be moved by muscles. At the level of behavior, those joints and muscles are the degrees of freedom that have to be constrained to perform a goal-directed action, and, thus, determine the effectivities.

The occurrence of a goal-directed action reflects the fit between the affordances in the environment and the effectivities in the body. For example, Warren (1984) showed that critical riser height (i.e., maximum climbable height in a bipedal manner) depends on the leg length of an individual; for short people this critical riser height was smaller than for taller people. However, when looking at the ratio of riser height to leg length, Warren found an invariant value over the range of leg lengths. Similar findings are found in experiments were children have to grasp objects that differ in width. Several studies have revealed that independent of the age, the way an object is grasped (one handed or two handed) depends on the ratio between hand span and object size (Newell, Scully, Tenenbaum, & Hardiman, 1989a; Newell, Scully, McDonald, & Baillargeon, 1989b; Newell, McDonald, & Baillargeon, 1993; Van der Kamp, Savelsbergh, & Davis, 1998). Those findings show that it is the relation between object size and hand size rather than the absolute object size, determined the kind of grip. Moreover, Konczak, Meeuwsen, & Cress (1992) found that such ratio’s depended not only on anthropometrics (i.e., leg length or hand size) but also on dynamical variables; flexibility in the leg determined also the critical riser height. Briefly stated, the opportunities for action in the environment are scaled to the actions that are possible (cf. Oudejans, Michaels, Bakker, & Dolné, 1996).

Tools change the properties of the end-effector, and therefore, affect the effectivities. Because changes in effectivities create new affordances in the environment, tools enable an actor to modify the affordances-effectivity relationship (Smitsman, 1997; Smitsman & Bongers, 2000). However, an implement can only change affordances when it can be controlled. For example, imagine a small child using an adult tennis racket; obviously the child will have difficulty producing enough force to swing the racket at the required speed and in the right position. In some situations the adult racket is more an obstacle to action for the child than it is a facilitator. In such a situation the tennis racket will certainly affect the relation between the child and the environment—the child may have
balancing problems—but it cannot be used to meet the goal—hitting an approaching ball. This implies that the racket does not contribute to a hitting effectivity. In other words, only tools that can be effectively controlled by an actor change the action possibilities, that is, affordances.

**Development**

The previous section emphasized the importance of studying the relation between environment and actor if one wants to understand the changes in action possibilities tools engender. In the present section, this change is addressed from a developmental perspective; it is hypothesized that the changes in action possibilities engendered by tools show deep similarities to changes in action possibilities following from bodily growth. This proposition finds its origins in a dynamic systems perspective on development of perception and action, which is explained in the present section.

In the first half of this century, studies of motor development were mostly descriptive and concentrated primarily on how motor skills changed with age; the different stages of motor capabilities children followed were determined in detail. The interest was more on neural maturation than on motor development itself because the underlying approach assumed that motor development originated from maturation of the central nervous system (cf. Bertenthal, & Clifton, 1998; cf. Ulrich, 1998). As a result, the interest was mainly in establishing the age at which and the sequence in which certain motor skills develop.

Those early approaches to motor development were limited in some important ways: explanations of behavior remained on a descriptive level and fell short of explaining processes behind the changes over time in behavioral patterns (Bertenthal & Clifton, 1998; Thelen & Smith, 1994; Ulrich, 1998). Moreover, those early studies emphasized the regularities in the development of motor behavior while this is characterized by variability. Recent advances in the studies of perceptuo-motor development, inspired by a dynamic systems perspective—that emphasizes variability and changes in variability—have just begun to do justice to the questions of change and variability of motor behavior. This was possible because new technologies made it possible to measure detailed aspects of actions directly (Bertenthal & Clifton, 1998). In addition, new theoretical insights made it possible to understand the
function of variability and address which changes in a system could be responsible for transitions between behavioral patterns (Goldfield, 1995; Savelsbergh, Wimmers, Van der Kamp, & Davis, 1999; Smitsman, 2000; Thelen & Smith, 1994; Van Geert, 1998). Although, this systems perspective was not completely new (cf. Von Bertalanffy, 1962), the mathematical and physical underpinnings of its tenets were developed in a rapid fashion in the sixties and early seventies under the umbrella of what is now called “Dynamic Systems Theory”. From such a perspective, the system under study is described in terms of its stable states, and attention is paid to how transitions between different states can take place. A key idea put forward is that in systems consisting of many interacting elements on the micro-level, stable patterns self-organize on the macro-level. Depending on changes in the elements, or subsystems, new patterns can emerge (Haken & Wunderlin, 1990; Kelso, 1995). Because studies of development should concern the origins of new behavioral patterns, this approach seems intrinsically suited to study development.

One of the hallmarks of this dynamics systems approach is that no single cause can determine the behavior of the system because stable patterns emerge from the interactions between the elements. When applied to behavior, this implies that factors originating from different parts of the body-environment system determine the behavior’s dynamic organization as an ensemble (cf. Thelen & Smith, 1994). Changes in behavior can take place when any of several subsystems changes. In other words, new patterns of behavior emerge from alterations in dynamics\(^1\) of the body-environment system. Bodily growth can be considered as a change of a subsystem: length and mass of one or more body segments increase. Those changes may destabilize the formerly stable behavioral patterns. New patterns emerge based on new dynamics of the system. For example, Thelen and colleagues (Corbetta & Thelen, 1995; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Thelen, Corbetta, & Spencer, 1996) observed that infants in their first year explore the intrinsic dynamics of the neuromotor system in order to learn goal-directed reaching. Note that in this viewpoint no single component of the

\(^1\) Note that the term ‘dynamics’ has two meanings in this thesis. On the one hand it refers to the nonlinear behavioral characteristics of open, nonequilibrium systems, and on the other hand it refers to the forces and torques that produce or change motion of matter. In the latter sense the meaning is equal to kinetics.
system determines the behavioral patterns that can be performed. It is the
ensemble of components that is important, not the order in which they
develop or the timing of their contribution.

The stable patterns of behavior that can emerge depend on the one
hand on the functional units in which the neuromotor system can be
organized (i.e., effectivities), and on the other hand on the properties of
the environment. Therefore, new patterns of behavior emerge not only as
a result of changes in the body but also because the new stable patterns
change the relation between the growing child and the environment. For
example, for a child that just has learned to crawl, distant objects have a
different meaning because they can now be approached. Important is that
children have to learn to detect the new affordances of the environment;
properties of the action reflect the relation between the effectivity and the
affordances. For example, Adolph (1997) found that children, who just
had learned to walk, tried to walk down slopes that they could crawl
down even though the slopes were too steep for their new, relatively
unstable, walking pattern. When their walking skill improved, the
children were more sensitive to the descendableness of the slopes. This
indicates that children have to learn to pick up the affordances (i.e.,
possibilities for action) in the environment. In the following sections will
be argued that similar processes are at work when action possibilities
change due to tools.

**Tool use, affordances and development**

In the previous section I explained how new patterns of behavior in a
growing body could emerge based on changes in the dynamics of the
action system. A key issue in the present thesis concerns the influence of
tools on the change in dynamics of the action system; it is proposed that
new patterns of behavior can emerge when the dynamics in the action
system change due to a tool (cf. Smitsman & Bongers, 2000). As an
example, holding a rod extends the position of the hand segment.
Moreover, changing the length, and thus mass, of the hand segment
changes forces and torques in joints and muscles of the whole body.
Those forces and torques will affect the behavioral patterns in which the
system can self-organize. Hence, new behavioral patterns can emerge
based on properties of the tool; the underlying processes are conjectured
to be similar to bodily growth. Although I am aware that changes in
behavioral patterns due to tools are much more abrupt and discontinuous compared to bodily growth, I expect that studying tool use may still open a window onto how children deal with changes in their action system resulting from a growing body (Smitsman & Bongers, 2000).

A child has to learn how to adapt actions to the new dimensions and dynamics of an action system changed by holding an implement. Adolph and Avolio (2000) found that younger infants (with less walking experience) had more difficulty perceiving their boundary of action when walking down slopes with a relatively heavy load on their backs than older children, implying that the child had to learn to detect the new affordances when the properties of the action system change. Tool use has its similarities in carrying a load on the back because both engender an artificial change of the properties of the action system. The findings of Adolph and Avolio suggest that an artificial change of the properties of the action system may be helpful in discovering the processes by which children learn new affordances. Changing the properties of the action system with tools has the advantage that properties of the effectivity can be systematically varied, independent of the stage of the developmental process. For instance, if it is hypothesized that the length of the effector system is the limiting factor at a certain stage in development, this length can be manipulated with a tool to disentangle its relative contribution. Therefore, studying tool use from an action perspective should pave new roads for those interested in development because the relative significance of properties of the effectivity can be systematically investigated.

Affordances are perceivable properties of the environment and therefore actions should be adapted prospectively to changes in affordances. As stated earlier, affordances change when, for instance, length of a hand-held tool changes. If actions are not prospectively adapted when the properties of the tool have changed, the new affordance is not perceived. The present thesis addresses whether the changes in shape and the changes in dynamics of the body + tool system affect the affordances of this system and whether children and adults detect those affordances and show prospective control based on them. To unravel the relative importance of those two aspects, I ask whether actions with a tool are preparatory adapted to changes in the tool’s shape, changes in tool’s dynamics, or both. Because affordances are perceivable, it is proposed that anticipatory adaptations in the actions reflect the
properties of the body + tool system that make up the affordance. A key question is whether affordances are determined by just the shape of the new end-effector or also by its dynamics.

The current thesis

The current thesis takes the changes in possibilities for action brought about by tools as the departure point for understanding tool use and developmental processes related to it. The focus on the change in action possibilities emphasizes the similarity in processes underlying tool use and action development. Typically, studies of tool use examined whether children recognize whether and how a tool can augment their capacities for action. A different route is taken in the present thesis. Both children and adults are clearly instructed how to use the tool and experiments try to determine whether participants adapt their actions to properties of the tool. The experiments are set up to search for variables that determine action possibilities with a tool.

The basic setup is similar in all studies; children or adults approach an object while carrying a rod pointing upward, stop, lower the rod and displace the object sideward with the tip of the rod. Lengths, mass, and mass distribution of the rods and the size of the to-be-displaced object are varied. Changes in length of the rod are expected to affect the geometrics of the body + tool system whereas changes in mass properties are expected to affect the dynamics of the body + tool system, independent from the length. Changes in object size are expected to affect the required control of the rod. It is conjectured that the dynamics and the required control affect the posture with which the rod can be controlled. For the participant to perform the task, the selected distance from which to displace the object should accommodate the length of the rod as well as the needed posture. The distance—which has to be selected with the rod pointing upward—is expected to reflect anticipatory adaptations to geometrics and dynamics of the body + rod system, and size of the object. Hence, the distance is expected to reflect changes in the affordance engendered by the tool.

In Chapter 2, children aged two to four used a rod to displace an object. The variables on the basis of which children adapted their distance to the table and the posture with which the object was displaced were examined. By distinguishing groups of children with different levels of
skill, it was possible to see how variables become important as the skill was mastered. This study was extended in Chapter 3, which examined how properties of the rod and to-be-displaced object size affected different phases in the unfolding of the activity. Deviations from the task instruction were tallied. This should reflect children’s functional adaptations in actions (i.e., different strategies) to properties of the rod and the object.

Chapter 4 and 5 reported experiments that were performed with adults in an attempt to find the variables that guide relatively expert tool users. Length, mass, and mass distribution of the rod were varied in three experiments, in Chapter 4. The selected distance and adjustments in postural angles were measured. In Chapter 5, object size was varied, together with length and mass properties of the rods. Those studies concentrated on the postural organizations controlling the rod and whether changes in the posture prospectively affected the chosen distance to the object.

Finally, Chapter 6 summarized the findings of all the experiments. I discussed the implications of those findings for ideas about affordances and the development of tool use. Moreover, the variables that guide tool-using behavior were considered. Finally, future directions in which the study of an action perspective on tool use and its development could evolve are presented.
Do young children prospectively adapt their actions to properties of rods that are used for displacing a toy?

Abstract
We asked children, aged two to four, to displace a toy with a hand-held rod. We examined their sensitivity to differences in the possibilities for reaching that depend on rod properties. Children held a rod (lengths 10 to 90 cm) with the tip in the air, walked toward a toy on a table, chose a place to stop, and displaced the toy with the rod’s tip. In 3 experiments, rod length, mass, and mass distribution were manipulated to determine whether and how geometric and kinetic properties affected chosen distance and posture. Chosen distance depended only on the length of the rod. Postures were affected by length and mass properties of the rods. Not all adaptations in posture were prospectively reflected in the distance. However, both length and mass properties of the rod affected the way children deviated from task instructions. Children need to discover how the dynamics of the action system, as affected by tools, determine the action possibilities.
Introduction

In the present paper we study whether young children are sensitive to how a tool may affect possibilities for an action. In general, we define tools as objects that can be held or attached to the body and that change the capacity for action. Using a tool allows the actor to solve a control problem for the action system, for example, a chair provides a stable platform from which other actions, such as eating or writing can be performed. In performing goal-directed actions, the action system must be constrained to fit the properties of the environment. To perform a goal-directed action with a tool, the degrees of freedom in the neuromotor system have to be constrained with reference to the properties of the tool (for instance, its shape or weight) and the goal of the action in the environment. In the present research we assume that new patterns of behavior can emerge based on how the tool affects the dynamics of the action system (Smitsman & Bongers, 2000). We ask whether young children are sensitive to the new possibilities for action when using a tool. This is an important question for those interested in development. Development can be conceived of as emerging from changes in the underlying dynamics of the action system resulting from changes in the subsystems (cf. Bertenthal & Clifton, 1998; cf. Goldfield, 1995; cf. Thelen & Smith, 1994). The study of tool use may open vistas on how underlying dynamics of the action system determine the emergence of new behaviors.

To examine their sensitivity to changes in the action possibilities caused by tools, we studied how young children used a rod to displace an object. Their sensitivity to how a rod changes the possibilities for action is reflected in the distance from which they choose to act and in the posture with which the toy is displaced. To manipulate the constraints on the action system we varied length, mass, and mass distribution of the rod. The relevance of the present work is that systematically modifying the properties of a rod enables us to systematically modifying the underlying dynamics of the action system. We study children’s sensitivity to how those modifications alter the action possibilities.

New behavioral patterns (e.g., grasping or walking) may emerge when constraints on the action system change or when properties of the environment change (cf. Newell, 1986; 1996). Some constraints on the
action system change slowly due to bodily growth. Growth, such as an increase in length and mass of limbs, affects the forces and torques in the action system. These changes may destabilize the existing behavioral patterns and urge for the emergence of new behavioral patterns to control the relation with the environment. A hand-held object also modifies forces and torques in the joints and muscles and, hence, affects the stable modes of behavior. Therefore, though this change occurs over a much faster time scale than in case of growth, new stable modes of behavior may emerge on the basis of properties of the implement. Note that not only kinetic, but also geometric properties of implements (i.e., the shape) are important. When wielding an implement such as a rod, a child may discover that the tip can contact objects at a larger distance than is possible for the arm alone. A child who holds an implement may explore these new possibilities for action. In sum, the changes in the geometrics and the dynamics of the action system, brought about by grasping an object, set the stage for the emergence of new behavioral patterns to regulate the relation with the environment. In exploring and exploiting the new behavioral patterns, the implement becomes a tool.

We have portrayed bodily growth and the picking up of a tool as presenting similar challenges for the child. Because of this we believe that studying tool use in young children provides a special glimpse into developmental processes. However, we are aware that there are differences in time-scale (i.e., growth takes time; changes due to tools are instantaneous) and in continuity (i.e., growth is gradual; picking up a tool results in abrupt changes) of the change of action possibilities. Still, we are hopeful that the study of children’s sensitivity to the changes may provide insights into how children perceive the (slowly changing) geometric and dynamic properties of their bodies (see Smitsman and Bongers (2000) for a more elaborate discussion of this issue).

We approach tool use as an action problem instead of as a cognitive problem because we believe that there lie its origins (cf. Smitsman, 1997; Smitsman & Bongers, 2000; for a similar approach, see Lockman, 2000). Traditionally, studies of tool use have focussed on cognitive abilities to solve a problem (Bates, Carlson-Luden, & Bretherton, 1980; Köhler, 1927; cf. Lockman, 2000; McCarty, Clifton, & Collard, 1999; cf. Steenbergen, Vander Kamp, Smitsman, & Carson, 1997; cf. Van Leeuwen, Smitsman, & Van Leeuwen, 1994). The emphasis in those studies was on determining whether children, in particular, understood the potential means-to-an-end
that an object might be said to offer. It was assumed that based on this understanding the selection of new action strategies could develop. In short, tool use has been studied to uncover cognitive mechanisms, particularly, how mental capabilities of planning and problem-solving can develop in children (Lockman, 2000; cf. McCarty et al., 1999).

However, such a cognitive approach easily neglects the movement-related aspects that are involved in tool use. For many daily activities, some sort of implement is needed to perform a certain task. For instance, when a cutting action is required, a tool with a sharp edge is used or when extra force is required a pole can function as a lever. In other words, grasping a tool modifies the action system for the specific task at hand. According to a traditional viewpoint, the child needs to focus on the creation of new building blocks in an action plan that incorporate the tool (cf. McCarty et al., 1999). We argue that the child has to discover how to constrain the degrees of freedom in the action system so that the new “end-effector”, which is displaced from the body to the tool, becomes effective. In this process, the child’s focus is presumably on the relation between the new end-effector and the environment (cf. Steenbergen et al., 1997), and not on building blocks of an action plan. In sum, a child who is developing the ability to use a tool has to discover how to modify the action system in keeping with the geometric and the kinetic properties of the tool. The experiments presented here address whether young children are sensitive to new possibilities for action when using a tool. Systematically modifying the different properties of a tool enables us to uncover this sensitivity.

We know that from the end of their first year onward children use implements as a means to perform goal-directed actions (McCarty et al., 1999; McKenzie, Skouteris, Day, Hartman, & Yonas, 1993; Van Leeuwen et al., 1994). However, it is unclear to what properties children are or are not sensitive when using an implement. McKenzie et al. (1993) showed that seated infants, 10 months old, have more difficulty in perceiving the extension of their reaching space by a wooden spoon than 12 months old infants. More important, the results showed that the implement did not extend the reaching range by its full length, suggesting that other variables are also important, though it was unclear what those variables were.

In the experiments that follow, we tested children in the age range of two to four years. We used this group because in this age children use
more and more implements to explore and adapt their action possibilities. From this we conjecture that different levels of skill will be present in this age range. In this way we might unravel how different properties of tools become important as the level of skill increases. In our task, children walked toward a small table while pointing a rod upward about 45° and selected the distance from which they could displace a toy duck on a table. They then lowered the rod and with the tip of the rod slid the duck off the table into a basin of water. Reaching successfully with a rod requires the selection of a distance that fits both the length of the rod and a posture that is a functional platform for the act. A child who is skilled in using tools, and, thus, sensitive to the needed modifications in the action system, should prospectively adapt the distance to the table to accommodate the length of the rod and to permit a posture in which the movement of the rod can be controlled. Children who are not that skilled might not show sensitivity to action system modification. We hypothesize that such children will not adapt the distance to the table to all the properties of the body + rod system.

Our earlier work showed that when adults perform such a task, both the distance to the table and the posture with which an object is displaced are prospectively adapted, depending on the length, mass, and mass distribution of a rod (Bongers, Smitsman, & Michaels, submitted-b). These findings indicate that not only the geometrics but also the dynamics of the action system were of importance for selecting a distance and displacing an object. We concluded that the dynamics of the action system are determined by the ability to manipulate the rod with muscular forces and to balance the body, given the rod’s kinetic properties (mass, mass distribution, etc.). When we say that adults prospectively adapted the selected distance to the table, we mean that they were sensitive to the way the properties of the rod affected the possibilities for displacing the object and prospectively adapted the actions accordingly. We consider adults to be experienced in adapting their actions to properties of tools. Our concern in the present paper is whether young children are sensitive to how properties of the rod affect the action.

Our first interest is simply to establish whether children are sensitive to changes in length of a hand-held rod. In Experiment 1, children used light wooden rods of different lengths to displace the toy. In Experiment 2 and 3 we also changed dynamic properties of the rods to examine the variables and mechanisms underlying the observed adaptations. We did
this by varying length and mass in Experiment 2 and by varying length and mass distribution in Experiment 3. In short, we change the physical properties of a rod used to displace an object to uncover the properties of the body + rod system to which young children adapt their actions.

In all the experiments reported in the present paper, the same experimental setup and task were used. The experiments differed only in the participants, the types of rods used, and some details of the experimental design. Thus, we begin with a general method section that describes features common to all our experiments.

General Method

Participants
The participants were preschoolers who ranged in age from two to four years. All attended a daycare center linked to the Department of Developmental Psychology of the University of Nijmegen. Some of the parents were staff of the university, other parents live in the vicinity of the university. Parents agreed on their child participating in experiments when registering.

Materials
A toy duck (approximately 10 cm wide, 8 cm high, 8 cm in depth, and weighing 44 g) was placed on a table (25x25 cm) adjusted to the participant's wrist height when standing with arms relaxed. The toy was placed against a panel (12.5x25 cm) such that the toy was flush with the front of the table; the panel ensured that the tip of the rod was used to displace the toy. To the left of the table stood a small basin of water (35x35 cm).

A board (2.0 m long and 0.6 m wide) on the floor formed a walkway to the table. The board had alternate light and dark striping of 5 cm perpendicular to its length. A small rail was created along the long sides of the board by five posts (50 cm high) connected by cord.

Procedure
A rod was handed to the participants when they were standing at the beginning of the board. The participant held the rod in his right hand at an angle of about 45° upward from the horizontal and walked toward the
Children reaching with rods

The task was to stop at a distance from which the child could reach and displace the toy on the table, lower the rod, and, using the tip of the rod to slide the duck off the table into the water basin. The approach and reach were videotaped. A video digitizing system was used to compute the positions of handle of the rod, tip of the rod, and the various anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, wrist) in a 2D plane at the moment of object displacement.¹

![Image of children reaching with rods](image)

Figure 1. Several stages in the unfolding of a trial, in which a rod of 0.4 m length was used.

¹ Due to constraints on the experimental room it was not possible to film the left side of the participants. Casual perusals during pilot studies showed that only in a few occasions children showed a preference to use the left hand. However, asking those children to perform the task with the right hand did not seem to affect their performance. Therefore, children were instructed to use their right hand to hold the rod, independent of their hand preference.
Dependent variables
Participants were instructed to not move their feet once they started to lower the rod. Therefore, the selected distance to the table remained unchanged during the displacing of the duck. For the bodily posture with which the object was displaced we took the initial posture in the displacement of the duck. Therefore, all the dependent variables were measured at the onset of the displacement of the duck. There were four dependent variables: one measure concerned the selected distance to the table and the other three measures concerned the posture with which the object on the table is displaced. The foot distance was defined as the horizontal distance between the foot nearer to the table and the table. Casual perusal of the tapes suggested that the general posture is usually upright and that most adaptation takes place in the hip and the arm. Hip angle, shoulder angle, and elbow angle, are dependent measures that reflect such adjustments. The hip angle measured the bending of the trunk, where zero indicated that the trunk was upright. Forward bending (shoulder in front of the hip) had a positive value whereas backward bending in the hip gave a negative value. The shoulder angle of zero was defined as the arm’s aiming straight down. Negative angles have the upper arm behind the shoulder, also referred to as retroflexion, and positive angles indicate anteflexion—the upper arm is anterior to the shoulder. The fully extended elbow angle is defined as 180° and smaller angles denote flexion.

Experiment 1

Experiment 1 was designed to establish young children’s sensitivity for changes in rod length. We asked two-to-four year old toddlers to displace an object using light wooden rods, which varied in length. We studied whether and how the distance to the object and the posture were adapted.

Method

The participants were 19 preschoolers ranging in age from two years and two months to 4 years and 2 months. Four were girls and 15 were boys. The average age of the whole group was three years and two months.
Nine rods (diameter 1.25 cm) were made of light wood (density 0.67 g/cm³); they ranged in length from 0.1 to 0.9 m, in 0.1-m steps. A handle was added to each rod by simply extending it with 6.5 cm. A small disc separated the handle from the rod.

There were 10 conditions, formed by 9 lengths and a condition in which the child displaced the duck with the tip of the fingers (a rod length of zero). Each condition was presented 4 times in randomized blocks that consisted of 10 trials. The experiment was conducted in one session. Due to fatigue or motivation not all participants completed the whole experiment. The total number of trials was 711, an average of 37.4 trials (out of the 40) per participant.

Results and Discussion

Preliminary examination of the videotapes showed that most of the trials were performed with a pattern as might be extrapolated from Figure 1. However, sometimes children choose different strategies, which changed over trials. For instance, sometimes the elbow was put upward so that the rod was controlled with a kind of “overhand” grip. Sometimes a child got engaged in play (for instance, imitating a swordsman) during the experiment, which resulted in a deviation from the regular performance. Because it was difficult to keep the children motivated, those trials were repeated only if the child’s motivation had not lapsed.

Foot distance
A linear regression analysis applied to all the raw data showed that the foot distance (i.e., the distance of the front foot to the table) was systematically adapted to rod length. The longer the rod that was held the further from the table the children stopped to act from (see Table 1). The $r^2$ of .76 shows that the task is performed in a consistent way. The slope of the regression line over all subjects shows that a change in rod length of 1 m results in a change in foot distance of 0.67 m. This finding is consistent with findings of Smitsman (1997), who showed in a similar experiment that the slope of the regression line between rod length and foot distance was 0.66 for two years old and 0.81 for three years old. Similar regression analyses were performed for each participant separately. Those analyses reflected similar patterns as found in the overall analysis. The $r^2$ varied
between .61 and .92 with an average of .81. The slope of the regression lines varied between 0.45 and 0.84.

In sum, the regression line slopes indicated that while children reliably choose a larger distance for a longer rod, they select a relatively shorter distance to the table with longer rods. Because the adaptation in foot distance changes over rod length, it requires an adjustment in posture to make a displacement possible. The following analyses examine how the posture was adapted.

Table 1. Overview of regression analyses of rod length on foot distance for all experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Rod Type</th>
<th>Slope</th>
<th>Constant</th>
<th>$r^2$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>Wood</td>
<td>0.67</td>
<td>0.38</td>
<td>.76</td>
<td>2253.71</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>Wood</td>
<td>0.43</td>
<td>0.25</td>
<td>.37</td>
<td>163.30</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.48</td>
<td>0.25</td>
<td>.38</td>
<td>160.13</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>0.51</td>
<td>0.23</td>
<td>.42</td>
<td>180.79</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>No weight</td>
<td>0.68</td>
<td>0.23</td>
<td>.41</td>
<td>174.34</td>
</tr>
<tr>
<td></td>
<td>Weight handle</td>
<td>0.73</td>
<td>0.22</td>
<td>.47</td>
<td>225.05</td>
</tr>
<tr>
<td></td>
<td>Weight tip</td>
<td>0.64</td>
<td>0.26</td>
<td>.39</td>
<td>160.16</td>
</tr>
</tbody>
</table>

Note. All regression equations had $p < .001$.

Table 2. The means of the significant effects of the postural angles in Experiment 1.

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Hip angle (degrees)</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>29°</td>
<td>44°</td>
<td>144°</td>
</tr>
<tr>
<td>0.1</td>
<td>23°</td>
<td>37°</td>
<td>148°</td>
</tr>
<tr>
<td>0.2</td>
<td>19°</td>
<td>30°</td>
<td>139°</td>
</tr>
<tr>
<td>0.3</td>
<td>16°</td>
<td>23°</td>
<td>139°</td>
</tr>
<tr>
<td>0.4</td>
<td>21°</td>
<td>21°</td>
<td>129°</td>
</tr>
<tr>
<td>0.5</td>
<td>15°</td>
<td>12°</td>
<td>129°</td>
</tr>
<tr>
<td>0.6</td>
<td>18°</td>
<td>8°</td>
<td>120°</td>
</tr>
<tr>
<td>0.7</td>
<td>14°</td>
<td>3°</td>
<td>117°</td>
</tr>
<tr>
<td>0.8</td>
<td>13°</td>
<td>-6°</td>
<td>111°</td>
</tr>
<tr>
<td>0.9</td>
<td>15°</td>
<td>-6°</td>
<td>115°</td>
</tr>
</tbody>
</table>

Postural adjustments

To examine the adjustments in the posture we analyzed each postural angle separately with a multivariate ANOVA with Rod Length (0, 0.1, ..., 0.9m) as a within-subject factor.\(^2\) The analyses were performed on the

\(^2\) We expected the range in which the angles could vary to be much smaller than the range of the foot distance. The explained variance of a regression analysis will be small when the dependent variable
averages for each participant for each condition. Because the rod length linearly increased, we expected a linear adaptation in the dependent variables. Therefore, we looked only at the linear contrast in the analyses. The means of the significant effects are presented in Table 2.

For the hip angle, which was more positive with a more forward bending, the linear contrast was significant \((F(1, 18) = 19.08, p < .001)\), showing that the hip angle decreased when rods were longer (see Table 2). The means show that the decrease in hip angle is most prominent for the short rods, with longer rods the hip angle seems to vary around the 15°. This implied that the children stood more upright with longer rods. The linear contrast was also significant for the shoulder angle, \((F(1, 18) = 68.65, p < .001)\). The shoulder angle was smaller for longer rods, showing that the upper arm was in front of the shoulder for small rods and behind the shoulder for the long rod. The elbow angle was smaller for longer rods, which was shown by the significant linear contrast, \((F(1, 18) = 45.04, p < .001)\). This implied that the elbow was more bend with longer rods.

The analyses on the postural angles showed, in general, systematic adaptations in the posture when rod length was varied. With longer rods, the children stood more upright, held their upper arm behind the shoulder and bend their elbow more. The contribution in the hip seems to be the smallest but because the trunk segment is relatively the largest, a small adaptation in the hip results in a relatively large adjustment in the possible arm extension (measured as the distance the hand extends from the waist). When we take a closer look at the averages presented in Table 2, deviations from the linear trend can be observed, especially for the hip angle, suggesting that the adaptations in the posture were variable, which might indicate that posture was underconstrained. The systematic tendencies in the shoulder and elbow suggest that they form a synergy. However, it is not clear how the adaptations in the hip relate to those adaptations.

In sum, the results showed that children consistently adapted the foot distance to the manipulations of rod length. This seems to indicate that participants were sensitive to the change in action possibilities engendered by reaching with rods. The adaptations in foot distance had a correspondence with rod length smaller than one. This required adaptations in posture to displace the toy with all the rods. We saw that

\[\text{has a relatively much smaller range than the independent variable. Therefore, we choose to analyze the postural angles with ANOVAs.}\]
the posture was adapted systematically to the changes in rod length but that the posture might be underconstrained in the present experiment. In the introduction we hypothesized that a manipulation of the kinetic properties of the rods are important for the posture with which the toy can be displaced. Manipulating the kinetic properties of the rods might enable us to unravel the relative contribution of the posture in the selection of the distance. Therefore, in subsequent experiments we manipulated next to length the mass and mass distribution of the rods.

Experiment 2

In Experiment 1, children adapted their distance from which to displace an object according to the length of a light wooden rod that was used. In the following experiments we try to unravel the variables and mechanisms from which the adaptations originate. In Experiment 2, we manipulated, in addition to length, the homogeneous mass of the rod. We thereby attempted to assess the relative importance of length and kinetic properties of the rod.

We presume that children in our task select a distance to the table that both accommodates the length of the rod and allows for a posture in which the forces that the rod creates can be controlled. This implies that any adaptations in posture necessary for controlling the rod should be reflected in the adopted reaching distance. If we manipulate both length and mass of the rods, what types of adaptations in posture are to be expected? A change in mass influences the forces and torques in the body. Such changes may result in a different constraining of the degrees of freedom in the action system and can influence the postures with which the task is executed. In short, changing length and mass of the rods may create differences in what we term postural constraints.

Postural constraints could affect the action in many different ways, two of which will be discussed here. First, a heavy rod will displace the center of mass (CM) of the body + rod system more toward the rod. This shift in CM could compromise balance and may require compensation. Leaning backwards at the ankle or the hip or more retroflexing the shoulder could offset heavier rods. Second, a heavy rod, especially one creating torques near the maximum of joint moment strength, could severely restrict movement. Chaffin and Andersson (1991) present equations that predict joint moment-strength in any given posture for adults. For each joint, one
can compute the expected muscle-produced joint moment that can counteract moments created by external loads. Using these formulas, we modeled our task and found that if very heavy rods need to be handled, the shoulder needs to be retro-flexed (upper arm behind the shoulder) and the elbow moderately flexed. Although, we are not aware of any literature that computes such relations for children in the age of two to four years old, we assume that the same relations hold for them. In short, we hypothesize that holding relatively heavier rods will require in more retro-flexion in the shoulder and more flexion in the elbow. Those postural adaptations would require the children to select a closer distance to the table with heavier rods.

To be able to select a proper distance to the table—one that anticipates the changed postural constraints—requires sensitivity to those changes. Children who do not have such sensitivity may select a distance that requires an awkward or an uncomfortable posture to displace the toy. For instance, one strategy is to select the distance to the table only based on the length of the rod and not on its mass. In such a case, the selected distance depends on a standard posture and the length of the rod. This standard posture may create comfortable torques for rods of average weight but might create uncomfortable high torques when a heavy rod is used. To reach with a rod in a controlled fashion, the distance to the platform needs to be prospectively adapted to changes in postural constraints. For this reason, we take this distance as a measure of the prospective control. However, it is not only the distance that is informative about the prospective control. The way children followed the task instruction may also give insight in children’s ability to solve the action problem created by properties of the rod. Therefore, we distinguished the degree to which children follow task instructions as an additional measure to determine how the properties of the rod affect the performance. Moreover, we examine differences in performance among children.

Is it reasonable to assume that two- to four-year-old children are sensitive to the changes in postural constraints and adapt the distance to the table? Research in several areas has shown that from a very young age infants are sensitive to their action possibilities and prospectively adapt their actions accordingly. Research on the development of reaching has shown that young infants reach less often for objects when visual information specified that the objects were beyond their reach (cf. Field,
1976; Yonas & Granrud, 1985). This indicates that even at a very young age infants possess sensitivity for their possibilities to act. Furthermore, young children prospectively adapt their actions to upcoming forces. For example, Forssberg et al. (1992) studied the grip force employed when objects that differed in weight had to be lifted with a precision grip. Even in the second year, children used information about the previous object weight. And, closer to the task at hand, Riach and Hayes (1990) showed that four year olds prospectively organize their posture to upcoming forces in the joints when self-initiating a movement. Findings like these show that from early in the development of action capabilities, young children prospectively adapt their actions to upcoming forces, and, thus, appear sensitive to information about those upcoming forces. This makes it likely that in our task the selected distance to the table will reflect adaptations in posture that are required to control the rod when displacing the target.

In the current experiment we manipulated length and mass of rods children used to displace a toy. The heavier rods used in this experiment were intended to be possibly unwieldy or otherwise difficult to handle. Our first interest was in whether the children could execute the task as instructed. We hypothesized that the way the performance of the children deviated from the task instructions was informative about how properties of the tool affected their actions. To examine the performance we contrived a list of qualitative criteria that distinguished successful (stopping and then lowering the rod) from unsuccessful trials (deviating from the task instructions). We measured the selected distance to the platform and the posture with which the toy is displaced in the successful trials. From the postural constraints related to the shift in CM and the maximum torques in the joint we predict that heavier loads on the arm will lead to more retroflexion in the shoulder and smaller elbow angles. Those postural adaptations would require participants to select a closer distance to the table with heavier rods.

Compared to Experiment 1, where we were interested in the effects of rod length, the aims of the present experiment are to reveal the relative importance of kinetic properties of the rod. The effects we expected to find were relatively small, therefore we extended our analyses to scores on the behavioral level. Although, also in Experiment 1 we found deviations from the task instructions we believe that not analyzing them did not influence our findings that children were sensitive to changes in rod length. This was supported by an analysis on the raw data of Experiment 2, which revealed an effect of rod length. This implies that independent of the correction for the following of the task instruction, the analysis revealed sensitivity to rod length.
Method

Twenty-three preschoolers ranging in age from 2 years and 3 months to 4 years with an average age of 3 years participated. Four of them were girls and 19 boys.

Rods with a diameter of 1.25 cm were used; they ranged in length from 0.1 to 0.4 m, in 0.1-m steps. Three sets of four rods were constructed, one set from wood (density 0.67 g/cm³), one from solid aluminum (density 2.70 g/cm³), and one set from solid steel (density 7.80 g/cm³). A handle was added to each rod by extending it 6.5 cm and a small disc separated the handle from the rod. The rods were painted white to make them look similar, independent of the material. To prevent participants from feeling differences among the rod surfaces, PVC-tubing was put over the rod handle.

In each session the 12 rods were presented in a random order. Each session was performed on another day, within a three week period. There were nine children that performed four sessions (48 trials) and 14 children that performed five sessions (60 trials). Two trials were lost due to technical reasons, so that in total data from 1270 trials were gathered.

Two participants were removed because of the way they performed the task. One used a ‘sword-fight’ posture in most of the trials. In this posture the legs were spread and the feet pointed perpendicular to the direction of the rod. The whole body is turned and one shoulder faced the toy, which was displaced with a stretched arm. The other participant ran or skipped when approaching the target. After removing those two participants, we had 1162 trials from 21 children.

Rod characteristics

The torques and forces produced by the rod can be captured at the wrist. To get an indication of the torques a rod can produce, we computed the torque at the end of the handle when the rod was horizontal (i.e., 0°). The torque actual at any moment varies with the orientation of the rod (i.e., whether it points upward or downward) because the horizontal distance between the CM and the end of the handle varies with the rod’s orientation. The largest torque is produced with the rod horizontal

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4 Holding a rod not only affects the torque in the wrist but also the torque in the other joints. However, those other torques will be related to the torques in the wrist. Therefore, we present the torque in the wrist to illustrate our point.
because then the perpendicular distance is largest. Hence, to get an indication of the torque a rod can produce we computed the maximum torque, that is, the torque at the end of the handle when the rod is oriented horizontally. This was done by multiplying the gravity force acting on the rod’s CM by the distance between the CM and the end of the handle.

In Figure 2A we present the torques at the end of the handle when the rod is held horizontal. To be able to compare the rods used in Experiment 2 and 3, the torques of all the rods are presented in one figure. We focus now only on the rods used in Experiment 2. It can be seen that the torque gradually increases for larger rods and rods that have more mass. Because of this increase in torques, the effect of postural constraints related to the shift in CM and muscle strength should be more apparent for those rods. Thus, we expect children to select a closer distance to the platform with longer rods and with rods with more mass.

**Scoring the data**
The children did not always follow the task instruction of simply lowering the rod and displacing the duck equally well on each trial. Therefore, before we analyzed the digitized data, we evaluated the videotapes to distinguish between trials that were performed according to the instructions and trials that were not. Each trial was scored for: 1) the approach to the table, 2) the realization of the actual distance to the table, 3) the posture with which the actual displacement was performed, and 4) the hands that were used. The precise categories with which we scored the children’s behavior are presented in Table 3. Items scored in the left column of Table 3 were considered to be according to instructions whereas items scored in the right column of Table 3 were regarded as contrary to instructions.
Figure 2. (A) The relation between rod length and torque at the end of the handle when the rod is horizontal for the rods used in Experiment 2 and 3. (B) The relation between rod length and second moment of inertia computed in the wrist for the rods used in Experiment 2 and 3.
We considered the way in which participants followed the task instructions regarding the approach toward the table (rod pointing up) and the realization of the distance to the table (in one go) to be indicators of the general level of performance. To determine the level of performance we scored for each trial whether it was scored with item 1, or 2, and 3 in the left column of Table 3. For each participant we computed the percentage of the trials that were scored on those items. When this percentage was larger than 70% the performance was labeled as “instructed-style”, whereas a percentage smaller than 70% was labeled as “alternative-style”. In this way two groups of participants were created. Eleven participants had an alternative-style performance and 10 participants had an instructed-style performance. We expected that children who performed the task according to the task instructions were able to prospect the changed action possibilities in the distance to the platform. Therefore, we distinguished the children according to their performance level and not according to their age.

Results and Discussion

Behavioral analyses
The trials were checked against the criteria listed in the right column of Table 3. In 258 trials, the approach was scored as aberrant. In 198 trials participants adjusted the distance to the table. In 76 trials participants used an awkward posture to displace the object, and in 19 trials participants used two hands to hold the rod when displacing the toy.

In Figure 3, we present the percentage of the trials for each child that fell into none of the categories on the right of Table 3. The results are ordered according to the child's chronological age. It is clear that older children have far fewer awkward and aberrant trials than younger children. The younger children found different solutions to the task than we saw with the older children and that we have reported earlier with adults. These differences compromise some of our dependent variables. For instance, holding the rod horizontally while approaching the toy is a clever way of determining where one should stop, but we do not know whether the child would otherwise have showed prospective control. Therefore, those trials were omitted when analyzing the foot distance and the postural angles.
Table 3. The bases of behavioral categories.

<table>
<thead>
<tr>
<th>Acceptable approach</th>
<th>Aberrant approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The rod pointed upwards and was lowered when the participant stands still.</td>
<td>1. The rod is horizontal during the approach and the participant stops when the tip of the rod is near the table.</td>
</tr>
<tr>
<td>2. The rod points upwards during the approach and is lowered in the last two steps.</td>
<td>2. The rod is horizontal during the approach and the participant stops when the tip of the rod hits the toy-duck or the screen behind it.</td>
</tr>
<tr>
<td>3. The tip of the rod drags over the floor or the rod is pointed downward during the approach.</td>
<td>3. The tip of the rod drags over the floor or the rod is pointed downward during the approach.</td>
</tr>
<tr>
<td>4. During the approach the child swings the rod in the air.</td>
<td>4. During the approach the child swings the rod in the air.</td>
</tr>
<tr>
<td>5. During the approach the rod is held with two hands.</td>
<td>5. During the approach the rod is held with two hands.</td>
</tr>
<tr>
<td>6. The participant is distracted.</td>
<td>6. The participant is distracted.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>One-go distance selection</th>
<th>Distance adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Once the participant stops no adjustments of the feet are made.</td>
<td>7. The approach is made with the rod pointing upward but the feet are adjusted when the rod already is lowered.</td>
</tr>
<tr>
<td></td>
<td>8. During the approach the rod is held horizontal and the distance to the table is based on fine-tuning in the last steps.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal posture</th>
<th>Awkward posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. The legs are relatively straight, the bending at the hip is minimal. The arm is stretched out with the wrist almost on hip height.</td>
<td>9. The feet are spread and the body is turned with one shoulder facing the object (a sword-fighting posture).</td>
</tr>
<tr>
<td>5. During the displacement of the object, the longitudinal axis of the rod is in the walking direction. To displace the object, the movement of the rod is almost perpendicular to its longitudinal axis.</td>
<td>10. The hip is extremely bend.</td>
</tr>
<tr>
<td>11. During the displacement of the object, the longitudinal axis of the rod is held parallel to the frontal plane.</td>
<td>12. The elbow is held upward.</td>
</tr>
<tr>
<td></td>
<td>13. The wrist is pushed against the body (a freezing of the degrees of freedom in the arm), and the torso is turned to make the displacement possible.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>One hand</th>
<th>Two hands</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Only the right hand holds the rod.</td>
<td>14. Both the right hand and left hand are used to control the rod. The left hand might be at the handle or farther down the rod.</td>
</tr>
</tbody>
</table>
The way trials were performed—at what point the participants departed from the instructions—clearly was affected by the rod that was used and thereby might be informative about the way children were able to adapt actions to the properties of the rods. To determine this relation we analyzed how the number of trials scored as successful according to a set of criteria depended on the rod that was used. A variety of sets indicated in Table 3 were analyzed and we report four: (a) Acceptable approach, (b) One-go distance selection, (c) Additional step (trials scored with items 1 and 2 in the left column of Table 3 and item 7 in the right column), and (d) One-hand. The Additional step criterion reflects the trials in which the approach to the platform was acceptable but in which the distance selected in the approach phase was adjusted to make the displacement possible. In other words, children tried to follow the task instructions but adapted the distance when the rod was horizontal. For each dependent variable we performed a three-way multivariate ANOVA with Rod Type

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5 Note that we analyzed the number of trials in which participants followed the task instructions. However, the choice between analyzing the number of appropriate trials or the number of non-appropriate trials is arbitrary. Hence, the analyses presented here are also informative about the relation between trials in which the task instruction is not followed and the rod that is used.
Children reaching with rods

(wood, aluminum, and steel) and Rod Length (0.1, 0.2, 0.3, and 0.4 m) as within-subject factors and Performance level (instructed- vs. alternative-style performance) as a between-subjects factor.

Not surprisingly, there were more trials constituting an Acceptable Approach when the participants carried a shorter rod, $F(3, 17) = 3.94, p < .05$ (0.1 m = 3.90 trials, 0.2 m = 3.72 trials, 0.3 m = 3.54 trials, and 0.4 m = 3.31 trials). There was also a significant interaction between Rod Type and Rod Length ($F(6, 14) = 3.05, p < .05$) Acceptable approaches fell off faster with increasing length when steel rods were used compared to aluminum and wood. This indicated that the steel rods were primarily responsible for the main effect of Rod Length. The only other significant effect was the main effect of Performance Level, $F(1, 19) = 11.78, p < .005$. As was to be expected, this effect showed that the better participants had a higher rate of acceptable approaches than the poorer performers (4.21 trials vs. 3.02 trials, respectively). In sum, those analyses showed that children selected the distance appropriately (i.e., rod pointing rod upward) in less occasions when a long steel rod was used. These results admit to a simple biomechanical explanation—the rod is too heavy to hold upward. But it might also be that it is more difficult to anticipate the effects in the posture when using such a heavy rod. Selecting a distance with the rod lowered during the approach or making an extra last step once a distance is selected might overcome this problem.

The second set we examined was that in which the distance to the table was selected in one go, as opposed to needing an extra step. The three main effects were significant. The effect of Rod Length ($F(3, 17) = 9.73, p < .001$) showed that fewer trials were selected in one go with long rods (0.1 m = 4.16 trials, 0.2 m = 3.95 trials, 0.3 m = 3.85 trials, and 0.4 m = 3.40 trials). The effect of Rod Type ($F(2, 18) = 4.16, p < .05$) showed that fewer trials were selected in one go for rods with more mass (wood = 4.01 trials, aluminum = 3.78 trials, and steel = 3.72 trials). The effect of Performance level ($F(1, 19) = 7.87, p < .05$) showed that participants with a relatively bad performance selected the distance in one go on fewer trials (instructed-style = 4.10 trials and alternative-style = 3.58 trials). This showed that children who performed in an alternative style, used an extra step in more situations. In short, the analysis showed that children often needed an extra step when the rods were long and when the rods were heavy. This seems to suggest that when the postural constraints were more severe, children had more difficulty in selecting the distance to
reach in one go. This indicates that for those rods it was indeed more difficult to prospectively reflect their effects.

Our next analysis showed that the number of additional-step trials was only marginally affected by the length of the rod, $F(3, 17) = 3.04, p = .06$. This effect showed that this number of trials was larger for longer rods ($0.1 \text{ m} = 0.28 \text{ trials}$, $0.2 \text{ m} = 0.47 \text{ trials}$, $0.3 \text{ m} = 0.42 \text{ trials}$, and $0.4 \text{ m} = 0.63 \text{ trials}$), indicating that children had difficulty prospectively picking a distance that would accommodate longer rods. How does this effect relate to the other effects of selecting the distance we found? The one-go trials measured whether the children performed a particular aspect of the trial in an appropriate way. Those analyses revealed that aspects of the length and weight of the rod and the quality of the performance were all important for how children were able to perform the task according to those criteria. However, in the trials that were labeled as additional-step trials, children approached the table in an acceptable way but adjusted this distance to make the displacement possible. The present analysis showed that children adapted the acceptable selected distance in relatively a few trials because the means are relatively small. From this can be conjectured that children tried to select a distance in one go, and, thus, tried to follow the task instructions in one go. We found that only the manipulation of the length of the rod required the children to adapt the distance.

The behavioral analyses done so far indicated that the performance aspects involving selecting a distance are affected by several properties of the rods. But children also need to displace the toy and not just select a distance in our task. To examine the effects of properties of the rod on the posture that children used to displace the toy we examined the number of trials in which only the right hand was used to hold the rod. It was not necessary to perform an ANOVA for this dependent variable because children used two hands only in trials in which the rod was made of steel and when the length was $0.4 \text{ m}$ (there was one exception: one child in the alternative-style group who used two hands with a steel rod of $0.2 \text{ m}$). The children with an alternative-style performance used two hands in 15 trials while instructed-style performers used two hands in four trials. In sum, for long and heavy rods, that is, rods with stronger postural constraints, children more often used their left hand to control the rod. Moreover, this occurred more often for the children with an alternative-style performance. The children who used an alternative-style were in
general younger than the children who followed the instructions. It might be that those younger children needed two hands with the long and heavy rods to produce more force.

The foregoing analyses show that how children followed the task instruction depended on the rod that was used. More precisely, children deviated more from the instructions when the postural constraints were stronger. Moreover, children who were less able to follow the task instructions varied their performance more than children who were able to follow the task instructions. We are also interested in how properties of the rod affect the performance, given that participants followed the instructions. This is what we examine in the following analyses were dependent variables of the digitized data are analyzed.

**Foot distance**

For the analyses on foot distance we used the trials in which the table was approached acceptably (trials scored with items 1 and 2 in the left column of Table 3) and in one go (trials scored with item 3 in the left column of Table 3). In total, in 792 trials participants executed the trials in a qualitatively similar way and were used in these analyses. We computed the regression line of rod length on foot distance, for each rod type separately. The results are presented in Table 1. Again, there is a consistent relation between rod length and foot distance showing that children stood farther from the platform with longer rods. However, the regression lines in Experiment 2 had a much smaller \( r^2 \) than the regression line in Experiment 1. The slope of the regression line was considerably smaller in the present experiment compared to the slope of Experiment 1. To ensure that this difference did not stem from a range effect, we performed a regression analysis of four rod lengths used in Experiment 2 on the foot distance for the data of Experiment 1. The reduction in range did not affect the slope: foot distance = 0.38 + 0.65 * rod length, \( r^2 = .44 \) (see Table 1 for the comparison). This shows that the regression line we revealed for wooden rods depended on whether other rod types were used in an experimental block. In other words, in the context of other rods the children treated a rod differently. It might be that because of the random presentation of the different rod types it was difficult to detect the information necessary to adapt the distance, according to the rod’s mass. Children might use a “safe” strategy: adapting the distance relatively less for larger rods will require relatively
less extension of the arm for the long rods and, thus, relatively smaller torques are created in the joints. The small adaptation in the distance would result in smaller slopes for the regression lines. Though, most important is that those analyses indicate that children are sensitive to the changes in the manipulations.

The foot distance was analyzed by means of a three-way multivariate ANOVA with Rod Type (wood, aluminum, and steel) and Rod Length (0.1, 0.2, 0.3, and 0.4 m) as within-subject factors and Performance level (instructed- vs. alternative-style performance) as a between-subjects factor. The analysis was performed on the averages for each participant and each condition. Because we omitted the trials in which the task was not performed according to the instructions, one child had four missing cells and four children had one missing cell. The remaining 16 children had no missing cells and were included in the analyses. Only the effect of Rod Length was significant, $F(3, 13) = 68.57, p < .001$, showing, as expected, that the children stopped farther from the table when they used longer rods (0.1 m = 0.294 m, 0.2 m = 0.334 m, 0.3 m = 0.383 m, 0.4 m = 0.432 m). However, the effects of mass and level of performance were not significant. The non-significance of the performance level seems to indicate that when children performed a trial according to the instructions, they performed similar, independent of their general level of skill.

We had manipulated mass because of its expected impact on the posture, independent of manipulations of length of the rod. From considerations regarding the shift of CM of body + rod and maximum torques in the joints, we had hypothesized that children would select a distance closer to the table when they used heavier rods. However, contrary to this expectation, children did not prospectively adapt the distance to the platform according to manipulations of mass. However, it still might be that the children adapted the posture with which the toy is displaced systematically to manipulations of mass.

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6 The analyses done on this subset of the participants seems to be representative because similar results were obtained in an analyses in which the missing values were imputed. The imputation was based on the EM procedure in SPSS that estimates the means, the covariance matrix, and the correlation of quantitative variables with missing values, using an iterative process. We assumed the data were normally distributed. Similar to the analysis on 16 children that is presented in the text, the analysis with all the 21 children showed only a significant effect of rod length. Also when we corrected the degrees of freedom this result was similar (although, the correction of the degrees of freedom for the number of participants that had only one missing cell seems extremely conservative because in a multivariate approach one cell is not a degree of freedom).
Postural adjustments
A different subset of trials was selected to analyze the postural angles. We used the trials in which the approach was acceptably, the distance was selected in one go, the posture was normal, and the rod was held in the right hand, that is, trials with items scored only in the left column of Table 3. The analyses were done on a total of 737 trials, in which participants executed the task in a qualitative similar way. All the analyses were done on the averages for each condition for each participant. There was one child who had four missing cells and eight children who had one missing cell. Similar analyses as presented in the following were also performed when the missing cells were imputed (for the procedure see footnote 1). Because this affected the results only to a minor degree we take the results presented here as representative. All the postural variables were analyzed by means of a two-way multivariate ANOVA with Rod Type (wood, aluminum, and steel) and Rod Length (0.1, 0.2, 0.3, and 0.4 m) as within-subject factors and Performance level (instructed- vs. alternative-style performance) as a between-subjects factor.

The hip angle, which was defined as positive with a forward bending of the trunk and negative with a backward bending of the trunk, differed significantly for Rod Length, $F(3, 9) = 8.15, p < .01$. The means (0.1 m = 13.47°, 0.2 m = 14.83°, 0.3 m = 10.48°, 0.4 m = 9.12°) indicated that the hip was most bend forward using rods of 20 cm and that the posture was more upright for the longer rods. This revealed that the posture of the trunk solely depended on the length of the rod, but was this also the case for the posture in the arm? The shoulder angle was positive when the upper arm was in front of the shoulder (anteflexion) and negative when the upper arm was behind the shoulder (retroflexion). Rod Length had a significant effect; $F(3, 9) = 38.23, p < .001$; the shoulder was less anteflexed with longer rods and even retroflexed with the longest rod (0.1 m = 22.37°, 0.2 m = 16.16°, 0.3 m = 5.49°, 0.4 m = -7.80°). The main effect of Rod Type was also significant ($F(2, 10) = 5.15, p < .05$) showing that the shoulder was less anteflexed with heavier rods (wood = 10.91°, aluminum = 9.51°, and steel = 6.75°). None of the other effects were significant. The ANOVA on the elbow angle, which was defined as larger when the arm was more stretched, also showed only significance of the two main effects. Rod Length was significant, $F(3, 9) = 9.54, p < .005$. This shows that the elbow was more flexed with longer rods (0.1 m = 141.86°, 0.2 m = 139.87°, 0.3 m = 135.50°, 0.4 m = 125.97°). In addition, the effect of Rod
Type \( F(2, 10) = 4.00, \ p = .05 \) showed that the elbow was more flexed with heavier rods (wood = 138.72°, aluminum = 135.97°, and steel = 132.71°). Moreover, the main effect of Performance level was significant, \( F(1, 10) = 4.99, \ p = .05 \). The means show that children with a relatively poorer performance level bend their arms more than children with a more instructed-style of performance (instructed-style = 138.94° and alternative-style = 131.41°). This showed that the relatively younger children, who are probably less strong, adopted a posture in which the torques in the joints were smaller. It is peculiar why the level of performance only affects the elbow angle and not the other postural angles.

In sum, the hip is adapted to changes in length whereas shoulder and elbow are adapted to both changes in length and mass. Those adaptations are in the direction as we expected from the postural constraints related to the shift in CM and the maximum joint moment strength. We expected that the shoulder would be less anteflexed (or even retroflexed), and the elbow more flexed with longer and heavier rods. The postural adaptations we found are in agreement with those hypotheses. We also hypothesized that to be able to control the rod during the displacement, those postural adaptations should be reflected, at least in part, in the distance to the table. The analysis on the foot distance showed that children prospectively adapt this distance to changes in rod length but not to changes in mass, which might suggest a nonsensitivity to weight manipulations. However, postural adaptations depended on mass properties of the rod indicating at least some sensitivity to mass in the execution of the displacement. To get a better understanding of the origins of the adaptations in posture we take a closer look at the adaptation we would expect from the displacement of CM due to handling a rod.

**Shift in CM**

To provide a crude test of the relative contributions of shift of the CM, we compared participants’ behavior with what we would expect on the basis of a shift of the CM alone. If the adaptations in posture are equal to the magnitude and in opposite direction of the expected displacement of the CM when holding a rod horizontally, it is more likely that the adaptations in the posture are made to compensate for the shift in the CM. To test this, the body was modeled in 2D; the only degrees of freedom were shoulder
angle and elbow angle of the right arm, along with rod mass and length. For anthropometric measures such as segment mass and segment length, we used the averages of four years old boys and girls found in a Dutch population (Molenbroek, 1994). For estimations of CM’s of body segments we used the anthropometric models presented by Chaffin and Andersson (1991). To simulate the arm posture of the children in the task, we used the averages for all the conditions of the shoulder and elbow angles. We computed the position of the CM of the body + rod system for each of the 12 rods. We averaged the CM displacement over the different rod lengths to be able to interpret the effect of mass.

Holding wooden, aluminum, and steel rods in a horizontal attitude shifted the anterior-posterior position of the CM an average of 0.3 cm, 0.5 cm, and 0.9 cm, respectively. Thus, the CM would tend to shift about half a centimeter more with steel rods than with wooden rods. To compensate for this, and bring the center of pressure to the same position under the foot, one would have to adjust the arm so that the CM shifts closer to the body. The adaptations we found in the arm do indeed bring the CM closer to the body so the direction of shift of CM is right, but what about the magnitude of the displacement in the arm? To compare the predictions based on this simple biomechanical model to the experimental findings we computed the average horizontal shift in the wrist compared to the shoulder for the wooden and steel rods, for trials that were used in the ANOVAs on the postural angles. With steel rods the wrist was 0.2 cm closer to the shoulder than with wooden rods. This shows that the adaptation of the arm posture is in the same direction as what is predicted by the model. However, all those adaptations, simulated and in the experiment, are very small. Our measurements are rather crude and, therefore, definite conclusions, other than that in general the adaptations are in agreement to what we would expect on the basis of the shift in CM, are difficult to draw.

To conclude, the qualitative analysis of the performance revealed that children of a younger age, in general, had more difficulty following the task instructions. However, there was a relation between the properties of the rod and the way children followed the task instructions. This suggests that the deviations from the task instructions that children used are functional. For example, when the postural constraints were stronger (i.e., longer and heavy rods) the rods are easier to control with two hands which was confirmed by our results. The analyses on the digitized data,
were we analyzed sets of trials in which participants performed the task in a qualitatively similar way, led us to conclude that children prospectively adapt the distance to the platform according to changes in length of the rod but not to changes in mass. Moreover, the distance did not depend on the performance level indicating that when a trial was performed according to the task instructions, the participants behaved similar independent on their general level of skill. However, the posture was adapted dependent on the length and mass of the rod. Those results seem to suggest that in this experiment children adjusted the posture to changes in mass of the rod but that this does not affect the prospective control of the action. Using a simple biomechanical model we showed that the postural adaptation might stem from the postural constraints related to the shift in CM. A closer look at the postural constraints we thought might be important in the present task, reveals that those constraints seem to originate from rather static approaches. For example, the shift in CM as measured in our biomechanical model is determined with a static posture in which rods of different properties are held. Moreover, the procedure that Chaffin and Andersson (1991) report with which the maximum joint moment strength relationships are determined is also rather static. However, only studying the effects of postural constraints that were measured in a static situation ignores the fact that in the present task the rod had to be moved sideward and not just had to be held. It might be that the constraints related to the sideward movement of the rod are much more important for the present task, and, therefore, may be reflected in the foot distance. In Experiment 3 we modify the properties of the rod in such a way that the forces required to move the rod sideward vary in a larger range. We do this by modifying the length and the mass distribution of the rods. In this way we examine whether a manipulation of the constraints related to the movement of the rod affects the distance to the platform and the posture with which the children displace the toy.

**Experiment 3**

Experiment 3 was designed to examine the relative importance of constraints related to the sideward movement of the rod that is required to displace the toy. The opportunity for lateral movement of a rod is an aspect of its wieldability. We manipulated length and mass distribution of
the rods which both affect the wieldability of the rod. To manipulate mass
distribution of rods we used hollow tubing in which weight was inserted
in either the tip or at the handle. The postural constraints created by rods
with weight at the tip should be similar to those involved by steel rods,
however, the ease with which a rod with differences in mass distribution
can be wielded might differ from steel rods. In the present experiment we
study whether a manipulation of the wieldability of the rod affects the
prospective control, that is, the distance selected, and the posture with
which the toy is displaced.

The difference between the rods used in Experiments 2 and 3 is in the
location of the CM in the rod. Given a certain length, rods with a
homogeneous mass distribution have their CM located at the same
relative position, independent of the mass of the rod. However, the
position of the added mass determines the location of the CM in rods
with nonhomogeneous mass distribution. The position of the rods’ CM
might be of importance for how a rod can be used to displace an object.
For example, and with other things being equal, a rod with a heavy tip
has more momentum at the tip. Although we are not aware of any
research that directly tests this, such momentum would benefit certain
tasks; smashing an object hard off the table is easier with a rod with a
heavy tip. However, when the task is not smashing but accuracy at the
tip, other mass distributions of the rod might be favorable. For instance, it
might be that a controlled movement of the tip requires the tip of the rod
to be relatively lighter than the handle. This reasoning suggests that
manipulating the mass distribution of the rods might affect the
constraints on the action system in at least two ways: a) postural
constraints related to the shift in CM and to the muscle strength both
important to hold the rod, and b) movement constraints related to the
wielding of the rod.

The wieldability of the rod is reflected by the moments of inertia of the
rod which indicate the resistance to a certain rotational acceleration.7 The
relevant moments of inertia of a rod that is held in the hand are about

7 The explanation of moments of inertia presented here is intended to give the reader an idea of what
the moments of inertia represent. For a more mathematically grounded explanation of moments of
inertia we refer to Barger and Olsson (1995), Gere and Timoshenko (1991), Goldstein (1980), Hartog
axes through the wrist. The center of mass of the rod remains at a fixed distance from the wrist, independent of the wielding. The resistance to rotational acceleration of the rod depends not only on the mass of the rod but also on how the mass is distributed around the axes of rotation. A mass farther away from the axis of rotation has a larger resistance to rotational acceleration about that axis than a similar mass closer to that axis. To manipulate wieldability, then, we placed masses at different distances from the rotation point (the wrist). To compute a rod’s moment of inertia all its masses have to be multiplied by their distances squared from the axis and summed. The resistance to rotational acceleration a rod possesses in Euclidean space can be represented by a 3x3 matrix. The diagonal of this tensor represents the resistance to rotational acceleration about three orthogonal axes which are referred to as the moments. The products of inertia are off the diagonal of this tensor and are the resistances to rotational acceleration in directions perpendicular to those rotations. For each rod that is rotated around the wrist the moments and products of inertia can be computed. Also, for each orientation of a rod in the hand the components of the inertia tensor will differ. However, there is a set of three orthogonal axes in which the products of inertia are eliminated. For this set of axes, that has its origin in the point of rotation and is fixed in the object, the moments of inertia are invariant and independent of the orientation of the rod. In this so-called diagonalized form the eigenvalues or principal moments of inertia are on the diagonal of the tensor. The eigenvalues are the resistance to rotational acceleration around the principal, or symmetry, axes of the rod that also go through the point of rotation. I_1, I_2, and I_3 refer to the eigenvalues or principal moments of inertia. I_1 refers to the largest moment of inertia, I_3 to the smallest, and I_2 to an intermediate value of the moment of inertia.

The rods we use are almost symmetrical in two dimensions or movement directions (i.e., an up-down and a left-right movement) and the only asymmetry is related to the point of rotation that is not in the rod but in the wrist. The end point of the handle of the rod is under the wrist when the rod is held firmly. This implies that for a left-right movement of the rod’s tip, the end-point of the handle is at the axis of rotation through the wrist. For an up-down movement of the tip of the rod, the distance

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8 However, the moments of inertia we computed depended solely on the properties of the rod. Although we assumed that the rod was rotated around the wrist, we did not include the mass of the hand in our computations.
between the end-point of the handle and its axis of rotation is about six cm. This implies that the rod rotates at a distance from the axis. Therefore, the resistance to rotational acceleration is larger for the up-down movement than for the lateral movement of the tip implying that the largest moment of inertia reflects the resistance to movements in the up-down direction and the middle moment of inertia reflects the resistance to lateral movement. However, the magnitudes of \( I_1 \) and \( I_2 \) are nearly identical. The smallest moment of inertia (i.e., \( I_3 \)) reflects resistance to rotations around the longitudinal axes of the rod. For our task, \( I_1 \) and \( I_2 \) seem to be important. Because \( I_2 \) is closest related to movement required to actual displace the toy, we think that changes in this moment might affect the selected distance to the table.

In Figure 2B we present the magnitudes of the second moment of inertia for the rods of Experiment 2 and 3. As can be seen, the second moment of inertia is larger both for longer rods and for rods that have mass more at the tip. The rods used in Experiment 2 show larger moments of inertia with longer and heavier rods. However, the range in which the second moment of inertia is varied differs for the two experiments. The resistance to sideward movement is much larger for the rods with weight at the tip in Experiment 3. From this we expect that if movement constraints are important, its effect will reveal itself with the rods with weight in the tip. To be able to compare the effects we find in Experiment 3 with the effects of Experiment 2, we kept the torques that the rod can produce in a similar range (see Figure 2A). Remember that we conjecture this torque to be related to postural constraints related to the shift in CM and muscle strength, important to hold the rod.

Experiment 3 investigated the effect of nonhomogeneous distribution in hand-held rods on the reaching behavior of young children. Research has shown that people are sensitive to changes in mass distribution of the rod and are able to judge a certain distribution for its appropriateness for a certain task. Beak, Davids, and Bennet (1999) found that experienced adult tennis players who were asked to select a racket to strike a ball to a maximum distance, selected rackets that had weight placed more at the tip than at the handle. However, when engaging in a similar task, children of 10 years old had more difficulty in selecting the appropriate racket.

Testing rods that vary in mass distribution enabled us to evaluate the relative importance of postural constraints and movement constraints (see
Chapter 2

Figure 2). Any differences between the results of Experiment 2 and Experiment 3 will reveal the relative importance of those aspects of the task. Similar to Experiment 2 we performed analyses on behavioral scores and the digitized data.

Method

Twenty-two preschoolers ranging in age from two years and two months to four years and three months participated in the experiment. Three were girls and 19 were boys. The average age of all the children was three years and one month.

The rods varied in length from 0.3 m to 0.6 m with 0.1 m steps.\(^9\) They were made of PVC tubing with a diameter of 2.2 cm. To manipulate the mass distribution, a lead weight of 100 g was inserted into the tube. Three types of rods were constructed in this way: no weight inserted, one weight inserted at the handle, and one weight inserted at the tip. The tubing was painted white and attached to it was a handle of 6.5 cm long and 1.2 cm in diameter. A small PVC disc separated the tubing and the handle.

There were 20 children who performed five experimental sessions and two children who performed four sessions. Each session consisted of twelve trials, the combinations of three rod types and four rod lengths, in a random order. The sessions were performed on separate days, within a three week period. There was a total of 1294 trials because four trials were omitted due to technical problems. Three participants were removed because their performance deviated too much from the behavior of the other participants. One of those three was too often distracted during the experiment and the other two did not point the rod sufficiently upward during the approach phase. After removing the data of those three participants, we had 1123 trials performed by 19 children.

We used the same category scale as used in Experiment 2 (see Table 3), to score the data. Similar to Experiment 2, we scored the way in which participants followed the task instructions regarding the approach to the table (rod pointing up) and the realization of the distance to the table (in one go). Again, we used the 70% criterion to distinguish between an

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\(^9\) The rods had to be longer in this experiment than in Experiment 2 because it is difficult to create differences in mass distribution in rods of 10 cm.
alternative-style and an instructed-style. Nine participants had an alternative-style performance and 10 participants had an instructed-style performance.

Results and Discussion

Behavioral analyses
We checked whether the trials were scored in the right column of Table 3. The approach was scored as aberrant in 251 trials; on 200 trials participants adjusted the selected distance to the table; on 60 trials participants used an awkward posture to displace the object; and on 78 trials participants held the rod with two hands. In general these numbers are in a similar range than Experiment 2. Except for the use of two hands. This implies that when manipulating the mass distribution, participants more often used two hands to control the rod.

In Figure 4 we show by participant’s age the percentages of trials in which the behavior was according to the task instructions. As in Experiment 2, older children tend to have more trials scored as appropriate than younger children. Similar to Experiment 2 we investigated whether the trials in which children did not behave according to the task instructions depended on the rod that was used. Clearly, this might inform us about the way children were able to adapt the actions to the properties of the rods. Similar to Experiment 2 we analyzed four dependent variables: (a) Acceptable approach, (b) One-go distance selection, (c) Additional step (trials scored with items 1 and 2 in the left column of Table 3 and item 7 in the right column), and (d) One-hand. For each of those dependent variables, we computed the number of trials for each rod and for each participant separately. For each dependent variable separately we performed a three-way multivariate ANOVA with Rod Type (no weight attached, weight attached at the handle, and weight attached at the tip) and Rod Length (0.3, 0.4, 0.5, and 0.6 m) as within-subject factors and Performance level (instructed-style vs. alternative-style performance) as between-subject factor.
The number of trials in which the approach was acceptable differed for the Performance level, $F(1, 17) = 6.78, p < .05$. As can be expected, this effect showed that the participants with a alternative-style performance selected the distance to the table in less trials than the participants with an instructed-style performance (instructed-style = 4.05 trials and alternative-style = 3.57 trials). This finding is similar to what we found in Experiment 2. The interaction between Rod Type and Rod Length, $F(6, 12) = 3.08, p = .05$, was also significant. This effect is shown in Figure 5. The most salient effect is that for rods with no weight attached more trials had an acceptable approach when the rods were longer compared to shorter rods whereas for the rods with weight attached at the tip this effect was reversed. This effect shows that the rods that create larger torques and have larger resistance to sideward movement are held upward in less occasions. In Experiment 2 we found that it was difficult to prospect the distance to the table with rods that created larger torques. Lowering the rod in a relatively early stage of the approach might solve this problem for the child. The present findings suggest that children used a similar strategy for the rods when mass distribution is varied. None of the other effects were significant.
The number of trials in which the distance was selected in one go differed only for the main effect of Rod Length \((F(3, 17) = 9.73, p < .001)\). This effect revealed that less trials were selected in one go with long rods (0.3 m = 4.35 trials, 0.4 m = 4.10 trials, 0.5 m = 4.01 trials, and 0.6 m = 3.71 trials), which suggests that children stopped early with longer rods. In other words, with long rods children had difficulty in selecting the right distance to the table and, therefore, more often needed an extra step.

We presumed that the number of trials in which children used an additional step (trials with items 1 and 2 in the left column of Table 3 and item 7 in the right column) reflected the trials in which children needed to adapt the distance that was selected with the rod pointing upward. The number of additional step trials differed for the length of the rod, \(F(3, 15) = 4.13, p < .05\). This effect showed that this number of trials was larger for longer rods (0.3 m = 0.32 trials, 0.4 m = 0.43 trials, 0.5 m = 0.45 trials, and 0.6 m = 0.62 trials); with longer rods children had more difficulty to prospect the distance that enabled them to displace the toy and an additional step was required to displace the toy. Similar to Experiment 2 the number of additional step trials only depended on the length of the rod.

![Figure 5. The interaction between rod type and rod length for the number of trials in which the approach was acceptable in Experiment 3.](image-url)
What were the effects of the properties of the rods on the hands that children used to displace the toy? The number of trials in which only the right hand was used to hold the rod varied for the length of the rod, $F(3, 15) = 3.34, p = .05$ (0.3 m = 4.81 trials, 0.4 m = 4.76 trials, 0.5 m = 4.49 trials, and 0.6 m = 4.28 trials). This significant effect revealed that participants used the right hand only on more occasions when a shorter rod was used. The main effect of Rod Type was also significant ($F(2, 16) = 9.67, p < .005$), showing that one hand was used in less occasions when weight was placed at the tip (no weight = 4.86 trials, weight at handle = 4.87 trials, and weight at tip = 4.03 trials). In sum, this analysis showed that for longer rods and for rods with weight at the tip more often two hands were used to control the rod. Note that the hands used to control the rod were not affected by the performance level of the children.

In the present experiment we addressed the relative importance of the sideward movement of the rod. The analyses done so far showed that participants adapted their performance mainly according to the length of the rod. The present results indicate that the way in which children performed the task does not depend on the rod type except for the hands that control the rod. Moreover, the level of skill of a child does not seem to affect the performance, except for approach phase. This is contrary to what we expected from the results of Experiment 2 because in that experiment the type of rod that was used affected how the task instruction was followed. Before we further interpret this we first analyze the digitized data.

**Foot distance**

For the analyses on foot distance we used the trials on which the distance to the table was selected appropriately (trials scored with items 1 and 2 in the left column of Table 3) and in one go (trials scored with item 3 in the left column of Table 3). In total, 770 trials were used in this analysis. We computed the regression lines (see Table 1) of rod length on foot distance for each rod type separately. The slopes of the regression lines in the present experiment were in a similar range as the slope of the regression line of Experiment 1. The fact that the slopes in the present experiment fell in a different range than the slopes in Experiment 2 indicates that the children adapted their actions depending on the manipulations.

The foot distance was analyzed by means of a three-way multivariate ANOVA with Rod Type (no weight, weight at the handle, and weight at
the tip) and Rod Length (0.3, 0.4, 0.5, and 0.6 m) as within-subject factors and Performance level (instructed- vs. alternative-style performance) as a between-subjects factor. The analysis was performed on the averages for each participant and each condition. Two children were omitted because they had a missing cell; thus, analyses were done on the remaining 17 children. The main effect of Rod Length was significant, $F(3, 14) = 65.74, p < .001$, showing, as expected, that participants stopped farther from the table when they used longer rods (0.3 m = 0.447 m, 0.4 m = 0.503 m, 0.5 m = 0.570 m, 0.6 m = 0.649 m). Moreover, the Performance level was significant ($F(1, 15) = 6.53, p < .05$). The means show that children with a relatively alternative-style of performance selected a closer distance to the table than children with an instructed performance style (instructed-style = 0.52 m and alternative-style = 0.57 m). It might be that, because of the age differences, children in the instructed-style group have longer arms than children in the alternative style group and that as a result of this the distance to the table differs. However, if this was the reason of this effect to occur, it was expected that this effect also would have showed up in Experiment 2, which it did not. Moreover, in that case, the direction of the effect was expected to be reversed from what was actually found. The fact that it did not, indicates that the present finding is related to the way how children with a different performance level deal with a manipulation of the movement constraints of the rod.

The adaptation of foot distance to the length of the rod indicated that the children prospectively controlled their actions according to some, but not all, properties of the rod. However, manipulations of mass distribution did not affect the selected distance to the platform. An analysis when the missing values were imputed showed the same results. Before we further interpret this finding, we take a closer look at the postural adaptations that accompany the adjustments in foot distance.

Postural adjustments
The hip angle, shoulder angle, and elbow angle were analyzed with a similar three-way multivariate ANOVA. As in Experiment 2, those analyses were performed on the trials with items only scored in the left column of Table 3 (a total of 697 trials). There were seven children who had one missing cell so the analyses were done on the remaining 12 children. Performing similar ANOVAs when those missing values were
imputed did not affect the results. Again, all the analyses were done on the averages for each condition for each participant.

The analysis on hip angle showed a significant effect of Rod Length ($F(3, 9) = 3.80, p < .05$). The means showed that the posture was more upright with longer rods (0.3 m = 12.66°, 0.4 m = 11.23°, 0.5 m = 10.19°, and 0.6 m = 8.81°). All the other effects were not significant. The shoulder angle, which was defined as positive when the upper arm was in front of the body, had also only one significant effect ($F(3, 9) = 5.39, p < .05$). The shoulder was less anteflexed with longer rods (0.3 m = 25.57°, 0.4 m = 15.46°, 0.5 m = 12.63°, and 0.6 m = 7.64°). For the elbow angle, defined as larger when the arm was more extended, the main effect of Rod Length was significant ($F(3, 9) = 14.66, p = .001$). The means show that the elbow was relatively more flexed with the longer rods (0.3 m = 145.82°, 0.4 m = 135.84°, 0.5 m = 135.19°, and 0.6 m = 133.34°). The interaction effect of Rod Type and Rod Length was also significant ($F(6, 6) = 10.58, p < .01$) but this effect disappeared when the analysis was performed on the data-set with the imputed data. The averaged pattern of the seven participants who had missing cells deviated from the pattern of the other participants. Therefore, we will not further interpret this interaction effect.

In the present experiment we varied length and mass distribution of the rods to examine the relative importance of postural and movement constraints for the selected distance and the posture. A manipulation of the mass distribution of the rods affects the wieldability of the rods, because its resistance to rotational acceleration varies with the place of the CM. We expected that differences in wieldability between rods might necessitate different postures with which the object can be displaced. Measuring the posture enabled us to determine whether a different posture was required to displace the toy; measuring the foot distance enabled us to determine whether adjustments in posture were prospectively reflected in the distance to the platform. In the present experiment, only the length of the rod reliably affected the distance to the platform and the posture. Therefore, adjustments in posture depending on the mass did not have to be prospectively adapted in the distance. This suggests that changes in the movement constraints do not affect the posture and, thus, not the distance. However, changing the mass distribution affects not only the wieldability but also the torque required to hold the rod. The rods in this experiment were constructed in such a way that the maximal torques required to support the rods fell in the
same range as of the rods used in Experiment 2 (see Figure 2A). In Experiment 2, the arm posture was adapted when torques of the rods varied. We expected that in Experiment 3, different torques required to hold the rod would create differences in postural constraints, and, thus adjustments in the posture as they had in Experiment 2. In sum, effects on arm posture disappeared when the range in which the wieldability of the rod is varied is larger while the torque range is similar, as is done in this experiment. From this we conclude that the arm posture in our task depends on a combination of postural constraints and movement constraints.

The children with an instructed-style performance choose a closer distance to the platform than children with an alternative-style performance. It might be that the children who followed the task instructions adapted the distance to the upcoming forces and torques. However, we found no interaction effects which implies that the adaptation in distance is not differentiated for differences in postural or movement constraints.

Although, the posture may not be differentially adapted for rods in which the mass distribution is modified, children do vary in how they follow the task instructions to displace the toy dependent on the mass distribution. We found that two hands were held on the rod on more occasions for rods with weight at the tip. Thus, despite that the postural angles may not be affected by the mass distribution, the left hand was used more frequently to control the rod. In Experiment 2 also two hands were used for the long steel rods. However, the general number of occurrences of this strategy was much larger in Experiment 3. This implies that for rods with a relatively large resistance to sideward movement, children deviated from the instructions to control such rods. Note that in Experiment 2, manipulations of the mass affected the approach and selection of the distance whereas the manipulations of mass distribution in Experiment 3 resulted in a postural adaptation to displace the toy (i.e., using two hands). To conclude, the results of the analyses on both the digitized and the behavioral data showed the relative importance of postural constraints and movement constraints created by a rod when it is used for displacing an object.
General Discussion

In three experiments we investigated young children’s sensitivity to changes in rod characteristics and consequently possibilities to act, when length, mass, and mass distribution were varied. The task involved displacement of a toy, located at a platform, with the tip of the rod. We measured the selected distance to the platform and posture at the onset of toy displacement to determine components of the action that were affected by properties of the rod. We took the distance as an indicator of prospective control while posture revealed how the displacement was executed.

In Experiment 1, light rods varying only in length were used. Children adapted the distance to the platform and the postural angles in accordance with changes in rod length, indicating prospective control on activities of reaching and displacement. In Experiment 2, length and mass were varied to reveal the role of kinetic properties of the rod. We argued that changes in postural constraints, as a consequence of varied kinetic properties of the rod, required the child to adapt the distance to the platform above and beyond that needed for rod length. Postural constraints related to a shift of CM and greater demands on muscle strength would require children to select a closer distance to the platform with the heaviest rods. As expected, children selected a larger distance to the platform with longer rods. However, contrary to what we expected, the distance to the platform was not adapted to a variation in mass. Arm posture, on the other hand, was adapted to changes in length and mass of the rod. Together, the results showed that adjustments found in the posture were not prospectively reflected in the distance from which children choose to reach. Comparison of the postural adjustments with predictions of a simple biomechanical model revealed that they were in the predicted direction and may have resulted to compensate for the shift of CM, due to the heavier rods.

Postural constraints related to a shift of CM and muscle strength refer mainly to static effects of holding a rod with a certain weight. Emphasizing the importance of those, relatively static, constraints seems to neglect the requirement to move the rod to displace the toy. To examine the importance of constraints related to wielding or moving the rod, we manipulated mass distribution in Experiment 3. Rods were constructed that had a much larger resistance to making a sideward
movement than the rods used in Experiment 2. Results of Experiment 3 showed that, similar to Experiment 2, distance was affected only by length of the rod. Different from Experiment 2, posture depended only on length and not on mass, although, torques created by the rods in Experiment 3 were comparable to the torques created by the rods in Experiment 2. However, in Experiment 3, resistance to sideward movement of the rod was manipulated over a much larger range than in Experiment 2. Therefore, differences in postural adaptations found in Experiment 2 and 3 may have resulted from the larger movement constraints that the rods in Experiment 3 imposed. This hypothesis is supported by the finding that in Experiment 3 children used more often two hands to control the rod when it contained additional mass at the tip (i.e., rods with larger resistance to sideward rotational acceleration), compared to when it had additional mass at the handle. With two hands the rod can be better controlled and larger force, necessary to move the rod laterally, can be produced.

In earlier work we asked adults to perform a similar task (Bongers et al., submitted-b). In those experiments, rod length explained most of the variance, but small and reliable differences in both distance and posture depended on mass and mass distribution. For adults, the selected distance to the platform was prospectively adapted to make a comfortable displacement possible. When mass of the rod was homogeneously varied, participants selected a closer distance to the platform with heavier rods. When additional mass was placed in the rod, a larger distance was selected for rods with weight at the tip compared to rods with weight at the handle. In the experiments presented here, children only adapted the distance according to the length of the rod and not to the mass, or distribution of mass. Compared to adults, children prospectively adapted the distance to only one characteristic of the action system that was changed—length. Adaptations in posture that depended on mass of the rod were not reflected in the distance. Thus, results on distance showed that, unlike adults, children prospectively adapt the behavior only to changes in geometrics, and not to changes in the dynamics of the body + rod system.

However, more global analyses of children’s performance, especially their deviations from task instructions, showed sensitivity to length as well as mass variation of the rod. It is important to note that the alternative performances were always aimed at controlling the relation
between the changed effector system and the environment. For example, lowering the rod in an early phase of the approach and using the gap between the tip of the rod and the toy to determine the distance, is a clever way of regulating the relation between the body + tool system and the environment. Obviously, controlling the relation with the environment is difficult when postural or movement constraints perturb the system. For some children the system may be less stable and be more easily perturbed by changes in the kinetic properties of the rod. Those children may have more difficulty following the task instructions. From this it may be expected that the children who follow the task instructions, will more easily control the rod and prospectively adapt the distance to the platform to all the properties of the rod. Although, in Experiment 2, this prediction was not confirmed, in Experiment 3, the distance to the platform differed for the two groups of children. Children who followed the task instructions selected a closer distance to the table than children who showed more deviations. However, the absence of any interaction effects with variations in length and mass distribution indicates that the selected shorter distance is not yet tuned to those variations. Nevertheless, adapting the distance, although in an undifferentiated way, enables children to control the changed dynamics. Therefore, it seems that children first have to control the dynamics of the action system before they are able to prospectively adapt their actions to it. In other words, in order to learn to control the body + tool system, children first have to explore the dynamics to regulate a stable relation with the environment (i.e., stepping closer to the platform or deviate from the task instructions). When the dynamics can be controlled, prospective control becomes possible.

It might be that children did not adapt the distance to the platform because the allowed variability in the end-point was rather large. For example, the size of the toy that needed to be displaced was much larger than the expected magnitude of the adaptation in the distance to the platform based on postural constraints. When a relatively large variability in the end-point is allowed, there is less need to adapt the distance to the table to adjustments in the posture. However, also in our earlier adult experiments (Bongers et al., 1999), the size of the object that had to be displaced was much larger than the adaptations in the selected distance to the platform. Because we found that manipulations of the dynamics of the action system affected the distance to the table with adults, there was
no reason to assume that those effects would not turn up in the present experiments with children. However, an important methodological point for future research is to tighten the task constraints so that the effects of organismic and environmental constraints cannot be absorbed by variations not captured by our dependent variables.

Figure 3 and 4 show that older children have less difficulty to follow task instructions than younger children do. This indicates that the older children were better able to control the dynamics of the action system that were affected by the properties of the rod. To develop the capacity to act smoothly and efficient, children have to learn to control those dynamics, which, presumably, takes an extended period of time and practice. For example, Thelen and colleagues (Corbetta & Thelen, 1995; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Thelen, Corbetta, & Spencer, 1996) reported that infants in their first year explore the intrinsic dynamics of the action system in order to learn goal-directed reaching. In our task, children also needed to learn the intrinsic dynamics of the arm to control a hand-held rod. The solutions that children found seemed to be aimed at maintaining a stable relation with the environment, that is, controlling the dynamics of the action system, while displacing the toy. Learning to constrain the degrees of freedom in the action system to fit the properties of the environment is a basic problem children face to perform goal-directed actions (cf. Adolph, Eppler, & Gibson, 1993; Ulrich, Thelen, & Niles, 1990). The present results indicate the relative importance of the dynamics for children to learn to control the action system. Moreover, similar to the way children learn to descent slopes (Adolph, 1997), children have to learn to prospect the changes of the dynamics of the action system. We think that learning to solve an action problem (i.e., constraining the degrees of freedom to make a goal-directed action possible) is a basic aspect for the child that learns to use tools (cf. Lockman, 2000; cf. Smitsman & Bongers, 2000).

This is a radical departure from more traditional accounts that tend to focus on mainly cognitive problems that a tool presents to the child (cf. Lockman, 2000). In those views, tool use is a special case of object manipulation, that is, tool use manifests a certain degree of cognitive complexity in that it is an indirect means of goal attainment. In other words, the tool must be incorporated into an action, which involves intermediate steps in an action plan. For example, several investigators have presented stage-models of the development of a tool using skill
(Connolly & Dalgleish, 1989; 1993; McCarty et al., 1999). All those models are strictly defined at the cognitive level and distinguish several stages in the developmental route of a child that masters a tool-using skill. For each of those stages, new processes are added to explain the more complex behavior of the child. However, those models do not account for aspects concerning the action, such as limitations in the movements of the limbs, or differences in forces when handling a filled spoon compared to an empty spoon. We argue that such cognitive stage models do not fully take into account the action problem that a child needs to solve when using a tool (Lockman, 2000; Smitsman & Bongers, 2000). For example, Steenbergen et al. (1997) investigated how young children used a spoon to scoop rice when the orientation between stem and bowl was manipulated. Their results showed that the grip employed and the variation of the position of the grip on the spoon depended on the type of spoon. It was the relation between bowl and rice that was controlled and the degrees of freedom in the action system were constrained dependent on the spoon to realize this. In a similar vein, in our experiments the degrees of freedom in the action system were constrained depended on the properties of the rod to displace the toy with the tip.

Acknowledgements

The authors are indebted to Roelof Schellingerhout and Herb Pick for valuable comments and helpful discussions. We thank Jules van Horen for drawing Figure 1.
Properties of tool and task determine young children's adaptations in actions

Abstract
We studied how the actions of children (two to four years old) depended on properties of tool and task when a rod was used to displace an object. Children held a rod (length .10 to .80 m) with the tip upward, walked toward an object, chose a place to stop, and displaced the object with the rod's tip. In 2 experiments rod length and mass, and the object size were varied. We compared how the older and younger children deviated from the task instruction in the approach, the selection of the stopping place, and the controlling of the rod. Younger children lowered the rod early, during the approach, when a longer rod was used. Moreover, changing rod mass or object size affected actions at a later stage, just before or during the displacement. This did not differ for different ages. We concluded that children need to discover how action possibilities depend on the dynamics of the tool and on the constraints of the task that is performed with it.
Introduction

In general, a tool can be defined as an object that is held in the hand or attached to the body and used to alter the capacity for action (e.g., a knife serves a cutting function that the hand does not). In the present study, young children used a rod as a tool to displace an object. We addressed whether and how young children adapted their actions (e.g., approach, selection of the distance to the object, and how the rod is held) according to properties of the rod and differences in the size of the object that was to be displaced. In this way we examined how the degrees of freedom in the action system were constrained in different phases of the performance and how this depended on tool and task. Comparing children of different ages provides hints as to how the capacity to perform a goal-directed action with a tool may develop. We supposed that a rod changes not only the shape of the body + tool system; it also changes the system's dynamics because the forces and torques required performing a goal-directed action change. Our departure point was that new possibilities for action emerge from changes in the dynamics of the action system that result from changes in its subsystems (cf. Bertenthal & Clifton, 1998; cf. Smitsman, 2000; cf. Thelen & Smith, 1994, cf. Van Geert, 1998). New patterns of behavior can emerge based on how the tool affects the dynamics of the action system (Smitsman & Bongers, 2000). Studying how properties of tools and task determine behavioral patterns may provide an indication of how changing dynamics in the action system affect the development of new actions.

Earlier studies of tool use have primarily focussed on cognitive abilities as prerequisites for tool use. It was supposed that higher stages of cognition needed to be developed because of the indirect goal attainment that was assumed to involve functional tool use. Those studies concentrated on new levels of symbolic thinking and representational skills required using a tool (Brown, 1990; Connolly & Dalgleish, 1989; Greenfield, 1991; McCarty, Clifton, & Collard, 1999). Underlying those viewpoints was the assumption that tool use comprised a higher cognitive level than the perceptions and actions required controlling the tool because of the indirect goal attainment. Thus, the underlying developmental process was discontinuous because of the cognitive leaps that are involved. We advocate a more continuous approach to the study
of tool use because we believe using a tool presents an action problem to the child that has deep similarities with the action problem presented by a growing body (for a similar viewpoint, see Lockman, 2000, and also Smitsman & Bongers, 2000). The action problem a child has to solve entails the constraining of the multiple degrees of freedom (for example, joints and muscles) in the neuromotor system to make a goal-directed action possible. The way in which the system should be constrained changes when the degrees of freedom change, as is the case when properties of tools change (e.g., a rod affects the available length in the hand but also the forces and torques). In a similar way, the constraining of the degrees of freedom is affected during growth (e.g., length and mass of body segments change the available length and the needed forces and torques). On the basis of this reasoning, we argued that the action problem a tool entails is similar to the action problem that a developing child is confronted with when acting without a tool (cf. Smitsman & Bongers, 2000). Although we are aware that changes in action possibilities due to tools are much more abrupt and discontinuous compared to bodily growth, we think that studying tool use may reveal how children solve the changed action problems that a growing body imposes.

In the present experiments we changed the possibilities for action by giving a child a rod with which to displace an object. Children approached an object with a rod pointing upward, stopped, lowered the rod and displaced the object with the rod's tip. To perform the task, children had to stop at a place that accommodated the length of the rod and allowed for a posture with which the rod could be controlled. Important was that children approached the object with the rod pointing upward, so that choosing a good stopping place required prospective adaptation to length and the posture. This task was similar to our earlier experiments (Bongers, Smitsman, & Michaels, submitted-a), however, there the to-be-displaced object was relatively large. In the previous study we varied length, mass, and mass distribution of the rod. We expected length to be related to geometric properties of the body + tool system and the mass (which also depends on the length) to be related to the dynamic properties of this system, with the latter affecting the posture with which the rod can be controlled. We found that children adapted the stopping location to the length of the rod but not to variations in mass and mass distribution. However, the posture with which the object was displaced depended on length, mass, and mass distribution of the rod. Those results
were interpreted as that young children prospectively adapted the distance to the table to changes in the geometrics of the action system but not to the dynamics of the action system (Bongers et al.). In the present paper we aimed to refine those findings by on the one hand using different dependent variables, and on the other hand manipulating characteristics of the to-be-displaced object.

In our earlier study (Bongers et al., submitted-a) we analyzed whether children followed or failed to follow some aspects of the task instructions. Those analyses showed that deviations from task instructions depended not only on variations in geometric properties of the body + tool system but also on variations in dynamic properties. Variations in length, mass, and mass distribution of the rod affected the constraining of the action system at different phases in the execution of the task. This indicated that the main dependent variables used in that study (i.e., selected distance and posture), may not have been sensitive to the adaptations in the action system and that scoring whether task instructions were followed seemed more promising in that respect. Therefore, in the present experiment we applied a fine-grained list of behavioral criteria to evaluate which properties of tool and task determined the children’s actions. We examined different phases of the task execution, such as the approach phase, how the distance is realized and adapted during the displacement. This enabled us to determine which properties of the body + tool system or the task were relevant at particular moments in the performance.

We assumed that children would deviate from the task instruction either to reduce the problems present at the selecting of the distance, or to provide for more control of the rod. Task instructions can be regarded as an extra set of constraints and deviations from the instructions provide information about how children adapt their actions to meet the constraints imposed by the rod and to-be-displaced object. Adaptations of the distance after the rod has been lowered reflect whether the postural adjustments required controlling the rod during the displacement are prospectively reflected in the distance. In our previous study (Bongers et al., submitted-a) we found different deviations from the task instruction; one way to handle the problem of selecting the distance is to lower the rod in an early action stage so that the task reduces to closing the visual gap between tip of the rod and object. An other possibility is to approach the table with the rod upward but fine-tune the position of the feet after the rod has been lowered. Using two hands to hold the rod is a way to get
more control over the rod. These were all deviations from the task instructions that children used while displacing the object with a rod. We believed that those deviations are functional and, as such, their dependence on variations in rod and object properties might show age-related changes in how children develop mastery of the degrees of freedom in the body + tool system. Thus, our analyses focus on the approach, the selection of the stopping place, and the manner in which the rod was controlled.

We asked first whether children adapt their actions both to properties of the rod (i.e., its length and mass) and to properties of the to-be-displaced object (i.e., its size). Varying the mass of the rod affects the rod's kinetics independent of its length. In our previous study (Bongers et al., submitted-a) we found that the posture was adapted to changes in mass whereas selected distance was not. Therefore, variations in mass might result in adjustments of the distance after the rod is lowered, which violates the task instructions. Moreover, the selection of the stopping place becomes more important for a long and heavy rod because fewer postural adjustments are allowed (cf. Bongers et al.). Children who are sensitive to the properties of the body + tool system will, we assume, prospectively adapt the stopping place to the changes in length and mass of the rod. However, children who are less skilled, or have a less stable system, presumably have more difficulty in selecting the stopping place that allows them to displace the object. As in our earlier experiment (Bongers et al.) we expected to find that skilled children deviate in fewer cases from task instructions than children who are less skilled do. Moreover, our earlier results confirmed that younger children were in general less skilled. How children of different ages deviate from the task instruction may shed light on the developing sensitivity to variables of the body + tool system that must be prospectively reflected in activity.

The importance of variables of the body + tool system should depend on the requirements of the task. For example, the amount of force that needs to be produced depends on the weight of the object that needs to be displaced. In addition, the rod's tip needs to be controlled more accurately when a small object is to be displaced than when a large object is to be displaced. Differences in the size of the object will affect the posture with which the rod should be controlled and, we supposed, the deviations from the task instructions. Younger children, who presumably have less stable behavior, will have more difficulty to adapt their actions
in an anticipatory fashion to differences in task constraints. Moreover, we expected that this anticipatory control is more important when the task constraints are more important. For example, displacing a small object (which requires a better control of the tip of the rod) with a heavy rod (which is requires much force to hold) will allow for less freedom in the posture and, thus, the stopping place, than displacing a large object with a light rod. We expect that a difference in allowed variability in the stopping place and the posture will affect how children follow the task instructions.

To summarize, we sought to determine how young children adapt their actions to changes in the action system and changes in the task. The task-displacing an object with the tip of rod-unfolds over several seconds and we were especially interested in whether degrees of freedom at different phases of the action were constrained differently. In Experiment 1 a relatively large object was displaced and only the length of lightweight rods was varied. In Experiment 2 we varied length and mass of the rods and the size of the object. We scored the approach phase, the selection of the distance, and how the rod is controlled against a list of criteria. In this way we examined whether children's deviations from the task instructions was functional in executing the task at hand.

**Experiment 1**

In the first experiment we addressed how the different phases of the performance were affected when the geometrics of the body + rod system were modified. We did this by varying just the length of the rod that consisted of hollow aluminum tubing, which was very light. Obviously, children had to adjust their stopping place dependent on rod length, which is what we found in our earlier experiments (Bongers et al., submitted-a). In that study we found adaptations in the posture due to variations in length. We assume that the determination of the stopping place is more difficult for longer rods because a long rod perturbs the available length in the reaching system more, that is, at a sudden instance a longer length is available. The adaptations in posture and distance, found in our earlier research, might have stemmed from the increased control that is required for longer rods. For example, oscillations in the wrist have larger effects on the tip when the rod is long than when it is short. On the basis of this reasoning we expected that control of longer
rods is more difficult and should yield adapted actions. Moreover, we supposed that effects would be stronger for younger children because their behavior is less stable. To provide for better control of the rod, children could deviate from the task instructions in several ways: (a) simplifying the control problem during the approach phase, which could be done by lowering the rod early, (b) stopping at a roughly determined distance and fine-tuning before or during the displacement, or (c) using both hands to hold the rod to increase the stability of the system. Examining adaptations to length in the unfolding action will, we hope, provide insight in the order of the variables to which children adapt their actions when available reaching length was perturbed.

Before proceeding, two contrasts with our previous research deserve mention. First, to make it easier for the children to hold the rod at 45° during approach, we changed the form of the rod over that used in our previous work (Bongers et al., submitted-a). In former experiments, the handle was just an extension of the rod (an angle of 180°); in the present experiment the angle between handle and rod was 135°, so that the rod would point 45° upward when the handle was parallel to the ground. In the present experiment we kept the size of the object constant, as in previous experiments. However, the allowed variability at the tip was reduced in the depth dimension by using a smaller object than in the earlier experiments. We expected that change in accuracy constraints affected the required control of the rod, and, thus, the adjustments of the action at different phases.

Method

Participants
All participants attended a daycare center linked to the Department of Developmental Psychology of the University of Nijmegen, six of them were girls and 11 were boys. Some of the parents were staff of the university, other parents lived in the vicinity of the university. In the younger sample, consisting of nine children, the average age was two years and seven months (age range from two years to three years and one month). The eight children in the older sample had an average age of three years and nine months (range from three years and seven months to four years).
Chapter 3

Figure 1. A drawing of several stages in a trial in which a rod of 0.8 m length was used.

Materials

Eight rods ranging in length from 0.1 to 0.8 m, in 0.1 m steps were made of aluminum tubing (outer diameter 1.2 cm, inner diameter 1.0 cm). A handle, pre-shaped to fit a child’s hand, was attached to each rod at an angle of 135°. This facilitated the upward pointing of the rod during the approach when the handle was grasped comfortably.

A board (2.0 m long and 0.6 m wide) on the floor formed a walkway to the table (see Figure 1). The board had alternating light and dark 5 cm stripes perpendicular to its length. A small rail was created along the long sides of the board by posts (50 cm high) connected by cord.

A square panel (8x8 cm) attached to a weighted base (3 cm) made of white PVC was placed on a table (25x25 cm) adjusted to the participant’s wrist height when standing with arms relaxed (see Figure 1). On the panel a picture of a water animal was painted (fish, duck, or a sea lion). A small weight was attached to the base of the panel so that it would not topple over. The panel was placed against a screen (12.5x25 cm) such that the panel was flush with the front of the table; the screen ensured that the
tip of the rod was used to displace the object. On the floor to the left of the table stood a small basin of water (35x35x15 cm).

Design and Procedure
There were four experimental sessions within a three-week period. In each session the eight rods were presented in a randomized order.

Rods were handed to the children when they were standing at the beginning of the walkway. The child held the rod in the right hand at an angle of about 45° upward from the horizontal and walked toward the table (see Figure 1). The task was to stop at some point, lower the rod, and slide the panel off the table into the water basin, using the tip of the rod.

The approach and displacement were videotaped. After the experiment was finished, the behavior of the children was scored from the tapes. For each dependent variable different criteria of the performance were important. The criteria important for a dependent variable were explained in the Results and Discussion section.

Results and Discussion

Differences between the age groups
The instructions emphasized three aspects of the task: (a) children had to approach the table with the rod upward, (b) when the rod was horizontal, the position of the feet (i.e., the distance to the object) should not be changed, and (c) the rod was to be held only in the right hand during the selection of the distance. The three levels of Table 1 refer to those three aspects and the left column contains behavioral indicators in which the task instructions were followed. For each participant we computed the percentage of the trials that were scored with all items scored in the left column of Table 1. In Figure 2, we present this percentage of the trials for each child, ordered to the child’s chronological age. It is clear that older children have more trials on which they followed the task instructions than younger children did. Three children, who were among the five

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1 Due to constraints on the experimental room it was not possible to film the left side of the participants. Casual perusals during our earlier studies (Bongers et al., 2000) showed that only in a few occasions children showed a preference to use the left hand. However, asking those children to perform the task with the right hand did not seem to affect their performance. Therefore, children were instructed to use their right hand to hold the rod, independent of their hand preference.
youngest, had fewer than 20% of the trials scored as acceptable. The data of those children were not used for subsequent analyses.

Table 1. The bases of behavioral categories.

<table>
<thead>
<tr>
<th>Acceptable approach</th>
<th>Aberrant approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The rod pointed upwards and was lowered when the participant</td>
<td>1. The rod is horizontal during the approach and the participant stops when the</td>
</tr>
<tr>
<td>stands still.</td>
<td>tip of the rod is near the table or when the tip of the rod hits the object or</td>
</tr>
<tr>
<td>2. The rod points upwards during the approach and is lowered in</td>
<td>2. The tip of the rod drags over the floor or the rod is pointed downward during</td>
</tr>
<tr>
<td>the last two steps.</td>
<td>the approach.</td>
</tr>
<tr>
<td>3. During the approach the rod is held with two hands.</td>
<td>3. During the approach the rod is held with two hands.</td>
</tr>
<tr>
<td>4. The participant is distracted.</td>
<td>4. The participant is distracted.</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>One-go distance selection</th>
<th>Distance adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Once the participant stops no adjustments of the feet are made.</td>
<td>5. One or two extra steps forward are made while the rod is horizontal before the</td>
</tr>
<tr>
<td></td>
<td>displacement starts.</td>
</tr>
<tr>
<td></td>
<td>6. One or two extra steps backward are made while the rod is horizontal before the</td>
</tr>
<tr>
<td></td>
<td>displacement starts.</td>
</tr>
<tr>
<td></td>
<td>7. During the displacement a step forward or backward is made.</td>
</tr>
<tr>
<td></td>
<td>8. The displacement fails, while the rod is still horizontal a new distance is</td>
</tr>
<tr>
<td></td>
<td>selected and the displacement is performed.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>One hand</th>
<th>Two hands</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Only the right hand holds the rod.</td>
<td>9. The left hand holds the rod, either at the handle or farther down the rod during</td>
</tr>
<tr>
<td>5. During the lowering and/or the positioning of the rod, the</td>
<td>the approach and the displacement.</td>
</tr>
<tr>
<td>left hand assists the right hand by holding the rod, either at</td>
<td>10. Only the left hand is used.</td>
</tr>
<tr>
<td>the handle or farther down the rod.</td>
<td>11. The rod is not grasped at the handle but both hands are placed on the rod.</td>
</tr>
<tr>
<td>6. The left hand holds the rod, either at the handle or farther</td>
<td></td>
</tr>
<tr>
<td>down the rod, during just the displacement or during lowering</td>
<td></td>
</tr>
<tr>
<td>and displacement.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. The relation between the age and the number of acceptable trials in Experiment 1.

**Body orientation**

Casual perusals indicated that the task was executed in two ways, which differed mainly in the orientation of the body to the platform. The main difference was whether the front of the body or the left side of the body was facing the platform during the displacement. In one strategy (Table 2, left column) children approached the platform with the rod held in front of them, stopped, lowered the rod and displaced the object while they stood behind the rod, with the front of the body facing the platform. Sometimes the feet were spread or the shoulders were turned, but important was that during the lowering and the displacement the pelvis was perpendicular to the walking direction. We call this body orientation "behind the rod". In the second strategy (Table 2, right column), children approached the platform in a similar way as in the behind the rod orientation but made a final step which brought the body left from the rod, with the left side of the body toward the platform. In this last step, which often was made in the process of lowering the rod, the feet, pelvis,
and trunk were turned; the pelvis and trunk became parallel to the walking direction. The front foot, which was always the left foot in this orientation, was brought much closer to the platform, greatly reducing its distance to the platform. We call this strategy “beside the rod”. Note that, as long as the feet stood still when the rod was horizontal, the children were not constrained by the task instructions to perform the task in either way.

Table 2. Bases of the categories distinguishing the two body orientations

<table>
<thead>
<tr>
<th>Body behind the rod</th>
<th>Body beside the rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The legs are relatively straight, the bending at the hip is minimal. The arm is stretched out with the wrist almost on hip height. Important is that the pelvis is perpendicular to the walking direction.</td>
<td>1. The last step, which is made with the left foot brings the body beside the rod, facing the camera. The feet are turned towards the camera, perpendicular to the walking direction. The right arm is bending backwards when displacing. Important is that the pelvis is aligned with the walking direction.</td>
</tr>
<tr>
<td>2. A similar posture as under (1) but now with feet a bit spread, or the right or left shoulder turned.</td>
<td></td>
</tr>
</tbody>
</table>

The trials were checked against the criteria listed in Table 2. We performed a multivariate ANOVA on the number of trials that were scored as behind the rod with Rod Length (0.1, 0.2, ..., 0.8 m) as within-subject factor and Age Group (a median split of younger vs. older) as between-subject factor. We expected a linear or near-linear adaptation in the performance because rod length increased linearly. Therefore, we looked only at the linear and quadratic contrast in the analysis. The linear contrast of Rod Length was significant ($F(1,12) = 6.72, p < .05$). The means showed that with longer rods, fewer trials were performed behind the rod and, thus, more trials beside the rod (of a maximum of four, the means were 4.0 trials, 4.0 trials, 4.0 trials, 3.9 trials, 3.9 trials, 3.6 trials, 3.5 trials, 3.5 trials for rods increasing in length from 0.1-0.8 m). It might be that standing beside the rod provided for a better control of longer rods, presumably related to fact that a larger part of the rod is above the surface of support created by the feet. Though, the wrist is still at the handle, and, thus, the distance between the rod’s tip and the hand that holds and controls the rod is remote.
The strategy of standing beside the rod was not often selected, given the small decrease in the number of trials. Thus, most of the trials are performed behind the rod. None of the effects of Age Group were significant showing that age did not affect the degree to which children used different orientations to the platform.

**Approach phase, distance selection and control of the rod**

We examined three aspects of performance that might be affected by our manipulations; the approach phase, the realization of the actual distance to the platform, and the hands used to control the rod. We investigated the relation between the experimental manipulations and the point at which participants departed from the instructions. To determine this relation we analyzed how the number of trials scored as successful according to a set of criteria depended on the rod that was used and on the age of the participant. During the scoring of the tapes it became clear that trials fell primarily into five categories. Those five categories were: (a) Rod Horizontal: the trials on which the rod is held horizontal during the approach (items 1 and 2 of the right column of Table 1), (b) Appropriate Distance: trials on which the rod pointed upward during the approach and the feet were not adjusted (trials scored with items 1, 2, and 3 in left column of Table 1), (c) Extra Step: the rods points upward during approach but while the rod is horizontal a forward or a backward step is made before the displacement starts (items 1 and 2 left column and item 5 and 6 right column), (d) Displacement Step: the approach is acceptable and the feet are not adjusted but during the displacement of the object a step forward or backward is made (items 1 and 2 in the left column and item 7 in the right column), and (e) One Hand: only the right hand was used during the approach, the lowering of the rod and the displacement (item 4 in the left column of Table 1). For each dependent variable we performed a multivariate ANOVA with Rod Length (0.1, 0.2, ..., 0.8 m) as within-subject factor and Age Group (younger vs. older children) as between-subject factor. Because rod length was varied gradually, we expected only linear or near-linear adaptations in the dependent variables. Therefore, we looked only at the linear and the quadratic contrast in the analysis. The significant effects and the F-values were reported in Table 3 and the means of the significant interactions were presented in Figure 3.
Figure 3. The means of the significant interactions of Experiment 1.

Table 3. The ANOVA table for the dependent variables of Experiment 1.

<table>
<thead>
<tr>
<th>Effect</th>
<th>df</th>
<th>Rod Horizontal</th>
<th>Appropriate Distance</th>
<th>Extra Step</th>
<th>One Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age Group</td>
<td>1</td>
<td>4.85 *</td>
<td>15.51 **</td>
<td>9.06 **</td>
<td>7.64 *</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rod Length</td>
<td>1</td>
<td>0.65</td>
<td>37.86 **</td>
<td>32.17 **</td>
<td>14.31 **</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age X Length</td>
<td>1</td>
<td>13.82 **</td>
<td>5.84 *</td>
<td>9.28 **</td>
<td>9.24 **</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < .05 **p < .01
The first set represents the trials on which the rod was horizontal during the approach. Holding the rod horizontal is typically expected for longer rods because the length available in the arm is more perturbed. Holding the rod horizontal might overcome the control problems this might impose. Figure 3 and Table 3 show that for the older group of children this number of trials was independent from the rod length, whereas for the younger group, this number of trials was larger and depended parabolic on rod length (the significant interaction was between Age Group and quadratic contrast of Rod Length). As we expected, the young children had most problems with holding the rod upward in the approach phase. However, it is not clear yet why this occurred mostly with the intermediate rod length, and not with the longest rods.

The trials with an appropriate distance showed that older children had only a slight decrease in the number of acceptable distance trials when rods varied from short to longer. However, for the younger children, acceptable trials decreased sharply for the longer rods. Thus, young children more often used deviating solutions to accomplish the task when using longer rods, rods that ought to perturb the system more than short rods. This finding was also in agreement with our global expectation that the behavioral patterns of young children were less stable.

We analyzed the trials on which children approached the platform and stopped with the rod upward but made an extra step when the rod was lowered but before the actual displacement started. On those trials, the distance, which was selected with the rod upward, was not appropriate to make the displacement and, therefore, required an adjustment. We supposed that the extra step was needed because the available distance provided by the body + rod system did not match the stopping place. The increase in such trials occurred primarily for longer rods and the increase was steeper for the younger children then for the older children. We also distinguished between trials on which the extra step was forward and the trials on which the extra step was backward. Figure 4 showed that Forward Step trials had a higher incidence than Backward Step trials; children selected a relatively far distance on more occasions than a relatively close distance. This seems to suggest that the distance to reach provided for by the long rods is more likely to be overestimated than underestimated. In sum, the extra-step analyses indicated that the control problem longer rods imposed resulted in deviations from the instructions for younger children. In the situation that the task was difficult the
children used a clever solution: Stop at a distance to the table, lowering the rod and then make a final step to be able to make the displacement. This extra step can be seen as a fine-tuning of the initial stopping place.

![Figure 4. The number of Forward step and Backward step trials for each rod length.](image)

We also counted the trials on which a step was made during the displacement of the panel. We supposed that on those trials the stopping place was at such a distance that the displacement compromised balance or that the arm could not be comfortably moved. However, in the Displacement-Step trials, children did not adapt the stopping place prospectively but only when the act of displacing had started. Making a step during the displacement occurred on only 8 trials, mostly for the longer rods.

In addition to rod orientation and selected distance, the rod was to be held and controlled. This latter requirement was particularly important for the longer rods because for those rods small rotational movements at the wrist had large effects at the rod’s tip. One way to reduce this tip movement is to hold the rod with two hands (one hand at the handle and the other supporting the rod). To examine whether children used this control strategy, we counted the trials on which only one hand was used throughout the performance. For the older children the number of one-
handed trials remained fairly constant over rod lengths, whereas for the younger children this number sharply decreased for the intermediate and longer rods. Again, we supposed using two hands reduces the movement of the tip and provides for a more stable reaching system.

To summarize, our analyses showed that the length of the rod affected the body orientation with which children displaced the objects—with longer rods the beside the rod strategy was more often used—but that this was independent of the age of the children. All the other dependent variables—reflecting aspects of the approach, distance selection, and how the rod was controlled—showed that younger children deviated from the task instruction more often and the deviation depended on properties of the rod. For example, when the rod was longer, and presumably more difficult to control, either it was lowered early or the child determined the position of the feet by fine-tuning. The children adapted their actions in two ways: (a) two hands were used, presumably to improve the control of the tip, and (b) presumably to overcome difficulties of properly anticipating distance, either the rod was held horizontally or the stopping place was adjusted. Furthermore, these strategies were more prominent in the behavior of the youngest children, which was in accordance with our expectation that their behavioral patterns were less stable. Different kinds of deviations may reflect different strategies; instructions may be regarded as soft constraints that can be neglected when other constraints become stronger (i.e., longer rods or lower level of skill).

The results presented here clearly show the importance of the geometrics of the reaching system for the adaptations in the behavior. However, we think it was not just the geometrics but also the changes in the dynamics of the body + rod system that were of importance in this tool using task. Moreover, we expected those characteristics of the body + rod system to interact with constraints of the task. To disentangle whether and how those aspects determined the behavior, we also varied the mass of the rod and the size of the to-be-displaced object in Experiment 2.

**Experiment 2**

Experiment 1 showed that the actions were adapted according to the length of the rod and that younger children had more difficulty performing the task according to instructions, especially with longer rods. The results pointed to the relative importance of the required control of
the rod. We inferred that the forces required to hold the rod and the allowed movement variability of the rod tip might have determined the behavior observed in Experiment 1. Experiment 2 focussed therefore on these two candidates: the force required to hold and control the rod (affected by the mass) and the end-point variability for the different stages in the action (affected by object size). We assessed how those variables determined the behavior at different phases in the act and how this differed as a function of age. In particular, we varied both the length and mass of the rods to distinguish between effects resulting from geometric and dynamic modifications of the body + tool system. In earlier experiments we showed that children adapted their posture and reaching style to geometric and kinetic properties of the rod (Bongers et al., submitted-a). The present experiment was aimed at unraveling how properties of the tool and characteristics of the task affect different parts of the action and how this changed over age. We looked at how children simplified the control problem regarding the length, how increasing load affected the unfolding of the act, and how stability in the behavior was increased to meet precision requirements.

We expected that adjustments in the action resulting from a change in the dynamics of the body + rod system were more prominent for the small object than for the large object because a small object required a better control of the rod. For example, we expected to find more trials on which an extra step was made to adjust the stopping place when a heavy rod was used to displace a small cube than when a large cube was displaced because a heavy rod allowed for less postural adjustment. Moreover, we expected such effects to be stronger for the younger children because their system is less stable.

Method

Participants
The participants were 17 preschoolers who ranged in age from two years to three years and 11 months with an average age of three years and two months. Six of them were girls and 11 were boys. The children were recruited from the same daycare center as in Experiment 1. Eight children (M age = two years and nine months, range from two years to three years and three months) were assigned to the younger group and nine children
Children’s adaptations in actions

(M age = three years and seven months, range from three years and three months to three years and 11 months) assigned to the older group.

Materials
The nine rods used in this experiment were made of aluminum tubing (outer diameter 1.2 cm, inner diameter 1.0 cm). To manipulate the mass of the rods, steel rods, with a similar length as the aluminum tubing, but varying in diameter were inserted in the tubing. The steel inner rods were kept in place with small plastic discs. Three rod lengths were used: 0.3, 0.4, and 0.5 m. For each of the three lengths, three rod types were constructed: in these types the inner steel rod had a diameter of 0.2 cm, 0.5 cm, and 0.8 cm, respectively. As in Experiment 1, a pre-shaped handle was attached to the rod with an angle of 135°. The masses of the rods and an estimation of the torque produced in the wrist when the rods were held horizontally are presented in Table 4. The estimation of the torque is computed by multiplying the mass, gravitational acceleration, and moment arm (half of the length of the rod).

Table 4. Mass [g] (estimation of the torque produced in the wrist [Nm*1000]) of the rods used in Experiment 2.

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Diameter inner steel tube (cm)</th>
<th>Rod length (m)</th>
<th>Diameter inner steel tube (cm)</th>
<th>Rod length (m)</th>
<th>Diameter inner steel tube (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>85 (125)</td>
<td>122 (180)</td>
<td>195 (287)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>96 (188)</td>
<td>148 (290)</td>
<td>244 (479)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>108 (265)</td>
<td>172 (422)</td>
<td>293 (719)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Between two poles separated by 32 cm, a slot (15x1 cm) in a panel (35x24 cm) could be adjusted to the participant’s wrist height with the arm at the side (see Figure 5). Two small pins that could slide on a carriage behind the panel, stuck out of the slot. A small cube (of 3.5 cm) or a large cube (of 6.5 cm) could be attached to the pins. A hanging weight of 87 g resisted the movement with a force of approximately 0.04 N. The back of the cubes just touched the screen; this ensured that the tip of the rod was used to displace the cube. At the end of the slot, a sticker that pictured food was stuck on the screen. The small cube had a sticker of a rabbit and the large cube had a sticker of a dog. The child was asked to help the animal with feeding by moving it to its food (i.e., move the cube a horizontal distance of approximately 15 cm).
Design
The task was similar to the task in Experiment 1. Participants were handed a rod and asked to walk toward the stand with the rod pointing upward. Participants' task was to stop, lower the rod and displace the cube horizontally. Again, the behavior of the children was scored from the tapes, after the completion of the experiment.

Because of the children's short attention span, the experiment was conducted in five sessions, all in a three-week period. Each rod was presented six times in randomized blocks, three times with the small cube and three times with the large cube. In addition, there were six practice trials for each cube. The order of presentation of the cubes was balanced over participants.

In the first session, we started with four practice trials followed by nine experimental trials. The second session started with one practice trial followed by the nine experimental trials of the second block and then the first three trials of the third block. The third session started with one practice trial followed by six experimental trials of the third block. Then we changed the cube and the session was continued with four practice trials followed by three experimental trials of the fourth block. In the fourth session we started with one practice trial followed by six experimental trials of the fourth block and then six trials of the fifth block. The fifth session started with a practice trial followed by three trials of the fifth block that were followed by the nine trials of the last block.

Results and Discussion

Differences between the age groups
As in Experiment 1, we considered the way in which participants followed the task instructions regarding the approach toward the table (rod pointing up), the realization of the distance to the table (in one go)
and whether the rod was held in the right hand during the approach (one hand). The categories according to which the behavior is scored are listed in Table 1. In Figure 6, the percentage of acceptable trials for each child, according to the three criteria, is shown by age. As in Experiment 1, older children had more trials on which they followed the task instructions than younger children did. Note that the youngest child had a very small percentage of trials that were acceptable. Therefore, the data of this child were not used in further analyses.

Figure 6. The number of acceptable trials ordered according to age for Experiment 2.

**Body orientation**

As in Experiment 1, children varied the body orientation in the experiment. Again, we found two general styles: a behind-the-rod orientation in which the pelvis during displacement was perpendicular to the walking direction and a beside-the-rod orientation in which the pelvis during the displacement was aligned with the walking direction (see also Table 2). We performed a four-way multivariate ANOVA on the number of trials that were scored as behind the rod with Cube Size (small vs. large), Rod Type (steel diameter of 0.2 cm, 0.5 cm, and 0.8 cm), and Rod Length (0.3 m, 0.4 m, and 0.5 m) as within-subject factors and Age Group (younger children vs. older children) as a between-subject factor.
Two main effects were significant. The main effect of Cube Size ($F(1,14) = 4.55, p = .05$) showed that with the smaller cube fewer trials were performed with a body orientation behind the rod (small = 2.7 trials and large = 2.9 trials). The number of trials on which the body orientation was behind the rod decreased for the heavy rods, as the effect of Rod Type showed, $F(2,13) = 6.19, p = .01$ (0.2 cm = 2.9 trials, 0.5 cm = 2.8, and 0.8 cm = 2.6 trials). The main effects showed that the frequency of the body-behind orientation was less, and, thus, the frequency of the body-beside orientation more for the smaller cube and heavier rods.

Only one interaction effect was significant. The interaction between Cube Size and Age Group ($F(1,14) = 5.17, p < .05$) revealed that for the younger group of children the body was oriented behind the rod in fewer trials when the cube was small than when the cube was large (younger: small cube = 2.4 trials, large cube = 2.8 trials). For the older children the number of behind the rod trials were independent from the cube size (older: small cube = 3.0 trials, large cube = 3.0). Stated differently, in a situation where the tip of the rod needed to be controlled more precisely, the younger children used more often the strategy with the body beside the rod.

Together these results show that age, cube size, and rod weight (or perhaps torque) are important factors in determining which orientation a child will use to perform the task. Note, too, that orienting the body beside the rod reduces the shift in the center of mass (CM) as a consequence of holding the rod, because a larger portion of the rod remains above the base of support. Thus, the higher incidence of this strategy with heavier rods might be a result of a compensation of the large shift in CM, however, it is peculiar that this strategy is not used when the CM is shifted due to the length of the rod. In addition, the higher incidence of the beside-the-rod strategy when young children had to displace a small cube suggested that this strategy improved the control over the tip of the rod because this is required for the small cube.

**Approach phase, distance selection, and control of the rod**

We were interested in whether and how the length and mass of the rod and the size of the cube affected the approach, as well as how the distance is realized, and how the rod is controlled. As in Experiment 1, we analyzed the number of trials that were scored according to the criteria: (a) Rod Horizontal, (b) Appropriate Distance, (c) Extra Step, (d)
Displacement Step, and (e) One Hand. For each of these dependent variables we performed a four-way multivariate ANOVA with Cube Size (small vs. large), Rod Type (steel diameter of 0.2 cm, 0.5 cm, and 0.8 cm), and Rod Length (0.3 m, 0.4 m, and 0.5 m) as within-subject factor and Age Group (young vs. old) as between-subject factor.

Holding the rod horizontal during the approach phase made it easy for the child to determine where to stop and we considered this to be a clever way of performing the task. However, such a behavioral pattern prevented the child from showing prospective control, and, thus, compromised some of our other dependent variables. Therefore, we encouraged the children to hold the rod upward during the approach.

The analysis on the number of trials on which the rod was held horizontal during the approach showed two significant main effects, and one significant interaction. The main effect of Rod Length, $F(2,13) = 6.45, p = .01$, showed that the rod was more often held horizontally when it was longer. The main effect of Age Group ($F(1,14) = 6.69, p < .05$) showed that young children held the rod horizontally on more trials than did the older children. These variables also interacted, $F(2,13) = 11.73, p = .001$; only the younger group was responsible for the increase in horizontal-rod trials when rod length increased. This increase occurred mainly between the change in rod length of 0.3 m to 0.4 m (younger: 0.3 m = 0.38 trials, 0.4 m = 0.71 trials, and 0.5 m = 0.69 trials; older: 0.3 m = 0.17 trials, 0.4 m = 0.11 trials, and 0.5 m = 0.13 trials). None of the other effects were significant.

The number of trials on which the rod was held horizontal did not depend on rod type, and, thus, does not appear to be related to the torques and forces required holding the rod. This seems to rule out a strictly mechanical explanation of the incidence of holding the rod horizontal. The non-significance of effects of cube-size effects also seems to rule out explanations in terms of the required precision at the rod’s tip. Holding the rod horizontal only increased for longer rods and younger children. It seems that the younger children just lowered the rod in an early stage of the performance to determine where to stop, that is, lowering the rod provided the necessary information of where the tip was in relation to the to-be-displaced cube, and, thus, where to stop. Our results confirmed that this information was most important in the cases when the available length was perturbed most (i.e., longer rods) and when the system was less stable (i.e., younger children).
The second set we analyzed was the numbers of appropriate distance trials, where the distance to the stand was selected with the rod upward and the feet were not adjusted. All the main effects were significant. The effect of Cube Size showed that with the smaller cube fewer trials had an Appropriate Distance ($F(1,14) = 7.58, p < .05$; small = 2.0 trials and large = 2.3 trials). Moreover, when weight of the rods increased, the incidence of Appropriate Distance trials decreased (0.2 cm = 2.4 trials, 0.5 cm = 2.2 trials, and 0.8 cm = 1.9 trials) as was shown by the effect of Rod Type ($F(2,13) = 11.86, p = .001$). Also Rod Length was significant, $F(2,13) = 3.97, p = .05$, showing that with longer rods fewer trials had an Appropriate Distance (0.3 m = 2.3 trials, 0.4 m = 2.2 trials, and 0.5 m = 2.0 trials). As expected, the effect of Age Group ($F(1,14) = 9.04, p < .01$) showed that older children had more trials with an Appropriate Distance (young = 1.8 trials and older = 2.5 trials).

Two interaction effects were significant. The interaction between Cube Size and Rod Type ($F(2,13) = 10.49, p < .005$) showed that the decrease in the number of Appropriate-Distance trials with more rod mass was steeper for the small cube than for the large cube. This is what we expected; when the tip of the rod needed to be controlled more precisely (i.e., for the small cube), the effects of the dynamics (rod weight) became more important. We found it interesting that the small cube showed the sharpest decrease in the Appropriate-Distance trials between the lightest and the intermediate rods, while for the large cube this decrease was sharper between the intermediate and the heaviest rods. This implied that with a small cube, the weight of the rod needed to increase less before the number of Appropriate-Distance trials decreased whereas with a large cube the weight of the rod could increase more before this number of trials was affected.

Finally, the interaction Rod Length X Age Group ($F(2,13) = 6.71, p = .01$) revealed that for the older group of children the number of Appropriate Distance trials was almost unaffected by increasing rod length, whereas the younger children had a decrease in the number of Appropriate-Distance trials when rods were longer. This means that the younger children were mainly responsible for the main effect of Rod Length. Note that the analyses on the rod horizontal trials showed a similar interaction effect.

To summarize, the incidence of trials on which the approach was made with the rod upward and the feet were not adjusted was lower when a
small cube had to be displaced with the heavy rod, and when younger children used a long rod. The decrease in acceptable trials when young children used a long rod seemed to result from holding the rod horizontal during approach. This suggested that the other effects—rod weight and cube size—depended on how the distance was realized. This was examined in the following analyses.

*Extra Step* trials, recall, were trials on which children had stopped with the rod pointing upward but then took another step (backward or forward) with the rod horizontal. This set of trials represented the trials on which children adapted their initially selected stopping place. The direction of this extra step was most often in the forward direction (forward = 97 trials and backward = 15 trials), suggesting that the distance children initially selected was usually too far from the object, as we had seen in Experiment 1. In the following analysis the forward and backward step trials were pooled.

The number of Extra Step trials increased with increasing weight of the rod (0.2 cm = 0.09 trials, 0.5 cm = 0.27 trials, and 0.8 cm = 0.60 trials), $F(2,13) = 16.55, p < .001)$. In addition, the distance adjusted more with increasing Rod Length, $F(2,13) = 5.31, p < .05$ (0.2 cm = 0.23 trials, 0.5 cm = 0.23 trials, and 0.8 cm = 0.50 trials).

Of the other effects, only one three-way interaction was significant. The Cube Size X Rod Type X Rod Length interaction ($F(4,11) = 8.65, p < .005$) is shown in Figure 7. This interaction is due to one aberrant pair of points, namely the large increase in incidence between 0.4 m and 0.5 m for only the small-cube/0.8 mass condition. While other conditions appear to increase apace, this combination of heaviness, length, and increased need for precision seems to have led to a discontinuous increase in frequency of stepping. Note that none of the age group effects were significant indicating that the problems the increased force presented did not depend on age.

The trials on which the position of one or both feet was adjusted during the displacement of the cube (i.e., *displacement step* trials), varied with Cube Size ($F(1,14) = 7.11, p < .05$). With a larger cube fewer trials were adjusted during displacement (small = 0.21 trials and large = 0.07 trials). The main effect of Rod Length ($F(2,13) = 4.38, p < .05$) had a large decrease in the number of trials between the intermediate and the largest length (0.3 m = 0.15 trials, 0.4 m = 0.19 trials, and 0.5 m = 0.08 trials).
Two two-way interaction effects were significant. The Cube Size X Age Group interaction \( (F(1,14) = 7.11, p < .05) \) revealed that the younger children had more displacement step trials for the small cube than for the large cube while this difference vanished for the older children. The interaction between Rod Type and Cube Size \( (F(2,13) = 5.03, p < .05) \) showed that the number of Displacement-Step trials gradually increased with heavier rods and was largest with the small cube. However, the difference between the small and large cube was relatively large for the intermediate weight.

Given the definition of Displacement-Step trials, adaptations in the chosen distance and adopted posture were presumably not appropriate to displace the cube. Although some of the effects related to the rods were significant, the number of displacement step trials depended most strongly on the size of the cube. This suggests that the children had more difficulty prospectively determining the stopping place appropriate to accuracy constraints, which were affected by cube size. Note, too, that this effect was stronger for the younger children.
The one hand trials, it will be recalled, were the trials on which only the right hand was used to control the rod during all the phases of the task. For those trials the effect of Cube Size was significant, $F(1,14) = 5.62, p < .05$; revealing that for the smaller cube there were fewer one-hand trials (small cube = 2.1 trials and large cube = 2.3 trials). The main effect of Rod Type ($F(2,13) = 10.42, p < .005$) showed that one-hand trials were more infrequent for heavier rods (0.2 cm = 2.6 trials, 0.5 cm = 2.2 trials, and 0.8 cm = 1.9 trials). Moreover, with longer rods there were fewer trials in which one-hand was used ($F(2,13) = 35.50, p < .001$; 0.3 m = 2.5 trials, 0.5 m = 2.3 trials, and 0.8 m = 1.9 trials). The between-subject factor, Age Group, was also significant, $F(1,14) = 17.33, p = .001$; the younger children had fewer one-hand trials than did the older children (1.7 trials vs. 2.7 trials, respectively).

Three two-way interaction effects were significant. The interaction Cube Size X Rod Type ($F(2,13) = 6.51, p = .01$) showed that the number of one-hand trials decreased more for the small cube than for the large cube with increasing weight. The interaction Rod Type X Rod Length ($F(4,11) = 3.9, p < .05$) revealed that the decrease in one-hand trials with rod length was steeper for the heavier rods. Finally, the low frequency of one-hand trials when rods were longer was more dramatic for younger children than for older children, as the interaction Rod Length X Age Group showed, $F(2,13) = 10.95, p < .005$.

Children were less likely to use a single hand when wielding longer and heavier rods and when the cube was smaller. This seems to suggest that the additional hand was used to produce more force to hold the heavier rods. Moreover, using two hands seemed also to provide more stability as is shown by the effect of cube size. However, a horizontal rod produces more torque in the wrist than a rod that is held upward. The interaction between length and age had also been significant for the Rod-Horizontal trials; it might be that both hands are used more often when younger children used longer rods to reduce the torque that one hand had to produce while the rod was oriented horizontally.

To summarize, we varied properties of the rod and properties of the task to determine their relative importance, and how this importance changed over age. The orientation of the body-behind or beside the rod was affected mainly by the size of the cube; with a smaller cube leading to more beside-the-rod trials. Note that in Experiment 1 we found that the number of these trials depended on the length of the rod, which was not
replicated with this smaller range of rod lengths. Three aspects of the task might be of importance to come to a distance from which to displace the cube: (a) aspects related to the increase of the available length, (b) aspects related to required strength to hold the rod, and (c) aspects related to precision requirements. Especially younger children using longer rods held the rod horizontally during the approach. We supposed that the need to create information about where to stop resulted in an early lowering when rods were longer, presumably because the relation between the tip of the rod and the cube was visible at all instances in such a performance. The one-hand trials also decreased for those cases, probably because the torque increased when the rod was horizontal. The increasing load produced by longer and heavier rods forced the children to fine-tune the selected distance when the rod was horizontal, because the extra step trials increased in those cases. This suggested that the postural adaptations required to control those rods, which produced more forces and torques, were not prospectively reflected in the distance. Note that this effect did not depend on age. The position of the feet was adapted in the last phase of the performance when accuracy constraints increased; the number of displacement steps increased mostly for the small cube. The accuracy constraints were not reflected anticipatory in the distance and this depended on the age of the children.

Stated briefly, to create visual information about where to stop the rod was lowered in an early phase. The postural adaptations to control heavier rods were not anticipated but the position of the feet was fine-tuned with the rod horizontal. Postural adaptations to increase the control when accuracy constraints increased were also not anticipated but during the displacement the feet were adapted.

General Discussion

The present study addressed how properties of the action system and properties of the task determined how the degrees of freedom in the neuromotor system were constrained at different phases of acting with a tool. We studied how children two to four years old adapted different phases of their actions when using a rod of some length and mass to displace an object of some size. The task was to approach the object while the rod was held upward, select a distance to the target, lower the rod, and displace the object with the rod’s tip. To displace the object, children
should adapt the selected distance not only to rod length but also to the posture required for controlling the rod during displacement. Changes in the action that took place before the rod was lowered to displace the object may be considered to prepare the displacement of the object. We chose the way participants selected the distance as one of the variables to measure whether actions were anticipatory adapted. Other variables were whether the rod was held upward during the approach phase and the number of hands that controlled the rod.

In the first experiment only the length (i.e., geometrics) of the rod was varied. However, we hypothesized based on our earlier work that not only the geometrics, but also the dynamics of the body + rod system were of importance. Therefore, in Experiment 2 we modified the length and mass of the rod together with the size of the cube that had to be displaced. The goal was to manipulate (a) the force that was required to hold the rod independent of the length of the rod, and (b) the required control of the rod by varying the allowed variability at the tip. We measured how children of different ages varied in their deviation from the task instruction during the approach phase, the selection of the distance, and the control of the rod.

In Experiment 1 we found that the younger group of children adapted different phases of the actions when rods were longer. In Experiment 2 we found that younger children often lowered longer rods early in the approach phase, contrary to instructions, probably to create optical information about the correct stopping place. Holding a rod horizontal produces larger torques than pointing it upward, which was often overcome by using both hands to hold the rod. Notably, the adjustment in action-lowering longer rods early-take place during the approach. We proposed that adaptations in action before the rod was lowered are anticipatory to make the displacement possible. Therefore, we conclude that children prospectively adapted their action when the perturbation of the length of the reaching system was large and that this varied with children's age.

Is the action also prospectively adapted to changes in rod mass and cube size? Recall that we expected the distance to be prospectively adapted to changes in the rod's kinetics or accuracy constraints because of required postural adjustments. We found that children approached the cube with the rod upward but fine-tuned the position of the feet with the rod lowered in more trials for the heavier rods than for the lighter rods.
This strategy occurred with roughly the same frequency for the two age groups. To meet accuracy constraints, younger children in particular, adapted the position of the feet during the displacement. In short, the adjustments in the distance when rod mass and cube size varied took place just before or during displacement. Those results indicate that children did not prospectively adapt the distance to adjustments in body and arm posture required for displacing the cube because the distance adaptations took place after the rod was lowered. Nevertheless, differences in strategy observed with heavier rods and higher precision requirements could suggest anticipatory adaptations to those variables, as long as they occurred before the rod was lowered.

Did we observe any differences in strategy early in the action when rod mass and precision requirements were varied? As to the variations in precision requirements, children used more often two hands-presumably to provide for more stability of the rods-when a small cube had to be displaced with a heavy rod. In almost one third of the trials (56 trials out of the 174 two-handed trials) the two-handed control of the rod started early in the approach phase; in those trials children used two hands in anticipation to the higher precision requirements of the small cube. As to the variations in rod mass the results are more difficult to interpret; the fine-tuning of the distance with the rod lowered can be explained in two ways. One possibility is that children stopped at a place that did not match the posture to displace the cube and it required adaptation a posteriori. An other possibility is that children lowered the rod early to create information to fine-tune the distance according to the posture that was needed. We would call this latter strategy an anticipatory adjustment in the action. Although our scoring-system does not allow us to distinguish between those options, we believe that, given the anticipatory adaptations according to length and cube size, the fine-tuning of the distance with heavier rods is, at least partly, an anticipatory strategy.

To conclude, children prospectively adapted their actions to manipulations of rod length, rod mass, and cube size but in a different way than we expected; children adapted the strategies in the task instead of prospectively adapting the distance. Moreover, younger children used some of the alternative strategies more often. Note that the strategies were functional with regard to the experimental manipulation. For instance, when length of the body + tool system was perturbed, the rod was lowered early to create visual information about the relation between
tip and object, and when more precision at the tip was required the rod was held with two hands to create stability at the tip. In other words, children adapted their strategies to control the relation between the tip of the rod and the to-be-displaced object. The findings indicate that other constraints in the task were neglected to create information to control this relation. For instance, lowering a longer rod early created optical information about tip-object distance and, thus, was directed at controlling the relation between the rod’s tip and the to-be-displaced object, independent of the torque that was produced.

How do the present findings relate to our earlier study where we analyzed selected distance and the posture at the moment the object was displaced, when children reached with rods differing in length, mass, and mass distribution (Bongers et al., submitted-a). We found that children adapted the stopping place to changes in geometries of the action system, whereas the posture and displacement style were also adapted to changes in dynamics of this system. Those earlier results suggested that changes in the geometrics prospectively affected the behavior while children had to learn how to adapt their actions to changes in dynamics. The present findings refined those conclusions; we found differences in strategies according to dynamics of the rod and precision requirements. Therefore, we argue, that children prospectively adapted their actions to changes in geometrics and dynamics of the body + rod system and to changes in the task constraints.

A major difference between the rods used in the earlier experiments (Bongers et al., submitted-a) and the experiments presented here was that the orientation between the rod and the handle differed. However, this did not seem to affect the behavior of the children. We used rods with a pre-shaped handle that made an angle of 45° with the rod, which should facilitate the holding upward of the rod. This upward position of the rod was important because we were interested in how children adjusted their actions prospectively when the action possibilities had changed. Therefore, we had to prevent that participants just controlled the gap between the rod’s tip and the object visually to determine where to stop (which happens when the rod is held horizontal). The length extending from the wrist was independent of the orientation between the handle and the rod. The present results indicated that the children adapted their actions to this length, independent of the orientation between handle and rod.
The effects we found showed that children adapted their actions according to properties of rods and properties of the task; when the constraints of the task changed, different properties of the rod were important to perform the act (see Figure 6). This indicated that the children were able to scale their new action possibilities to changes in constraints of the task. Ulrich, Thelen, and Niles (1990) found that children in the age of 8 months to 25 months selected a stairs with a riser height appropriate for their climbing ability, indicating that children's choice was not arbitrary but scaled to the capacity for action. Similar findings are found in experiments were children have to grasp objects that differ in width. Several studies have revealed that at several ages the way an object is grasped (one handed or two handed) depends on the ratio between hand span and object size (Newell, McDonald, & Baillargeon, 1993; Newell, Scully, McDonald, & Baillargeon, 1989a; Newell, Scully, Tenenbaum, & Hardiman, 1989b; Van der Kamp, Savelsbergh, & Davis, 1998). Those findings show that it was not the absolute size of the object that was of importance for the way it was grasped but how the size related to the size of the hand, that is, which actions were possible. The present findings extend those findings in showing that actions are not just scaled to relations between the task and the metrics of the body but actions are scaled to the dynamics of the action system. The available length in the body + rod system was not just a metric length but a dynamic length, depending on length of the rod, mass of the rod, cube size, and skill of the children. This implies that the possibilities for action in the environment are merely action-scaled (cf. Konczak, Meeuwsen, & Cress, 1992; cf. Oudejans, Michaels, Bakker, & Dolné, 1996). The present results showed that the younger group of children had more difficulty in scaling the actions to a perturbation of length of the action system. Moreover, both age groups, ranging from two to four years, had difficulty in prospectively scaling their actions to changes in the dynamics of the body + rod system which indicated that this capacity needs to be more developed. This latter finding is in agreement with results of Adolph and Aviolo (2000) who changed the body dimensions of young children by attaching weight to their backs. Young walking infants had more difficulty in selecting the slope that could be traversed down when the attached weight was heavier. This implied that those young infants had more trouble adapting the actions to
the new properties of the action system, which is in agreement with our findings.

In the present paper we focussed on the action problem a tool presents to the child. The capacity to use tools starts around the first year of life. For example, McKenzie, Skouteris, Day, Hartman, & Yonas (1993) found that infants of 10 months old have more difficulty in perceiving the reaching range by a wooden spoon than do 12-month-old infants. The experiments presented here addressed candidate variables on the basis of which children discovered the reaching range of an implement that is held. Children functionally adapted their behavior according to their own capacity, the properties of the rod, and the characteristics of the task. This showed that actions were adapted to fit the properties of the body + rod system to possibilities for action in the environment. Research in other areas had shown that learning to adapt actions to the relation between the properties of the child and properties of the task is a general phenomenon during the development (cf. Adolph, 1997; Adolph, Eppler, & Gibson, 1993; Ulrich et al., 1990). Actions are adapted to new possibilities for action of the child, independent whether this change is engendered by bodily growth or by a tool that is held. This strengthens our view that the action problem a tool presents is similar to the action problem a growing body presents to the child. Therefore, studying tool use as an action problem opens vistas to study the processes of change underlying the development of action.

Acknowledgements

The authors are indebted to Roelof Schellingerhout for valuable comments and helpful discussions. We also thank Jules van Horen for drawing Figure 1 and Figure 5.
Abstract
Reaching with a hand-held rod provided a simple paradigm for studying tool use. We asked how reaching was affected by manipulations of rod properties. Adults held a rod (length 0.10 to 1.5 m) with the tip in the air, walked toward an object on a table, chose a place to stop, and displaced the object with the rod’s tip. In 3 experiments, rod length, mass, and mass distribution were manipulated to determine whether and how geometric and dynamic properties affected the chosen distance and the posture. Chosen distances and postures were well accommodated to rod characteristics. Postural adaptations took place only in the arm, which was organized as a synergy. Predictably, rod length explained most of the variance, but small and reliable differences in both distance and posture depended on mass and mass distribution. Chosen distance anticipated not only changes in rod length but also postural adaptations that were needed to control the rod.
Introduction

The amount of routine tool use in human behavior stands in sharp contrast to the amount of attention it has received in psychological studies. The few studies addressing tool use appear to agree on the definition of tools as objects that can be attached to the body to adjust the capacity for action. However, the changes in the capacity for action when using a tool tend not to be the concern in those studies. This is the focus of the present research; we ask which aspects of an action are affected by particular properties of tools. We phrase this question in the context of a simple task involving a tool: reaching with a hand-held rod.

Traditionally, studies of tool use have focussed on cognitive abilities to solve a problem (Bates, Carlson-Luden, & Bretherton, 1980; Köhler, 1927; McCarty, Clifton, & Collard, 1999; cf. Steenbergen, et al., 1997; cf. Van Leeuwen, Smitsman, & Van Leeuwen, 1994). The emphasis in those studies was on determining whether children, in particular, understood the potential means-to-an-end that an object might be said to offer. Most of this early work concerned the features on the basis of which a child selected an object to perform a certain task. In other words, tool use was studied to uncover cognitive mechanisms, particularly, how an individual conceives of the features of an object when using it as a tool.

In the present paper we approach tool use as an action problem instead of as a cognitive problem because we believe that there lie its origins (cf. Smitsman, 1997). Tools are used in situations in which our own action system falls short or when the action goals can be achieved more conveniently. Hence, tools are used to expand and enhance possibilities for action. After Gibson (1979), we label the environmental properties that afford opportunities for action affordances. Their counterparts in the organism, that is, the possible ways the action system can be organized into functional units, are called effectivities (Shaw & Turvey, 1981; Turvey & Shaw, 1979). Affordances and effectivities are mutual concepts and the realization of an action reflects the fit between them (cf. Shaw, Flascher, & Kadar, 1995; cf. Warren, 1984). The characteristics of actions reveal properties of the fit.

Properties of the action system such as segment length, segment mass, and muscle strength determine the way the action system can be organized into functional units (i.e., task-specific devices) to perform a
certain task. An organization in functional units makes it possible for the end-effector of the action system to be properly oriented and to be directed with the right force relative to the environment, given a specific task. If action-system properties such as length or mass change, such as during tool use, the action system might have to be organized differently in order to maintain the relation between end-effector and environment. We are interested in two main changes in the action system that are entailed by using a tool: (a) with most tools, the point where effective contact is made with the environment is displaced from the body to the tool (i.e., the end-effector is displaced), and (b) the dynamics of the effector system, e.g., the forces and torques in the joints and muscles, change. In short, using a tool changes the metrics and the dynamics of the action system.

In this context we define expert tool use: the implement and the action system function as an integrated whole; the new action system consists of body + tool. This means that the affordances in the environment are in reference to the body + tool system. Because the means by which an affordance may be seized are called effectivities, body + tool can be understood as a change in the effectivity (cf. Shaw, et al.1995; cf. Smitsman, 1997). Couched in these terms, our focus is on how changes in effectivities and, thus, changes in affordances, manifest themselves in action.

In the present study, giving an individual a rod changed his or her effectivity for displacing an object. More particularly, participants were asked to walk toward a table while pointing a rod upward about 45° and to select the distance from which they could most comfortably displace a small cylinder on a table. They then lowered the rod and slid the cylinder back and forth with the tip of the rod. Presumably, one’s ability to displace the cylinder depends not only on the length of the rod, but also on one’s ability to manipulate the rod with muscular forces and to balance the body, given the rod’s kinetic properties (mass, mass distribution, etc.). The selected distance should depend on the changes in geometrics and dynamics of the reaching system, and thus, on geometric and kinetic characteristics of rods.

A comfortable reach can be performed in many ways; there is a large number of degrees of freedom available in the reaching system. In our experimental setup, the degrees of freedom include the place to stop and the posture that unfolds to displace the object. By the time the object on
the table is displaced, all the degrees of freedom in the body have been constrained. Characteristics of the rod may affect how this is done. Thus, performing a comfortable reach requires that the selected distance to the table should accommodate the length of the rod and allow for a comfortable posture, implying that postural adaptations necessary to control the rod should be reflected in the adopted reaching distance. The empirical question we tried to answer in the present paper is what characteristics of the rod constrain particular aspects of the action system, in particular, the selected distance to the table and the posture.

Dean, Brüwer, and colleagues investigated how actions were adapted to changes in length of a hand-held pointer. In a series of experiments (Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990; Cruse, Brüwer, & Dean, 1993; Dean & Brüwer, 1994; 1997) participants were asked to make pointing movements with and without pointers 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. Joint angles and kinematics of the trajectories depended on the size of the obstacle and the length of the pointer. On the basis of these findings, Dean and Brüwer (1997) suggested that the trajectory of the end-effector depended on constraints acting in the workspace and in the joint space. Moreover, they suggested that dynamic factors related to the arm posture, for instance, were of importance for the observed behavior. Based on these findings, we expected that in our task the use of a rod as an extension would affect postural degrees of freedom. We did not limit our focus to the elbow angle and the shoulder angle, but included the trunk and other body segments that might be relevant to making a comfortable displacement. We also focussed on whether the chosen distance to an object anticipated those upcoming postural constraints.

Our experiments began by trying to establish the phenomenon, that is, to establish the degree of participants’ sensitivity to characteristics of rods. In Experiment 1, participants used light wooden rods to displace an object. In subsequent experiments, we changed metric and dynamic properties of the rods to reveal underlying variables and mechanisms; we varied length and mass in Experiment 2 and length, mass, and mass distribution in Experiment 3.
Experiment 1

Given the ease and speed with which people organize their action systems to the properties of everyday utensils, we expected that participants would immediately adapt their actions when using a rod for reaching. To determine participants’ degree of sensitivity to changes in rod length when making a reach, we changed the reaching system in a very simple way: participants used light wooden rods of different lengths to make the reach. We studied whether and how the reaching distance and posture were adapted.

To assess which postural adaptations were to be expected when reaching with a rod, we started by examining the postural organizations employed to perform a goal-directed reach without a rod. We assume that posture is organized to meet two fundamental goals: the maintenance of stability and arm movement toward and displacement of the goal. Postural stabilization can be achieved by coordinating the leg, hip, and trunk joint motions (e.g., Crenna, Frigo, Massion, & Pedotti, 1987; e.g., Oddsonn, 1988; e.g., Patton, Pai, & Lee, 1999). A reach in a 2D plane is performed with a close linkage between motion at the elbow and the shoulder (e.g., Lacquaniti & Soechting, 1982). Studies that focussed on the relation between trunk and arm during reaching and grasping—participants were seated and reached to targets within and beyond reach—indicated that trunk served as a postural stabilizer (Kaminiski, Bock, & Gentile, 1995; Ma & Feldman, 1995; Saling, Stelmach, Mescheriakov, & Berger, 1996; Wang & Stelmach, 1998). Ma and Feldman (1995) suggested that two synergies controlled the postural organization: (a) the relation between trunk and arm is controlled leaving the hand unchanged, and (b) the other synergy concerns the control of the arm to bring the hand to the target. One of the key issues we raise in this article is whether similar postural synergies are used when a reach has to be made with a rod.

How did we expect the rod to affect the postural synergies? In the experiments that investigated the contribution of motion in the hip and arm during reaching, the experimenter selected the distance between the body and the target. However, in our experiments, participants were free to choose the distance to the target. Thus, they could vary both the distance from the feet to the object and the distance spanned by posture in bridging the remaining gap. However, these two distances must be
related. In other words, the to-be-adapted posture should be reflected, prospectively, in the stopping place. Rod length was expected to affect posture. We reasoned that a long rod required a better control than a short rod because movements of the wrist result in larger deviations at the tip for a long rod than for a short rod. This implies that longer rods demand a posture that provides for more stable control of the rod. Some of our analyses, therefore, focus on stability-related postural synergies adopted to control rods of different lengths. We ask whether all three factors—the length of the rod, the posture of the arm, and the stability-driven choice of body posture—are reflected in the selected distance to the table.

In all the experiments reported in the present paper, the same experimental setup and task were used. The experiments differed only in the participants, the types of rods used, and minor details of the experimental design. Thus, we begin with a general method section that describes features common to all our experiments.

**General Method**

All participants were right-handed and volunteered to participate in partial fulfillment of a course requirement or they were paid a fee for their participation.

*Procedure and Materials*

A 50 g PVC cylinder (diameter 5 cm, height 6 cm) was placed on a tabletop (25x25 cm). The height of the table was adjusted to the participant’s wrist height with the arm at the side. The back of the cylinder was placed against a barrier 12.5 cm high and the front of the cylinder was aligned with the front edge of the table; this ensured that the tip of the rod was used to displace the cylinder.

The rods stood in a rack about three meters from the target. The participant grasped the rod designated by the experimenter and, with the rod at an angle of about 45° upward from the horizontal, walked towards the table (Figure 1). The task was to stop at a distance from the table from which the object could be displaced most comfortably; then the object was displaced approximately 15 cm back and forth with the tip of a rod (or with the tip of the fingers in the control condition). The approach, reach, and displacement were videotaped. A video-digitizing system was used
Figure 1. Different phases in the unfolding of a trial are shown. Notice that the rod is held up during the approach and that overshoot of the target is prevented.

to determine the positions of the handle of the rod, the tip of the rod, and anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, and wrist) in a 2D plane at the moment the displacement of the object started.\(^1\) We measured *reaching distance* as the distance between the table and the foot nearer to the table.\(^2\) Postural angles were computed from the positions of the joints. The *hip angle* measured the bending of the trunk, using the positions of the knee, hip, and shoulder, where zero was defined as the

\(^1\) We were aware that measuring the behavior at one moment in the action provided a snapshot view of the behavior. This might be at odds with our stated interest in the ‘dynamics of the body + rod system’. However, we were not so much interested in the process of unfolding of the reach but more in whether dynamic aspects of the system affected the reaching distance in an anticipatory way and how the posture with which the object was displaced was adapted to those changes in dynamics. We believe that the adaptations in the actions according to the changes in the dynamics could be revealed in the snapshot manner as presented here.

\(^2\) On most trials the feet were closely aligned, but we always measured reaching distance from the foot closest to the table.
trunk being in line with the thigh. Forward bending (shoulder in front of the hip) had a positive value whereas backward bending in the hip gave a negative value. A shoulder angle of zero was defined as the arm’s aiming along the trunk. Negative angles have the upper arm behind the shoulder, also referred to as retroflexion, and positive angles indicate anteflexion—the upper arm was anterior to the shoulder. A fully extended elbow angle was defined as 180° and smaller angles denote flexion.

**Data analysis**
A preliminary analysis was done to remove the outliers from the data. Separate regression analyses on individual subjects were performed for the vertical and anterior-posterior values of each joint with rod length as the independent variable (if mass was also a condition, those analyses were done for each mass condition separately). Trials on which any unstandardized residual exceeded four times the SD from the mean of the residuals for that condition were omitted.

**Method**

Participants ranged in ages from 20 to 38 years, 7 were females and 2 were males. The rods had a diameter of 1.25 cm and ranged in length from 0.1 to 1.5 m, in 0.1 m steps. The rods were constructed from wood (density 0.67 g/cm³). A handle was added to each rod, extending it 11.5 cm. A small plastic disc divided the handle from the rod.

There were 16 conditions, formed by 15 lengths and the tip of the fingers (which appears in our tables and figures as a rod length of 0.0). Each condition was presented 10 times in randomized blocks, for a total of 160 trials per participant, run in one session. Of the total number of 1440 trials, 59 were omitted because a residual of the regression analyses exceeded the threshold.

**Results and Discussion**

**Reaching distance**
To examine whether the selected distance to the table depended on rod length, we performed a multivariate ANOVA on the reaching distance
Geometrics and dynamics

(i.e., the distance of the front foot to the table) with Rod Length (0, 0.1, …, 1.5 m) as a within-subject factor. The analysis was performed on the means of each participant in each condition. We expected that the distance gradually increased with longer rods, and, therefore, we only looked at the linear contrast. Participants chose to stop farther from the table with longer rods, $F(1,8) = 1419.21, p < .001$ (see Table 1 for the means and the standard deviations). This analysis showed reaching distance gradually varied with rod length, implying that participants were highly sensitive to changes in length when making a reach.

Table 1. Means (SD) for the significant effects of the ANOVA’s of Experiment 1.

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Reaching distance (m)</th>
<th>Ankle angle (degrees)</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.45 (0.11)</td>
<td>98.03 (3.35)</td>
<td>38.05 (11.98)</td>
<td>154.77 (10.69)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.47 (0.12)</td>
<td>98.14 (4.26)</td>
<td>31.31 (11.35)</td>
<td>150.29 (8.66)</td>
</tr>
<tr>
<td>0.2</td>
<td>0.53 (0.17)</td>
<td>97.85 (4.10)</td>
<td>29.13 (11.76)</td>
<td>148.30 (8.19)</td>
</tr>
<tr>
<td>0.3</td>
<td>0.59 (0.15)</td>
<td>96.97 (3.43)</td>
<td>24.41 (10.09)</td>
<td>145.14 (9.18)</td>
</tr>
<tr>
<td>0.4</td>
<td>0.70 (0.10)</td>
<td>96.63 (3.05)</td>
<td>23.30 (10.76)</td>
<td>142.26 (8.49)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.78 (0.10)</td>
<td>96.53 (3.22)</td>
<td>20.81 (10.78)</td>
<td>139.40 (9.55)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.86 (0.10)</td>
<td>96.15 (3.25)</td>
<td>18.18 (12.41)</td>
<td>136.04 (9.35)</td>
</tr>
<tr>
<td>0.7</td>
<td>0.95 (0.08)</td>
<td>95.93 (3.19)</td>
<td>15.71 (9.90)</td>
<td>135.19 (9.27)</td>
</tr>
<tr>
<td>0.8</td>
<td>1.03 (0.11)</td>
<td>95.72 (3.04)</td>
<td>14.96 (13.48)</td>
<td>134.46 (9.75)</td>
</tr>
<tr>
<td>0.9</td>
<td>1.13 (0.10)</td>
<td>95.53 (3.00)</td>
<td>13.58 (12.89)</td>
<td>132.28 (9.37)</td>
</tr>
<tr>
<td>1</td>
<td>1.18 (0.11)</td>
<td>94.73 (2.95)</td>
<td>7.82 (15.73)</td>
<td>128.63 (10.40)</td>
</tr>
<tr>
<td>1.1</td>
<td>1.27 (0.10)</td>
<td>94.47 (3.06)</td>
<td>7.24 (13.29)</td>
<td>127.61 (10.27)</td>
</tr>
<tr>
<td>1.2</td>
<td>1.40 (0.12)</td>
<td>94.76 (3.68)</td>
<td>11.29 (16.53)</td>
<td>129.55 (10.91)</td>
</tr>
<tr>
<td>1.3</td>
<td>1.48 (0.10)</td>
<td>95.00 (3.80)</td>
<td>9.04 (15.05)</td>
<td>128.09 (10.54)</td>
</tr>
<tr>
<td>1.4</td>
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<td>94.54 (2.89)</td>
<td>7.76 (18.21)</td>
<td>128.29 (11.93)</td>
</tr>
<tr>
<td>1.5</td>
<td>1.65 (0.12)</td>
<td>94.44 (3.18)</td>
<td>8.31 (16.89)</td>
<td>127.52 (11.49)</td>
</tr>
</tbody>
</table>

To examine whether participants differed in their strategies, we also performed linear regression analyses on the raw data of each participant separately. Those analyses showed that within participants, the reaching distance can be predicted well from the rod length; as can be seen in Table 2, the $r^2$'s were high and the slopes ranged between 0.74 and 0.93. These results showed that the rod length explained the vast majority of the variance in the reaching distance within participants. The adaptation in the reaching distance to rod length seemed to be immediate. Participants received visual and haptic feedback through performing the reach; hence, if the reaching distance were systematically uncomfortable, for example, standing too close with longer rods, a shift in reaching distance over the
repeated trials would be expected. However, our data showed no differences over the repeated trials; the data were highly consistent.

Table 2. Regression analyses between rod length and reaching distance.

<table>
<thead>
<tr>
<th>Participant</th>
<th>intercept</th>
<th>slope</th>
<th>$F$</th>
<th>$df$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35</td>
<td>0.91</td>
<td>3628.91</td>
<td>1, 151</td>
<td>.96</td>
</tr>
<tr>
<td>2</td>
<td>0.44</td>
<td>0.79</td>
<td>2744.90</td>
<td>1, 148</td>
<td>.95</td>
</tr>
<tr>
<td>3</td>
<td>0.41</td>
<td>0.76</td>
<td>4146.29</td>
<td>1, 150</td>
<td>.97</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>0.88</td>
<td>3660.44</td>
<td>1, 153</td>
<td>.96</td>
</tr>
<tr>
<td>5</td>
<td>0.31</td>
<td>0.81</td>
<td>3915.82</td>
<td>1, 153</td>
<td>.96</td>
</tr>
<tr>
<td>6</td>
<td>0.40</td>
<td>0.86</td>
<td>3161.86</td>
<td>1, 155</td>
<td>.95</td>
</tr>
<tr>
<td>7</td>
<td>0.54</td>
<td>0.74</td>
<td>1672.08</td>
<td>1, 150</td>
<td>.92</td>
</tr>
<tr>
<td>8</td>
<td>0.29</td>
<td>0.83</td>
<td>1006.66</td>
<td>1, 149</td>
<td>.87</td>
</tr>
<tr>
<td>9</td>
<td>0.23</td>
<td>0.93</td>
<td>6541.98</td>
<td>1, 154</td>
<td>.98</td>
</tr>
</tbody>
</table>

*Note.* All the regression equations had $p < .001$.

**Posture**

To see whether adaptations in reaching distance were related to adaptations in posture, we examined the change in postural angles with different rod lengths. Preliminary examination of the videotapes showed that, in general, with shorter rods, participants leaned forward somewhat and extended their arms. With longer rod lengths, the posture was more upright and the elbow was held closer to the body. In Figure 2 we show an example of how one participant adapted his posture to different rod lengths. The points shown in Figure 2 are averages over the 10 repeated measures for each rod for Participant 3.

We attempted to determine whether functional synergies were formed. In the literature, it has been suggested that two synergies are formed to perform goal-directed reaching actions: (a) a synergy coordinating the motion between trunk and arm, and (b) a synergy coordinating the motions of the angles within the arm (cf. Ma & Feldman, 1995). To assess whether those synergies were formed to control the rod in our task, we performed regression analyses between the angles. Because it is possible that participants may have differed in the synergies, these analyses were done separately for each participant.

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3 Some of the participants used also rotation in the trunk around the vertical axis, but this behavior could not be reliably measured because of the two-dimensional recording system.

4 The papers that originally addressed the occurrence of those synergies measured the relation between the angles within a trial, during the act of reaching. In the current experiment we measured the relation between angles at one moment in a trial. We analyzed how the synergy varied over trials.
Figure 2. The averaged posture of Participant 3 is shown for the different rod lengths. The posture with the smallest reaching distance belongs to rod length zero whereas the posture with the largest reaching distance belongs to the longest rod. Each dot is a value averaged over 10 repeated measures. The dots represent the toe, ankle, knee, hip, shoulder, elbow, and wrist of the right side of the body.

To examine the arm synergy, we compared shoulder angle and elbow angle. Table 3 shows that for most participants the adjustments in shoulder and elbow angle had a relatively high correspondence, implying that the shoulder and elbow angle were organized as a synergy. Remember that the shoulder angle increases when the upper arm is put more forward and the elbow angle increases when the arm is more stretched. The positive slope of the regression lines indicated that the upper arm was put more forward when the elbow was more stretched.

To evaluate whether the adjustments in the hip angle were related to the adaptations in the putative arm synergy, we performed regression analyses with hip angle as the dependent variable and shoulder angle and elbow angle as independent variables. The results for individual participants are presented in Table 4. Two groups of participants can be distinguished on the basis of the explained variance: Four participants have a small $r^2$ (smaller than 25%) indicating that the adjustments in the hip are not coupled to the adaptations in the arm for those participants. We believe that for those participants the trunk was fixed to serve as a stable platform from which the arm could be controlled. Five of the participants had a much larger $r^2$, which indicated that the adaptations in the hip were related to the adaptations in the arm.
Table 3. Regression analyses between shoulder angle and elbow angle.

<table>
<thead>
<tr>
<th>Participant</th>
<th>intercept</th>
<th>slope</th>
<th>$F$</th>
<th>$df$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-116.26</td>
<td>0.97</td>
<td>172.25</td>
<td>1, 151</td>
<td>.53</td>
</tr>
<tr>
<td>2</td>
<td>-150.64</td>
<td>1.21</td>
<td>415.57</td>
<td>1, 148</td>
<td>.74</td>
</tr>
<tr>
<td>3</td>
<td>-107.98</td>
<td>0.94</td>
<td>1002.09</td>
<td>1, 150</td>
<td>.87</td>
</tr>
<tr>
<td>4</td>
<td>-83.39</td>
<td>0.79</td>
<td>208.04</td>
<td>1, 153</td>
<td>.58</td>
</tr>
<tr>
<td>5</td>
<td>-131.38</td>
<td>0.97</td>
<td>394.34</td>
<td>1, 153</td>
<td>.72</td>
</tr>
<tr>
<td>6</td>
<td>-142.17</td>
<td>1.22</td>
<td>385.08</td>
<td>1, 155</td>
<td>.71</td>
</tr>
<tr>
<td>7</td>
<td>-150.03</td>
<td>1.24</td>
<td>833.54</td>
<td>1, 150</td>
<td>.85</td>
</tr>
<tr>
<td>8</td>
<td>-159.98</td>
<td>1.37</td>
<td>543.28</td>
<td>1, 149</td>
<td>.78</td>
</tr>
<tr>
<td>9</td>
<td>-44.69</td>
<td>0.43</td>
<td>117.44</td>
<td>1, 154</td>
<td>.43</td>
</tr>
</tbody>
</table>

*Note.* All the regression equations had $p < .001.$

Table 4. Regression analyses between hip angle and shoulder angle and elbow angle.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Intercept</th>
<th>Slope shoulder angle</th>
<th>Slope elbow angle</th>
<th>$F$</th>
<th>$df$</th>
<th>$p$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.40</td>
<td>0.21</td>
<td>-0.07</td>
<td>20.05</td>
<td>2, 150</td>
<td>.001</td>
<td>.21</td>
</tr>
<tr>
<td>2</td>
<td>21.31</td>
<td>0.47</td>
<td>-0.20</td>
<td>130.37</td>
<td>2, 147</td>
<td>.001</td>
<td>.64</td>
</tr>
<tr>
<td>3</td>
<td>20.91</td>
<td>0.41</td>
<td>-0.17</td>
<td>80.12</td>
<td>2, 149</td>
<td>.001</td>
<td>.52</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>0.36</td>
<td>-0.05</td>
<td>164.76</td>
<td>2, 152</td>
<td>.001</td>
<td>.68</td>
</tr>
<tr>
<td>5</td>
<td>1.72</td>
<td>0.07</td>
<td>-0.07</td>
<td>1.58</td>
<td>2, 152</td>
<td>.210</td>
<td>.02</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>0.37</td>
<td>-0.10</td>
<td>202.62</td>
<td>2, 154</td>
<td>.001</td>
<td>.72</td>
</tr>
<tr>
<td>7</td>
<td>19.37</td>
<td>0.50</td>
<td>-0.20</td>
<td>202.90</td>
<td>2, 149</td>
<td>.001</td>
<td>.73</td>
</tr>
<tr>
<td>8</td>
<td>529.98</td>
<td>-0.02</td>
<td>-3.85</td>
<td>20.26</td>
<td>2, 148</td>
<td>.001</td>
<td>.21</td>
</tr>
<tr>
<td>9</td>
<td>14.20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>2, 153</td>
<td>.980</td>
<td>.00</td>
</tr>
</tbody>
</table>

How are the synergies we found in reaching with rods related to the synergies yielded in reaching with just the arm? When studying reaching without a tool, Ma and Feldman (1995) had found two different synergies: one synergy constituted the arm and produced the hand movement to the target, and the other synergy was between the trunk and the arm but did not affect the endpoint of the arm. Our findings using rods that varied in length were somewhat different; we found evidence that the arm (i.e., shoulder angle and elbow angle) was organized as a synergy, but that for about half of the participants, the trunk was not coupled to the arm.

To examine how the posture was adapted to rod length we performed separate ANOVAs on the ankle angle, knee angle, hip angle, shoulder angle, and elbow angle. Only the analyses on ankle angle ($F(1,8) = 13.00, p < .01$), shoulder angle ($F(1,8) = 27.50, p = .001$), and elbow angle ($F(1,8) = 72.46, p < .001$) showed a significant linear contrast. The means are
presented in Table 1. For ankle angle, the shank was more upright for longer rods. The shoulder angle effect was that the elbow was closer to the body with longer rods. The elbow, in turn, was more bend with increasing rod length. The leg and trunk, it seems, were not systematically adjusted, which means that the orientation of the body to the ground is regulated in the ankle.

To summarize, we see that reaching distance, arm posture, and ankle angle changed systematically with rod length. All participants seemed to organize the shoulder and elbow as a synergy. For about half of the participants the hip formed a synergy with the shoulder and elbow. What were the origins of those adaptations? The adaptations in reaching distance and arm angles—and also the formation of the synergies for that matter—may reflect a common response to manipulation of a single variable. Other possibilities may be that adaptations of reaching distance and posture are influenced by different variables or that one follows from the other. We hypothesized in the introduction that the reachable distance depends on both the geometrics and the dynamics of the body + rod system. If only the geometrics were to determine the behavior, no postural adaptations would be expected; changes in distance should relate one-to-one to changes in rod length. However, posture was adapted which raises the question whether the adaptations stemmed from dynamics. To examine this we varied dynamics characteristics independent from the length in Experiments 2 and 3, by varying the rod’s mass and mass distribution. Moreover, length, mass, and mass distribution of the rod are expected to affect how wieldable the rod is, which might be important for the displacement of the object. Therefore, these rod characteristics were manipulated.

**Experiment 2**

The results of Experiment 1 revealed that reaching behavior was adapted to rod length and that functional synergies in the arm controlled the rod. We noted that not simply the geometrics of the system determined the reaching behavior because not only reaching distance but also posture was affected by rod length. This suggests either that participants failed to accurately detect the metrical properties, or that kinetic properties were also important. In Experiment 2, we manipulated, in addition to length,
the homogeneous mass of the rods. This enabled us to study kinetic effects independent of length.

The participants’ task is to make a comfortable reach; thus the stopping distance should accommodate the length of the rod and allow for a comfortable posture. This means that the to-be-adopted posture should be reflected in the chosen reaching distance. Manipulating both length and mass allows us to tease apart the relative contributions of information about length and information relevant to posture. There are two distinct sources of information. There is the obvious visual information about length, but in addition, there is information from dynamic touch. Changing the length and mass affects muscle and tendon deformations prominent when holding and manipulating a rod, that characterizes the haptic subsystem of dynamic touch (Gibson, 1966). Through the subsystem of dynamic touch, a variety of rod characteristics (length, wieldability, flexibility, required force, etc.) might be detected. Some of these properties might be used to constrain posture; others might constrain stopping location.

A large body of evidence has shown that the principle moments of inertia of an object are detected via dynamic touch (for an overview see Turvey & Carello, 1995). Moments of inertia reflect the extent to which an object resists rotational acceleration and depend on the size, the mass, and the mass distribution of an object. Several studies within the dynamic touch paradigm have shown that both the major (perpendicular to the longitudinal axis of the rod) and minor (along the longitudinal axis of the rod) moments of inertia ($I_1$ and $I_3$, respectively) are important for haptically perceived length. In a series of experiments, in which the relation between different rod properties and reported length were investigated, Fitzpatrick, Carello, & Turvey (1994) revealed the relation between haptically perceived length (HPL) and the moments of inertia of the hand held rod: $\text{HPL} = 3.8 \times I_1^{0.41} \times I_3^{-0.30}$. In one of the experiments on which this relation was based, it was found that heavier rods (i.e., rods with larger moments of inertia), which are held but not seen, are perceived as longer than lighter rods of equal length (Carello, Fitzpatrick, Flascher & Turvey, 1998; Fitzpatrick et al., 1994). For us, this would mean that if only haptic information about rod length determined the action, then a larger distance to the table would be selected with heavier rods.5

5 We were aware of the possibilities of the limited importance of results regarding haptically perceived length revealed in experiments where vision is prevented to situations where vision is permitted (see
Posture, which we expect to be determined by the dynamics of the body + rod system, ought to be affected by the moments of inertia. Because the moments of inertia measure the resistance to rotational acceleration, they ought to be related to the wieldability of a rod. In our experiment, once a stopping place has been selected, the rod is lowered and moved sideward to displace the object. The effort required to change rotational velocity of the rod is captured by the moments of inertia about the axes of movement. The resistance relevant to the lowering movement (in the sagittal plane) corresponds to the largest moment of inertia while the resistance to the sideward movement (in the transverse plane) corresponds to the intermediate moment of inertia ($I_2$). A long and heavy rod has larger moments of inertia on the basis of which we expect that it required more muscular effort to change the movement direction than did a short and a light rod. This change in required muscular effort may demand a postural adaptation. The effects of moments of inertia on the posture should be independent from the haptically perceived length.

Another property of the rod that might affect the posture with which the object is displaced is related to the center of percussion. The center of percussion, or sweet spot, of an implement is the point of impact that produces the least vibration in the hand holding the implement. In our experiments the point of impact on the rod was always at the tip. It might be that participants adapt their posture in a situation where the distance between the center of percussion and the tip of the rod is large, because the rod should vibrate more in such a case. Carello, Thuot, Anderson, & Turvey (1999) show that experienced and novice tennis players were able to report separately the length and the position of the sweet spot of an unseen, hand-held tennis racket. This research suggests that participants in our study also could have been able to adjust their behavior to the location of the center of percussion. To test for the possible importance of the location of the sweet spot, we computed this position for each rod and related it to the adaptations in the selected distance.

Displacing an object with a rod not only produces vibrations in the body but also forces and torques. Increasing the mass of a rod increases forces and torques above and beyond that related to length of the rod. Participants can use several strategies to counteract the torques produced

---

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---

Pagano, Aten, & Alley, 1998) as well as the established view of visual dominance above the other modalities. Though, we still want to examine the possible contributions of haptic perceived length via dynamic touch in the present experiment.
by the rods, of which we name three: (a) participants can avoid reaching maximum joint moments, (b) participants can keep the torque in a certain joint constant over a range of rods, and (c) participants can minimize the torque in one or more joints. As to avoiding the maximum joint strength, Chaffin and Andersson (1991) present equations that predict joint moment-strength in any given posture. For each joint, one can compute the expected maximal muscle-produced joint moment that can counteract moments created by external loads. Using these formulas, we modeled our task and found that if very heavy rods need to be handled, the shoulder needs to be retroflexed (upper arm behind the shoulder) and the elbow moderately flexed. To see whether participants used any of the other strategies mentioned, we computed the (sagittal-plane) torques in the joints in question. It is important to note that all of the strategies require a postural adaptation because the torques produced by the rods increase with increasing length and mass.

Lowering a rod is biomechanically similar to extending an arm because the center of mass (CM) is shifted outwards in both cases. Participants may adjust the posture to compensate for this shift. Several researchers have measured postural adjustments and muscle activity before and after the start of fast shoulder flexions bringing an arm at the side to the horizontal (Aruin & Latash, 1995a; Bouisset & Zattara, 1981; 1987; Brown & Frank, 1987; Horak, Esselman, Anderson, & Lynch, 1984; Lee, 1980; Lee, Buchanan, & Rogers, 1987; Van der Fits, Klip, & Van Eykeren, 1998; for an overview see Massion, 1992). In general, these studies report an increase in EMG activity of the postural muscles of the back; this results in a displacement of the CM opposite to that expected from the arm movements. Moreover, the postural muscles were activated prior to or in an early phase of the arm movement (depending on condition); this suggests that this activity has an anticipatory component. If load was varied, the EMG activity increased or the onset of the anticipatory activity was moderated, dependent on condition (Aruin & Latash, 1995; Bouisset & Zattara, 1987). Those findings imply that picking up a rod would yield a posture in which the body CM is more posterior, and that this effect would be larger for rods that produce a larger torque. This hypothesis is also consistent with experiments showing that maximum acceptable load decreases with increasing distance to the load (Ciriello, Snook, & Hughes, 1993; Garg, 1998). Therefore, we expected that a closer distance to the table would be selected with longer and heavier rods.
In sum, on the basis of haptically perceived length, a larger distance to the table with heavier rods is expected. However, from findings regarding the way a heavier rod affects the posture we expected a closer distance to the table with heavier rods. This should make it relatively easy to evaluate the importance of the two sources of information. A manipulation of variables related to wieldability is deferred until Experiment 3.

Method

Participants ranged in ages from 18 to 42 years, 14 were females and eight were males. Rods with a diameter of 1.25 cm were used; they ranged in length from 0.1 to 1.0 m, in 0.1 m steps. Three sets of ten rods were constructed, one set from wood (density 0.67 g/cm³), one from aluminum (density 2.70 g/cm³), and one set from steel (density 7.80 g/cm³). A handle was added to each rod, extending it by 11.5 cm. A small disc separated the handle from the rod. Moreover, a small plastic tube was put over the handle part of the rod. All rods were painted white to prevent that participants could see the difference in material. Characteristics of the rods (length, mass, moments of inertia, center of percussion) are presented in Table 5.

A variety of variables were calculated to see which best predicted reaching distance and posture. We computed the three moments of inertia of the rod with the rotation point in the wrist (to simplify the computations we neglected the mass of the hand). To compute the haptically perceived length we used the formula of Fitzpatrick et al. (1994): 
\[
HPL = 3.8 \times I_1^{0.41} \times I_3^{-0.30}
\]

The static moment, which is the invariant part of the static torque (Kingma, Beek, & Van Dieën, submitted), was computed as the distance between the wrist and the CM of the rod multiplied by the gravitational acceleration and the mass of the rod. The position of the center of percussion on the rod is computed as the ratio of the first moment of inertia to the static moment (Carello et al., 1999). Note that the determination of this position is based on the summed length of the rod and the handle and that the distance in Table 5 is measured from the end of the handle.
We also calculated the torque acting in the joints at the moment the cylinder started to be displaced. To do this, we computed the CM of the (compound) segment acting on a joint. For instance, for computing the torque around the elbow, the rod, hand, and forearm were used. The horizontal distance between the CM and the joint was multiplied by the gravity force (the sum of the segment masses times g). The torque varied with the orientation of the joint and the rod. The torque acting in a clockwise direction was labeled positive.
Each participant was tested in one session. There were 33 conditions, for each of the three rod-types a set of 10 rods and one control condition (the tip of the fingers). Each condition was presented 6 times in randomized blocks, for a total of 198 trials for each participant. Of the total number of 4356 trials, 31 were omitted because a residual of the regression analyses exceeded the threshold.

**Results and Discussion**

*Reaching distance*

Reaching distance was analyzed by means of a two-way multivariate ANOVA with Rod Type (wood, aluminum, and steel) and Rod Length as within-subject factors. The analyses were performed on the averages for each participant and each condition. The averages over participants for the levels of the significant factors of this experiment are presented in Table 6. The main effect of Rod Type was significant, $F(2, 20) = 5.26, p < .05$; when reaching with heavier rods, participants selected a distance closer to the table. The main effect of Rod Length was also significant, showing, as expected, that participants stopped farther from the table when they used longer rods, $F(10, 12) = 187.24; p < .001$. The interaction effect was not significant. The means in Table 6 revealed that in the ‘no rod’ condition a larger distance was selected than with the shortest rod. On the one hand, this might indicate that even the shortest rod adds enough torque to require an adaptation. On the other hand, this adaptation might indicate that participants select distance differently when they are holding a rod.

As to the basis of these effects, one suggestion was that haptically detected information about rod length should result in heavier rods of equal physical length being perceived as relatively longer (Carello et al., 1998; Fitzpatrick et al., 1994). If that were the case in the present task, the chosen distance from the table should be larger for heavier rods. That we found the opposite suggests that the haptically perceived length contributes little or nothing to determining the reaching distance. Amazeen (1998) tested the relative contribution of visual information to haptic information when participants had reported the perceived weight and the perceived volume of the objects that were held and seen. The objects were the same shape but differed in mass distribution. His
participants, although they could see the objects, reported differences in the objects in accordance with predictions stemming from an inertial model of weight perception by dynamic touch. In our experiments participants do not seem to adapt their actions to haptically perceived length.

Another suggestion was that the center of percussion affected the chosen distance from which to reach. However, the location of the center of percussion was independent of the different rod types because the CM on a rod of a given length is independent from the mass if it is homogeneously varied. Because we found an effect of mass on distance, we tentatively dismiss the relevance of the center of percussion.

Table 6. Means (SD) for the significant effects of the ANOVAs in Experiment 2

<table>
<thead>
<tr>
<th>Rod type</th>
<th>Reaching distance (m)</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>0.730 (0.277)</td>
<td>11.40 (13.55)</td>
<td>140.81 (13.59)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.728 (0.274)</td>
<td>10.28 (14.00)</td>
<td>139.01 (13.87)</td>
</tr>
<tr>
<td>Steel</td>
<td>0.719 (0.267)</td>
<td>7.94 (14.69)</td>
<td>136.73 (14.22)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Reaching distance (m)</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.399 (0.173)</td>
<td>19.65 (14.02)</td>
<td>146.87 (12.04)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.392 (0.109)</td>
<td>18.25 (13.92)</td>
<td>147.49 (13.23)</td>
</tr>
<tr>
<td>0.2</td>
<td>0.477 (0.103)</td>
<td>16.40 (13.17)</td>
<td>145.52 (12.86)</td>
</tr>
<tr>
<td>0.3</td>
<td>0.554 (0.100)</td>
<td>14.17 (12.64)</td>
<td>142.79 (12.41)</td>
</tr>
<tr>
<td>0.4</td>
<td>0.631 (0.101)</td>
<td>11.32 (12.72)</td>
<td>140.24 (12.79)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.720 (0.095)</td>
<td>9.03 (11.84)</td>
<td>138.02 (12.50)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.797 (0.098)</td>
<td>6.90 (11.95)</td>
<td>135.70 (12.97)</td>
</tr>
<tr>
<td>0.7</td>
<td>0.884 (0.098)</td>
<td>5.18 (12.21)</td>
<td>134.63 (13.10)</td>
</tr>
<tr>
<td>0.8</td>
<td>0.968 (0.095)</td>
<td>3.32 (11.93)</td>
<td>132.85 (12.90)</td>
</tr>
<tr>
<td>0.9</td>
<td>1.056 (0.093)</td>
<td>2.57 (12.22)</td>
<td>132.50 (12.85)</td>
</tr>
<tr>
<td>1.0</td>
<td>1.140 (0.092)</td>
<td>0.96 (12.55)</td>
<td>130.75 (12.89)</td>
</tr>
</tbody>
</table>

Previous experiments have shown that anticipatory postural adjustments to counteract movement-related CM shifts are larger for heavier loads. We therefore predicted that the posture would be more upright (less forward-leaning) for the heavier rods which, if anticipated, would result in a closer distance to the table. This adjustment in the reaching distance was indeed found. Examining the postural adaptations in the next subsection should make clear whether the effects on distance were the result only of the more upright posture or whether forces and torques in the arm joints contributed.
Posture
To examine postural effects we first determined whether synergies were formed in the arm or between the trunk and the arm. As in Experiment 1, we used regression analyses to discover which postural angles were related. We started by regressing elbow angle on shoulder angle. An analysis on the data of all participants together revealed that adjustments in shoulder angle corresponded to adjustments in elbow angle: shoulder angle = 0.79 * elbow angle –99.92 (F(1, 4354) = 6830.28, p < .001, r^2 = .61). This pattern was confirmed by the analyses on the individual participants; two participants showed a weak correspondence between the two angles (i.e., r^2 of .19, .30). For the other 20 participants the correspondence between the two angles was spread over a continuum with a smallest r^2 of .46 and largest value of .89. We conclude that the angles in the arm reflect a synergy. Note, however, that percentage of explained variance was smaller than we had seen in Experiment 1.

To examine the relation between trunk and arm, we performed a multiple regression with hip angle as the dependent variable and shoulder angle and elbow angle as the independent variables. The analyses on the data of individual participant showed that four out of the 22 participants had a weak correspondence between those angles (r^2 of .62, .55, .51, and .44). For the remaining 18 participants the r^2 varied between .01 and .31, indicating that in general the adjustments in the hip were independent from the adjustments in the shoulder and elbow. The lack of a systematic relation was also evident in the pooled data: hip angle = 29.95 + 0.22 * shoulder angle –0.24 * elbow angle (F(2, 4353) = 263.70, p < .001, r^2 = .11). This analysis showed that the trunk organization was independent from the adjustments in the arm. This may suggest that the trunk served as a stable platform from which the arm could be controlled, a thesis to which we will return after considering how the posture depended on variations in length and mass of the rod.

Separate ANOVAs were performed on ankle angle, hip angle, shoulder angle and elbow angle (given the non-significance of the knee angle in Experiment 1, this angle was not expected to be of importance for the present task). Two-way multivariate ANOVAs were performed with Rod Type (wood, aluminum, and steel) and Rod Length as within-subject factors. The averages for the levels of the significant main effects are presented in Table 6. Ankle angle and hip angle showed no significant effects. As to shoulder angle, the main effect of Rod Type was significant,
\( F(2, 20) = 18.20, p < .001; \) the shoulder was more anteflexed with lighter rods than with heavier rods; that is, with lighter rods the elbow was more anterior to the shoulder. The main effect of Rod Length was also significant, showing that with longer rods the shoulder was less anteflexed, \( F(10, 12) = 5.69; p < .005. \) As to elbow angle, the main effect of Rod Type was significant, \( F(2, 20) = 16.56, p < .001; \) the elbow was more extended with lighter rods than with heavier rods. The main effect of Rod Length was also significant, showing that with shorter rods the elbow was more extended (\( F(10, 12) = 9.12; p < .001). \)

Taken together, the results of the angle analyses show that only the arm is adapted to changes in length and mass of the rod. The leg and hip joints were not adjusted. Remember that we predicted from the literature on anticipatory postural adjustments that the posture would be more upright for the larger loads; however, we did not find such an effect. This suggests that only one posture in the leg and trunk was used. A single lower-body posture would provide a stable platform allowing the angles in the arm to be varied to make the displacement possible. The adjustments in the arm show that with longer and heavier rods the arm was held closer to the body and the elbow more flexed. Such a posture is consistent with the literature about people lifting loads. The acceptable load has been found to be higher when the distance to the load was larger (Ciriello et al., 1993). From this we expected that the arm might be bent to decrease the distance to the heavy rod and, indeed, heavier loads were held closer to the body. This may mean that the torque produced by the rods is critical to arm adjustments. Our final analyses focussed on whether the adaptations in the distance and the posture stemmed from the torque the rods produced.

**Torques**

One goal of our torque analysis was to evaluate whether the adaptations in the shoulder and elbow stemmed from minimizing torque or avoiding maximum torque in one of those joints. We computed the torque that acted in each joint at the moment the object was displaced. To compute the maximum joint-moment strengths for the observed postures, we used the equations of Chaffin and Andersson (1991, p. 250-251). These predicted maxima were much larger than the actual torques arising in the task. From this simple fact, we conclude that participants did use a strategy to avoid moments they would not be strong enough to sustain.
The torque a rod can produce increases with its length and mass and is maximal when the rod is horizontal. In the current task the orientation of the rod is nearly horizontal during the displacement, thus creating near maximum torques. In Figure 3 we plotted how the torque in the wrist, elbow, and shoulder depended on the length and mass properties of the rod. The torque in the wrist increased for longer and heavier rods; it seemed that the torque in the wrist followed the pattern of the torque produced by the rod alone. A similar pattern is observed for the torque in the elbow. The larger values for the torque in the elbow compared to the torque in the wrist resulted from the torque that is produced by the forearm. The torque in the shoulder was also larger for rods that could create larger torques (i.e., longer and heavier rods), and it was larger than the torque in the elbow because of the torque that the upper arm produced. In sum, the torques in the arm joints increased with increasing maximum torque that a rod could produce. The finding that torque in the joints during displacement varied in correspondence with the maximum torques a rod could produce led us to believe that participants did not adjust the posture to decrease the torques in the joints. In other words, the posture was not adapted to minimize the torques in the joints.

The deviation from the increasing pattern for the torque in the shoulder when the wooden rods were used was peculiar. Because the wooden rods were the lightest there was no reason to believe that this decreasing relation resulted from the torque that those rods produced. On the basis of this we inferred that a variable other than the torque should be important in the present task.

To summarize, both rod length and mass determine reaching distance: with longer rods a longer distance and with larger mass a closer distance to the table is selected. The effect of the rod length is consistent with what we expected. Moreover, the results showed that the reaching distance was not according to predictions related to the haptically perceived length or the center of percussion. The mass effects on reaching distance seemed to stem from constraints that affect the posture, however, examining the relation between the torque in the joints and the properties of the rod revealed that the torque was not minimized but

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6 We were concerned that randomizing vs. blocking rod types within a session might affect the magnitude of the mass manipulation. Therefore, we repeated Experiment 2 on 8 subjects, but with rod types grouped, such that participants reached with wooden rods on one day, aluminum rods on another day, and steel rods on yet another day. The results were all in the same direction as those reported above (Bongers, Smitsman, & Michaels, 1998).
Chapter 4

increased with longer and heavier rods. To control the rod, the shoulder and the elbow were organized as a synergy; if the shoulder was less anteflexed the elbow was more flexed and this posture occurred more for the long and heavy rods. Neither of the other joints varied with rod properties indicating that a similar posture provided stability for all the rods and that a more upright posture to compensate for the larger shift in CM for the heavier rods was not found.

Figure 3. The relation between the rod properties and the torques acting in the different joints in the sagittal plane for Experiment 2.
In the introduction to this experiment we suggested that the wieldability of the rod might affect the posture with which the rod is controlled during the displacement. This possibility might be consistent with our finding that only the arm posture is adapted to variations in the rod; the posture in the rest of the body provides for a stable platform on the basis of which the arm can be configured to control the rod. In Experiment 3 we modify the mass distribution of the rods to examine the explanatory value of the wieldability. A difference in reaching behavior between rods with homogeneously distributed mass and rods with nonhomogeneously distributed mass would help us track down the precise characteristics of relevance. Therefore, in Experiment 3 mass distribution of the rods is also varied.

**Experiment 3**

Experiment 3 was designed to evaluate the relative importance of the wieldability of the rods. We manipulated length, mass, and mass distribution which all affect (information about) the metrics and dynamics of the reaching system. To manipulate mass distribution we used hollow tubing in which weights could be inserted in the tip or the handle. Rods with weight at the tip, like the heavy rods of Experiment 2, displace the CM of the body + rod system the most. They also produce more torque. The difference between the rods used in Experiments 2 and 3 is in the location of the CM within the rod. With a homogeneous mass distribution, rods of any length or mass have their CM at the midpoint. However, the location of the CM in rods with nonhomogeneous mass distribution depends on the position of the inserted mass. The position of a rod’s CM might be of importance for how it can be used to displace an object. For example, and with other things being equal, a rod with a heavy tip could gather more momentum at the tip. Perhaps this momentum would make it easier to smash an object off the table (cf. Beak, Davids, & Bennet, 1999). Furthermore, and more important for the task at hand, more weight at the tip provides for more stability at the tip—because it resists tip movement more—which may require a type of control different from that needed for a rod less stable at the tip (i.e., a rod with weight at the handle). Both aspects may require postural adaptations for effective control. Note that the postural constraints (e.g., the shift in CM or the increase in torque), entailed by rods with weight at the tip
should be similar to those entailed by steel rods. Thus, we expect that participants would select a distance relatively closer to the table when using a rod weighted at the tip. Any deviations from that pattern might be a result from the aspects related to the rod’s wieldability or its stability at the tip. Any differences between the results of Experiment 2 and Experiment 3 will reveal the relative importance of that stability and wieldability.

Method

Participants ranged in ages from 19 to 23 years; 10 were females and seven were males. Fewer rod lengths were used to keep the experiment to one session. Also, to make the experiments comparable, we chose metric and dynamic rod characteristics that fell in the same range as the rods used in Experiment 2. Twenty-five rods were used. There were five lengths, ranging from 0.4 to 0.8 m, in 0.1 m steps. The rods were made of steel tubing (diameter 1.6 cm). To manipulate mass and mass distribution, one or two 82 g lead weights were built into the tube. Five types of rods were constructed this way: rods with no extra mass, rods with one mass in the handle, rods with one mass at the tip of the rod, rods with two masses in the handle, and rods with two masses at the tip of the rod. The properties of the rod we computed for the rods of Experiment 2 were also computed for the rods in this experiment and presented in Table 7. Each rod had a handle of 11.5 cm. The steel tube was put in a PVC tube with an outer diameter of 1.8 cm. A small plastic disc divided the handle from the rod. The part of the tube designated as the rod was painted white. Each of the 25 rods was presented 6 times in randomized blocks, for a total of 150 trials per participant, run in a single session. On 14 of the 2250 trials the SD of the residual exceeded the threshold. Those trials were omitted.
Table 7. Characteristics of rods used in Experiment 3.

<table>
<thead>
<tr>
<th>Rod type</th>
<th>Rod length m</th>
<th>Rod mass g</th>
<th>$I_1 \times 10^3$ kgm$^2$</th>
<th>$I_2 \times 10^3$ kgm$^2$</th>
<th>$I_3 \times 10^3$ kgm$^2$</th>
<th>CP mN m</th>
<th>Static moment kgm$^2$</th>
<th>HPL $\frac{kg}{m^4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>no weight</td>
<td>0.4</td>
<td>0.242</td>
<td>22.30</td>
<td>22.09</td>
<td>0.227</td>
<td>0.35</td>
<td>0.628</td>
<td>9.90</td>
</tr>
<tr>
<td>no weight</td>
<td>0.5</td>
<td>0.289</td>
<td>37.53</td>
<td>37.28</td>
<td>0.274</td>
<td>0.41</td>
<td>0.889</td>
<td>11.59</td>
</tr>
<tr>
<td>no weight</td>
<td>0.6</td>
<td>0.336</td>
<td>58.55</td>
<td>58.25</td>
<td>0.320</td>
<td>0.48</td>
<td>1.196</td>
<td>13.28</td>
</tr>
<tr>
<td>no weight</td>
<td>0.7</td>
<td>0.383</td>
<td>86.29</td>
<td>85.95</td>
<td>0.366</td>
<td>0.55</td>
<td>1.549</td>
<td>14.95</td>
</tr>
<tr>
<td>no weight</td>
<td>0.8</td>
<td>0.431</td>
<td>121.71</td>
<td>121.32</td>
<td>0.412</td>
<td>0.61</td>
<td>1.949</td>
<td>16.61</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.4</td>
<td>0.325</td>
<td>22.71</td>
<td>22.27</td>
<td>0.463</td>
<td>0.33</td>
<td>0.666</td>
<td>8.06</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.5</td>
<td>0.372</td>
<td>37.94</td>
<td>37.44</td>
<td>0.520</td>
<td>0.40</td>
<td>0.925</td>
<td>9.60</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.6</td>
<td>0.419</td>
<td>58.96</td>
<td>58.41</td>
<td>0.574</td>
<td>0.47</td>
<td>1.231</td>
<td>11.17</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.7</td>
<td>0.466</td>
<td>86.71</td>
<td>86.11</td>
<td>0.626</td>
<td>0.54</td>
<td>1.583</td>
<td>12.75</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.8</td>
<td>0.513</td>
<td>122.12</td>
<td>121.47</td>
<td>0.676</td>
<td>0.60</td>
<td>1.981</td>
<td>14.33</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.4</td>
<td>0.325</td>
<td>41.76</td>
<td>41.53</td>
<td>0.257</td>
<td>0.40</td>
<td>1.019</td>
<td>12.35</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.5</td>
<td>0.372</td>
<td>65.75</td>
<td>65.46</td>
<td>0.307</td>
<td>0.47</td>
<td>1.360</td>
<td>14.10</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.6</td>
<td>0.419</td>
<td>97.16</td>
<td>96.83</td>
<td>0.356</td>
<td>0.55</td>
<td>1.748</td>
<td>15.82</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.7</td>
<td>0.466</td>
<td>136.95</td>
<td>136.57</td>
<td>0.405</td>
<td>0.62</td>
<td>2.181</td>
<td>17.53</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.8</td>
<td>0.513</td>
<td>186.05</td>
<td>185.63</td>
<td>0.453</td>
<td>0.69</td>
<td>2.661</td>
<td>19.21</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.4</td>
<td>0.409</td>
<td>23.84</td>
<td>23.26</td>
<td>0.605</td>
<td>0.31</td>
<td>0.758</td>
<td>7.58</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.5</td>
<td>0.456</td>
<td>39.07</td>
<td>38.41</td>
<td>0.688</td>
<td>0.38</td>
<td>1.015</td>
<td>8.94</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.6</td>
<td>0.503</td>
<td>60.09</td>
<td>59.35</td>
<td>0.761</td>
<td>0.45</td>
<td>1.320</td>
<td>10.34</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.7</td>
<td>0.550</td>
<td>87.83</td>
<td>87.04</td>
<td>0.827</td>
<td>0.52</td>
<td>1.671</td>
<td>11.79</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.8</td>
<td>0.597</td>
<td>123.25</td>
<td>122.39</td>
<td>0.889</td>
<td>0.58</td>
<td>2.068</td>
<td>13.26</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.4</td>
<td>0.409</td>
<td>56.88</td>
<td>56.63</td>
<td>0.260</td>
<td>0.41</td>
<td>1.369</td>
<td>13.96</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.5</td>
<td>0.456</td>
<td>88.76</td>
<td>88.48</td>
<td>0.312</td>
<td>0.49</td>
<td>1.792</td>
<td>15.87</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.6</td>
<td>0.503</td>
<td>129.77</td>
<td>129.44</td>
<td>0.363</td>
<td>0.56</td>
<td>2.262</td>
<td>17.71</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.7</td>
<td>0.550</td>
<td>180.84</td>
<td>180.46</td>
<td>0.414</td>
<td>0.64</td>
<td>2.778</td>
<td>19.51</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.8</td>
<td>0.597</td>
<td>242.91</td>
<td>242.48</td>
<td>0.464</td>
<td>0.71</td>
<td>3.340</td>
<td>21.27</td>
</tr>
</tbody>
</table>

Results and Discussion

Reaching distance
Reaching distance was analyzed by means of a two-way multivariate ANOVA with Rod Type (no weight, 1 weight in handle, 1 weight at tip, 2 weights in handle, and 2 weights at tip) and Rod Length (0.4 m, 0.5 m, 0.6 m, 0.7 m, and 0.8 m) as within-subject factors. The averages and standard deviations are shown in Table 8.
Table 8. Means (SD) for the significant effects of the ANOVAs in Experiment 3

<table>
<thead>
<tr>
<th>Rod type</th>
<th>Reaching distance (m)</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No weight</td>
<td>0.815 (0.132)</td>
<td>10.85 (10.93)</td>
<td>136.91 (9.96)</td>
</tr>
<tr>
<td>1 weight handle</td>
<td>0.815 (0.128)</td>
<td>10.79 (11.29)</td>
<td>137.31 (10.76)</td>
</tr>
<tr>
<td>1 weight tip</td>
<td>0.827 (0.136)</td>
<td>11.16 (11.44)</td>
<td>136.61 (10.24)</td>
</tr>
<tr>
<td>2 weight handle</td>
<td>0.820 (0.136)</td>
<td>11.22 (11.01)</td>
<td>137.85 (10.28)</td>
</tr>
<tr>
<td>2 weight tip</td>
<td>0.827 (0.139)</td>
<td>10.69 (11.75)</td>
<td>136.01 (10.40)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Reaching distance</th>
<th>Shoulder angle (degrees)</th>
<th>Elbow angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.668 (0.078)</td>
<td>16.10 (10.82)</td>
<td>141.42 (9.41)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.748 (0.076)</td>
<td>14.01 (10.34)</td>
<td>139.66 (9.42)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.817 (0.077)</td>
<td>10.38 (9.96)</td>
<td>136.42 (9.29)</td>
</tr>
<tr>
<td>0.7</td>
<td>0.893 (0.081)</td>
<td>8.16 (10.92)</td>
<td>134.66 (9.96)</td>
</tr>
<tr>
<td>0.8</td>
<td>0.978 (0.085)</td>
<td>6.07 (11.28)</td>
<td>132.52 (10.97)</td>
</tr>
</tbody>
</table>

The main effect of Rod Type was significant; $F(4, 13) = 4.53, p < .05$. For rods with weight at the tip, a larger reaching distance was chosen than rods with no weight or weight at the handle (see Table 8). The usual main effect of Rod Length ($F(4, 13) = 214.69, p < .001$) was found. The results showed that participants selected a relatively larger distance to the table with longer rods and with rods with a weight in the tip. Similar to rods with larger mass, rods with weight at the tip produce more torque in the joints (see Figure 3 and 4). Contrary to the results of Experiment 2, the results of Experiment 3 showed that participants select a larger distance to the table when the torques produced by the rods are larger. Given that the rods used in Experiments 2 and 3 have differently located CMs, the different results seem to suggest that, independent of the forces and torques produced, participants need more “room” to displace the object with a rod with a weight in the tip. An analysis of the joint angles may provide a fuller picture of this.

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7 A multivariate ANOVA with Mass (one or two), Place of Weight (handle or tip), and Rod Length as within-subject variables confirmed this interpretation of the means.

8 To make certain that the difference in results of Experiment 2 and Experiment 3 was not due to the range of lengths used, the data of Experiment 2 for rods ranging in length from 0.4 - 0.8 m were reanalyzed. The subset of Experiment 2’s rods that approximated those used in Experiment 3 show similar effects to the complete set from Experiment 2. The reaching distance was smaller for heavier rods and the shoulder and elbow angles were adapted accordingly. Therefore, the difference between the two experiments—that heavy rods yield larger reaching distances when the mass distribution is manipulated but a smaller reaching distance with homogeneous masses—is not an artifact of the range difference.
Posture
To determine whether the arm was organized as a synergy, we regressed the shoulder angle against the elbow angle. The analyses on the data of individual participants showed that some participants had a weak correspondence between the arm angles and other had a strong correspondence ($r^2$ ranging from .30, .35, .37, and .38 to .78, .80, and .84). Most of the individual participants organized the elbow and shoulder angle as a synergy. However, this pattern is not that strong for the regression analysis on the data of all the participants pooled; shoulder angle = 0.70 * elbow angle – 84.36 ($F(1, 2546) = 1746.88$, $p < .001$, $r^2 = .41$). The coefficients of the regression line showed a correspondence between shoulder and elbow angle that is comparable to what we found in Experiment 2. However, the explained variance of this regression line was smaller than in Experiment 2, indicating that the synergy between the arm angles was less stable. This might suggest that to control rods with different mass distributions, the synergy in the arm was perturbed. We will address this aspect further after we examined the synergy between hip and arm.

To examine the relation between hip and arm, we performed a multiple regression with hip angle as the dependent variable and shoulder angle and elbow angle as the independent variables, which were both entered at once. The analyses done for each individual participant showed that for none of the participants was the explained variance larger than .30. This means that the adjustments in the hip were independent from the adjustments in the shoulder and elbow.

To test how posture was affected by the length and mass distribution we analyzed the angles in the body by means of two-way repeated-measures ANOVAs with Rod Type (no weight, 1 weight in handle, 1 weight at tip, 2 weights in handle, and 2 weights at tip) and Rod Length (0.4 m, 0.5 m, 0.6 m, 0.7 m, and 0.8 m) as within-subject factors. As in Experiment 2, only shoulder and elbow angle systematically depended on length and mass. The only significant effect for shoulder angle was Rod Length ($F(4, 13) = 14.35$, $p < .001$); the shoulder was less anteflexed with longer rods. As to elbow angle, the main effect of Rod Type was significant; $F(4, 13) = 7.60$, $p < .005$; the elbow was more flexed for rods with weight at the tip. The usual main effect of Rod Length ($F(4, 13) = 9.80$, $p = .001$) was also found; the elbow was more flexed with longer rods. The interaction was not significant.
Figure 4. The relation between the rod properties and the torques acting in the different joints in the sagittal plane for Experiment 3.

The adaptations in the angles revealed that, as in Experiment 2, only the arm was adapted to changes in length and mass properties of the rod. Note that the maximum torque that a rod could produce increased with its length, mass, and the mass more at the tip. To reveal whether postural adaptations minimized the torques in the joints, we plotted the torques in
the wrist, elbow, and shoulder for the different rods used in this experiment in Figure 4. As can be seen, the torque in the arm joints systematically increased with longer rods, with larger mass, and with mass more at the tip. From this followed that participants did not adjust the posture to compensate for the larger torques that the rods produced. Therefore, we conclude that, as in Experiment 2, participants did not adjust the posture to minimize the torque in one of the arm joints when displacing the object on the table with the tip of the rod.

To summarize, in the present experiment the adaptations in the posture were confined to the arm and the torque was not minimized. Although, the synergy between shoulder and elbow was not as stable as in Experiment 2, the postural adaptations were remarkably similar for the two experiments. In this light, is even more peculiar that a larger distance to the table was selected for a rod with weight at the tip while a smaller reaching distance is selected with relatively heavier rods. Varying the mass distribution affected the location of the CM on the rod, which we assumed to affect the momentum that could be produced at the tip and the stability at the tip. However, varying the mass distribution did not seem to affect the postural adaptations made to control the rod, that is, for rod’s that produced more torque in the joints the elbow was more bend, independent of the precise origin of this torque. This invites the question as to whether there is a common ground for the adaptations in the distance.

Multiple regression model
A key issue in the present study was the basis on which participants adapted their actions. Because the experimental setup and the task to be performed were similar in all the experiments we expected that one variable or set of variables could explain the behavior in all the experiments and, in particular, the selection of the reaching distance. To examine the origins of that variable we performed a multiple regression analysis on the pooled data of Experiment 1, 2, and 3. In this analysis, all the rod properties that we supposed to be of importance for the present task were tested (see Tables 5 and 7). Moreover, we included not only properties of the rod but also characteristics of the participants because it was expected that anthropometric differences, such as body height or arm length, also would affect the distance selected. We excluded the trials on which no rod was used and the object was moved with the fingers
(control conditions of Experiment 1 and 2). As dependent variable we used foot distance and as independent variables we used rod length, body height, upper arm length, lower arm length, rod mass, $I_1$, $I_2$, $I_3$, static moment of the rod, HPL, and the location of the center of percussion. The independent variables were entered with a forward stepwise procedure. The variables that significantly explained the variance in the foot distance were (in the right sequence): rod length, upper arm length, body height, static moment, center of percussion, $I_2$, rod mass, and lower arm length ($F(8, 7795) = 7592.73, p < .001, R^2 = .89$). The explained variance of the regression model was high, indicating the relevance of the variables. Of all the variables, rod length explained the majority of the variance (the model with only rod length as the independent variable explained 85 % of the variance). As can be seen in Table 9, rod length correlated most highly with center of percussion. Body height was not correlated with any of the other variables, whereas the lengths of the upper and lower arm were highly correlated. Moreover, the static moment and the mass of the rod were correlated.

Important was that anthropometrics of the individual participants affected the selected distance. Regarding the properties of the rod, length was obviously the most important property. The significances of the other rod properties indicated the importance of the force to hold the rod (i.e., static moment and rod mass), the vibrations that the impact created on the rod (i.e., center of percussion), and the force required to move the rod sideward (i.e., $I_2$). Note that all three aspects are closely related to the moment the object starts to be displaced; the torque created by the static moment is largest when the rod is horizontal (and increases with larger mass), $I_2$ is important to the sideward movement of the rod required to displace the object, and the location of the center of percussion affects the impact when the rod touches the object. In short, it seems that the chosen distance is affected by the posture that is required to control the rod at the moment of displacement. Note that the distance was selected with the rod upward and that the feet remained at the similar position during the rod lowering and the displacement. Therefore, the finding that rod properties important for the displacement are reflected in the distance is a genuine finding and not an artifact because we measured only at the moment the object starts to be displaced.

The multiple regression showed that reaching distance could be predicted from the rod length, metrics of the body of the participant, and
properties of the rod important at the moment of displacement. However, rod length explained far most of the variance in the distance indicating that the distance was selected based on the rod length and that the other variables were only of minor importance.

Table 9. Intercorrelations between the independent variables significant in the multiple regression analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rod length</th>
<th>Length upper arm</th>
<th>Body height</th>
<th>Static moment</th>
<th>CP</th>
<th>I²</th>
<th>Rod mass</th>
<th>Length lower arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod length</td>
<td>--</td>
<td>-.28**</td>
<td>.39**</td>
<td>.99**</td>
<td>.48**</td>
<td>.22**</td>
<td>-.28**</td>
<td></td>
</tr>
<tr>
<td>Length upper arm</td>
<td>--</td>
<td>.08**</td>
<td>.31**</td>
<td>-.27**</td>
<td>.21**</td>
<td>.43**</td>
<td>.99**</td>
<td></td>
</tr>
<tr>
<td>Body height</td>
<td>--</td>
<td>.04**</td>
<td>-.02</td>
<td>.02*</td>
<td>.05**</td>
<td>.09**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static moment</td>
<td>--</td>
<td>.43**</td>
<td>.98**</td>
<td>.94**</td>
<td>.32**</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CP</td>
<td>--</td>
<td>.52**</td>
<td>.24**</td>
<td>-.26**</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>I²</td>
<td>--</td>
<td>.85**</td>
<td>.22**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rod mass</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length lower arm</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < .05, 2-tailed. **p < .01, 2-tailed.

General Discussion

In three experiments we studied whether and how changes in rod characteristics affect aspects of participants’ selecting a stopping place and making a reach to displace an object. In the different experiments, length, mass and mass distribution of the rods were manipulated. We were interested in how those properties of the rod determined the action, that is, reaching distance and posture with which the object is displaced. In Experiment 1, light rods differing only in length were used. The resulting reaching distance was adapted to that length in a very consistent way, showing that participants were sensitive to the change in their reaching possibilities. The shoulder and elbow angles reflected a synergistic organization and most of the adaptations in the posture took place in the arm. We distinguished two broad categories of information available to the participants to perform the task: (a) information concerning the geometrics of the reaching system, related to the length of the rod, and (b) information concerning the dynamics of the reaching system, having postural consequences.
In Experiment 2, length and (homogeneous) mass of the rods were manipulated to investigate which variable(s) provided the basis for participants’ adjustments. Participants selected a closer distance to the table with the heavier rods. The only postural adjustments were made in the arm and, again, the shoulder and elbow were organized as a synergy. This indicated that the rest of the body, which remained independent of the properties of the rod, served as a stable platform from which the arm could be controlled. In addition, we found that participants did not adapt the posture to minimize the torque in the arm joints. To further explore which dynamic properties of the rod constrain reaching behavior, we manipulated the dynamics of the rod differently in Experiment 3, namely, through mass distribution.

In Experiment 3, we found that the reaching distance was relatively larger for rods with a weight in the tip, compared to rods with weight in the handle. The organization of the posture was similar to Experiment 2; the shoulder and elbow acted as a synergy. Moreover, postural adjustments were not made to minimize the torque. When comparing Experiment 2 and 3, one finding stood out: the elbow adjustment was similar (flexion) for both heavier rods and rods with mass in the tip, whereas chosen distance was adapted differently for those two rod types. It seemed that the adjustments in the posture were similar, independent of the distance to the table that was selected. This raises the question as to whether postural adjustments were anticipated in the selected distance. To examine whether the postural adaptations were related to the distance selection, it was examined whether the reaching distance anticipated the length of the arm with which the object was displaced (i.e., the effective length), independent of the precise posture. The effective length of the arm was computed as the horizontal distance between shoulder position and wrist position—a larger distance reflected more extension of the arm. For the two experiments this distance was analyzed in an ANOVA which showed that the effective length of the arm was in accordance with adaptations in the distance.9 In short, this suggests that the chosen

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9 For Experiment 2 and Experiment 3 the shoulder-wrist distance was analyzed with separate multivariate ANOVAs with Rod Length and Rod Type as the within-subject variables. We report here only the effects of Rod Type. In Experiment 2, the arm was less extended for heavier rods ($F(2, 20) = 15.85, p < .001$; wood = 0.223 m; aluminum = 0.219 m; and steel = 0.206 m). Because a closer distance to the table was selected with heavier rods, the posture was anticipated in the distance. In Experiment 3 the arm was more extended for rods with weight at the tip, in particular when only one weight was inserted ($F(4, 13) = 3.20, p = .05$; no weight = 0.223 m; 1 weight handle = 0.221 m; 1 weight tip = 0.226 m; 2 weights handle = 0.224 m; and 2 weights tip = 0.224 m). The chosen distance to the
distance was prospectively adapted to the posture with which the object was going to be displaced.

Based on this conclusion we searched for the variable on the basis of which the reaching distance was selected in the different experiments. Therefore, we performed a multiple regression on the pooled data of all three experiments. In this analysis we tested anthropometrics of the participants and a large set of rod properties for their explanatory value. We found that length of the rod was most important for determining the distance. Moreover, body height, arm length, and properties of the rod related to the act of displacement were significant predictors of the reaching distance. However, compared to length, those latter variables did not contribute much to the explained variance. What might be the implication of the finding that the contribution of those variables is relatively small? The variables that contribute only a small portion of the variance might reveal the part of the task in which learning is possible. For example, we assume that someone who is experienced in reaching with rods will adapt the reaching distance to small changes in the dynamics to anticipate the finest adjustment in the posture. However, an inexperienced tool user will not be that sensitive to the effects of dynamics and only adapt the actions to the length of the rod. Because the fine-tuning of the distance is related to the changes in posture that depend on the dynamics of the body + rod system, we expect that improvement of skill can take place based on the dynamics. We propose that variables which explained only a small portion of the variance in the chosen distance formed the basis for improvement in this task; expert tool users can improve their skill by adjusting their actions to this set of variables.

Our departure point for the reported research was that successful reaching requires the organization of the action system into a task-specific system matched to the environment. Changing the properties of tools makes it possible to systematically vary the characteristics of the action system, which we take to include whatever implements are held. Our results show that participants are sensitive to changes in the properties of their action system; adaptations in reaching distance depend both on geometrics and dynamics of the reaching effectivity. Regarding the geometrics of the body + rod system we tested the hypothesis that haptic object was larger for rods with weight at the tip, which is in agreement with the idea that postural adjustments are prospectively reflected in the distance.
information about length (cf. Fitzpatrick et al., 1994) influenced the selected distance. However, the behavior of the participants did not confirm this hypothesis. Moreover, in the multiple regression analysis the haptically perceived length did not add to the explained variance. In short, it seemed that the most important geometric property of the system was simply length of the rod, as specified by optical and not haptic information. Regarding the dynamics of the action system, we formulated hypotheses related to the shift in CM of the body + rod system (cf. Bouisset, & Zattara, 1987) and the minimization of the torque, among other things. Those two aspects of the task seemed to be of particular importance when we considered the literature on how reaching is accompanied by postural adjustments. However, our participants adapted only the posture of the arm, while the posture in the rest of the body was organized independently of the rod properties. To emphasize, the properties of the rod had their primary effect on the arm that held the rod. We believe our results indicate that the body posture served as a stable platform from which the arm could be organized as a synergy to control the rod for the displacement. The postural adjustments required to control the rod are reflected in the distance to the table. How the adaptations in the distance can differ for the homogeneous and nonhomogeneous varied mass is an issue we turn to later.

The results show that the way participants act upon the environment (in our case, the object on the table) depends on the metrics and dynamics of the body + tool system. We interpret those findings as illustrating that the effectivities (and, thus, the affordances) are affected not only by geometric, but also by kinetic properties of the action system. This finding is in agreement with research of Konczak, Meeuwsen, and Cress (1992) who show that the perceived climbability of stairs depends not only on the leg length but also on dynamic properties of the action system such as its flexibility and strength, which both change with age. Affordances, thus, are action-scaled rather than merely body-scaled and people appear to be sensitive to that action-scaling (see also Oudejans, Michaels, Bakker, & Dolné, 1996). The fact that our participants selected reaching distances in accordance with rod dynamics demonstrates that implements, too, can be integral to action-scaling. The advantage of using tools for investigating action-scaling is that the effectivities can be manipulated in a continuous and systematic way.
Not only do we find tool use to provide a useful inroad to studying action, but we believe that an action perspective provides a good inroad to studying tool use. As we noted in our introduction, earlier studies of tool use neglected the dynamics of the action system because they focussed on the shape of a tool that was selected given a certain task. Interest in cognitive abilities to conceive of an object of a particular shape as a tool is not likely to raise issues about the motor aspects of wielding the tool. However, the present findings imply that one cannot come to a general understanding of tool use without acknowledging the importance of kinetics. This reinforces our earlier claim that tool use should be approached as an action problem, instead as a cognitive problem (cf. Smitsman, 1997; Smitsman & Bongers, 2000).

We believe that our findings also have implications for models of reaching. Again, we argue that that most models do not consider the full implications of the fact that humans often reach with a tool in their hand. The data presented here show that the dynamic characteristics of a tool are important for the organization of the act. Models such as those of Bullock, Grossberg, and Guenther (1993) and Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, and Engelbrecht (1995) show simulations of reaching with tools, however, the modeling is limited to geometric and kinematic characteristics; neither model takes into account dynamic characteristics of the tool. Our results suggest that the principles by which those models control the reach need to be elaborated if they are to account for phenomena observed in reaching with rods.10

We conclude with an issue that the present research leaves unresolved. We discussed how the results showed that the effectivity is constrained to regulate the relation between end-effector and environment. However, aspects of the findings of Experiment 2 appear to contradict the findings of Experiment 3: when (homogeneous) mass is manipulated, a closer distance to the table is selected for heavier rods, whereas when nonhomogeneous mass is manipulated, a larger distance to the table is selected for rods with mass at the tip, which place similar constraints on the posture as heavier rods. Moreover, the postural adaptations for the rods with weight at the tip and of larger mass seem to share, at least in part, a similar basis; for both rod types the elbow is more flexed. For now, we must leave this issue open, though we can present hypotheses

10 There are “dynamic” models of reaching (Zaal, Bootsma, & Van Wieringen, 1999), but they emphasize abstract dynamic properties, and do not explicitly address the use of tools.
regarding this seeming contradiction, and suggest ways to test them in the future. One way to further explore how the reaching distance emerged from the postural adaptations would be an experimental setup where the movement sideways was restricted or absent at all (as in a poking task) to see if the same distance-posture relations would emerge.

Acknowledgements

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Abstract
The present research concerned whether and how characteristics of tool and task affect actions. Adults held a rod (length .4 to .8 m) with the tip in the air, walked toward an object, chose a place to stop, and displaced the object with the rod’s tip. In two experiments, rod length, mass, and mass distribution, and size of the to-be-displaced cube were manipulated. Displacement posture was organized in two synergies; one comprising the arm, and one comprising legs and trunk. The lower-body synergy provided a stable platform for the displacement. The arm was less extended for small cubes, longer rods, and handle weighted rods; conditions where better control of the rod would be required. Chosen distances accommodated postural adaptations. Because effects of cube size on distance could only result from postural adjustment related to required control, we conclude that postural adjustments are prospectively reflected in the chosen distance.
Introduction

In general, implements enhance the capacity for action. For example, cutting bread or smearing butter require the creation of certain relations between surfaces that cannot be created by the body alone. The relations to be established (e.g., knife-bread angle, direction of force, etc.) provide some of the constraints on which of many possible grips on a given tool is used and which of many possible movement patterns is effected. Other constraints on the actions depend on properties of the tool. In short, coordinated behavior emerges from the interaction of constraints originating in organism, environment, and task (Newell, 1986; 1996). Moreover, to perform a coordinated act the constraints must be prospectively reflected early in the evolving action; a tool must be grasped in light of the to-be-performed task, for example. Our previous research (Bongers, Smitsman, & Michaels, submitted-b) concentrated on how geometric and kinetic properties of a tool (length, mass, and mass distribution) prospectively affected actions. In the present contribution, we turn attention to a task constraint, needed precision.

Most psychological research on tool use emphasizes cognitive aspects (cf. Connolly & Dalgleish, 1989; cf. Greenfield, 1991; cf. McCarty, Clifton, & Collard, 1999). Our conceptual starting point, on the other hand, is that using a tool is an action and should be approached from an action perspective (see Lockman, 2000, and Smitsman & Bongers, 2000, for a comprehensive discussion of this viewpoint). An action perspective directs attention to postures and movements that are available when using a tool and to how postures and movements are anticipated in actions. Obviously, holding a tool affects the dynamics—the forces and torques in the muscles and joints—and thus, puts special demands on those postures and movements. The shape of a tool also affects what actions are possible. In addition to the shape and the dynamics of the new "end-effector", properties of the task also constrain the action. In the present article, we attempt to demonstrate the effects of such task constraints and whether characteristics of the body + tool system interact with task constraints in the unfolding of the action.

In our earlier experiments (Bongers et al., submitted-b), participants had to approach an object while carrying a rod pointing upward; they had to stop, lower the rod, and displace the object with the rod’s tip.
Those experiments tested whether the chosen distance depended on both geometrics (e.g., rod length) and kinetics (e.g., rod mass). Our expectation had been that both geometrics and kinetics of the rod would affect chosen distance. As to the kinetics, we had expected that kinetics would influence displacement posture, and that posture, in turn, would be prospectively reflected in chosen distance. Put more simply, we asked whether participants would choose a distance that not only reflected the length of the rod, but also would provide room for a posture to control the rod.

Bongers et al. (submitted-b) found that participants’ choices of distance and arm posture were indeed varied as a function of both geometrics and kinetics of the rod. Most of the variance in distance and posture was due to length; mass and mass distribution had smaller effects. A larger distance was selected with longer rods. The distance also depended systematically on the two types of mass manipulations. 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. This was a peculiar finding because heavier rods and rods with mass at the tip share several seemingly important properties; they both have larger torques and have larger resistances to movement. Even though the elbow angles were adjusted similarly, the distances resulting from the total arm posture did show differences under the two mass manipulations. Thus, in both cases, reaching distance prospectively reflected postural adaptations. Again, however, the effects of kinetics were small; a clearer test of how they affect perception and action requires that we find a way to exaggerate their influence.

The small adaptions to mass and mass distribution suggest that they do not constitute a major constraint on reaching distance—at least in this version of the task and with the range of values used. It may be that the relatively large size of the to-be-displaced object could have absorbed small differences in postural adjustments without yielding changes in chosen distance. That is, there was about 2-3 cm leeway in the anterior-posterior contact point between rod and object. A change in the precision requirement of the task might make the effects of postural adaptions more visible in the reaching distance. In addition to tightening constraints in the anterior-posterior direction, decreasing object size should also affect the required precision in vertical tip placement. The finer control that is needed under this task constraint might be seen in other aspects of
posture; for example, the rod may have to be held differently. In the present studies, our concern was not only with whether task variables would affect distance and posture, but also with whether higher precision requirements would enhance the effects of mass and mass distribution of the rod.

How might task constraints, in particular, the requirement for precision, be expected to influence how one displaces an object from a stable posture? Let us start with posture itself. The trunk has been characterized as a postural stabilizer (cf. Kaminiski, Bock, & Gentile, 1995), therefore, variations in accuracy constraints and thus, how much stability is needed from the trunk, should affect adaptations in trunk posture. For example, Martin, Teasdale, Simoea, Corbeil, and Bourdin (2000) performed an experiment in which standing participants had to make fast pointing movements at targets, the likelihood of which varied. The uncertainty of the target did not affect the hand kinematics, but did increase the bending in the trunk. In a different task, Saling, Stelmach, Mescheriakov, and Berger (1996) found that when seated individuals grasped objects beyond arm’s length, the motion of the wrist was affected by object size, whereas the motion of the trunk was not affected by size. The trunk functioned as a postural stabilizer independent of the precise adjustments in the trunk under different task constraints. It seems reasonable to suppose that stability is related to precision, so we expected that under higher accuracy constraints, a more stable postural platform would be required to control the rod.

The arm posture should also be affected by a task that requires reaching and displacing an object with a tool, and we have shown such effects elsewhere (Bongers et al., submitted-b). Studies focussing on the 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). Although those synergies were found in reaches without a tool, it is likely that similar synergies underlie reaching with a tool. Given that synergies reflect the functional units of the action system, their coupling must depend on the variations in tool and task. Determining whether that coupling is anticipated in the distance from which the actor chooses to reach is one key goal of the current research.
How have individuals adapted their actions to changes in available length and task constraints in other experimental setups? Dean, Brüwer, and colleagues investigated how the kinematics of actions were adapted to changes in length of a hand-held pointer. In a series of experiments (Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990; Cruse, Brüwer, & Dean, 1993; Dean & Brüwer, 1994; 1997), participants were asked 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. In the current study we focussed not only on adaptations in actions but also on the anticipatory character of those adaptations. In addition, we studied how increases in rod length affected the organization of the whole body posture; Dean and Brüwer studied only the arm. Finally, our implementation of task constraints was different from theirs; we manipulated accuracy constraints.

The general finding that actions are adjusted according to precision requirements is a robust one within the motor control literature. Fitts’ Law is one such example; it related movement speed to end-point accuracy (Rosenbaum, 1991; Schmidt, 1988). In the earliest of Fitts’s experiment, participants held a stylus that was tapped between two targets. Fitts’ Law has been confirmed many times over. It has also inspired a wide variety of aiming and reaching studies (cf. MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; cf. Bootsma, Mottet, & Zaal, 1998; cf. Soechting, 1984). We, too, hope to observe an effect of “index of difficulty”, but in the present study, the size of the to-be-displaced object was varied to manipulate accuracy constraints. In Fitts law, the anticipation can be seen in the differential movement time; in our task it is to be seen in the stopping distance.

What are the predictions that follow from the issues raised thus far? How should postural adjustments and distance adaptations depend on length, mass, mass distribution, and precision requirements? Obviously, we expected that with longer rods participants would select a larger distance to the object. Distance is also expected to be adapted to mass manipulations in one of two ways. The first possibility is that participants select a closer distance to the object when using rods that have larger
torques (heavier rods or rods with more mass at the tip). This prediction is consistent with people’s judgments that the maximum carryable load decreases with increasing distance between body and load (Ciriello, Snook, & Hughes, 1993; Garg, 1989). However, in our earlier experiments, we found that torque in the joints was not minimized, suggesting that some other variable guided behavior. The second possibility, then, is based on our earlier findings that participants stood closer to the object with heavy rods with homogenous mass distribution and farther from the object with mass placed at the tip (Bongers et al., submitted-b). We were not able to identify the single physical description that captured those mass effects, though various candidates were evaluated. In any event, note that those two possibilities make contradictory predictions regarding the effects of mass distribution. The variation in precision requirements in the current work was intended to enhance the effects of mass and mass distribution. We expected that rods with less rotational inertia (a brief description of candidate variables is presented in the Appendix), that is, rods that are lighter or have mass at the handle, would be noisier—show more movement—at the tip because small variations in muscle-produced torque would yield a bigger effect. This noisiness would be particularly important when accuracy is needed. Therefore, lighter rods that have mass distributed homogeneously would require more control when the to-be-displaced object is small. Needed torque, by itself, might also affect posture; rods weighted at the handle produce less torque in the joints and, thus, would not require a posture that produces so much torque.

Until now, we have assumed that our manipulations affect posture and have asked whether those effects are to be anticipated in distance. However, it is possible that our manipulations “directly” affect distance, and then posture 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 stand; this would then have to be compensated for by posture. The combinations of postural adaptations and distance adaptations that are created by manipulations of rod characteristics will always be ambiguous; however, this is not the case for manipulations of precision requirements. In the case of variations in cube size, any observed distance adaptations must anticipate postures, because nothing else differs but the posture required to control the rod. Hence, the effect of cube size on distance can be regarded as a test case in our paradigm for whether upcoming postures reveal themselves earlier in the act.
To summarize, the present study examined the effects of geometric and kinetic properties of the body + rod system and of a task property (precision, operationalized as the size of a to-be-displaced object) on distance and posture in our displacement task. In Experiment 1 we varied the length and the homogeneous mass of the rods and in Experiment 2 we varied length and mass distribution. The manipulations of the size of the to-be-displaced cubes were similar in the two experiments.

Experiment 1

Method

Participants
Participants ranged in age from 22 to 39 years, nine were females and nine were males. 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.

Procedure and Materials
Twenty-five rods were used, five mass densities by five lengths: 0.4 to 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; these rods differed in diameter, and their length corresponded to the aluminum tubing. The inner steel rods were kept in place with small plastic discs. For each of the five lengths, five rod types were constructed: in these types the inner rod had a diameter of 0.2 cm, 0.4 cm, 0.6 cm, 0.8 cm, 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. Mass and other variables related to the wieldability and controllability of the rods are presented in Table 1. In the Appendix we explain the possible relevance of the presented variables to the current task and how they were computed.

Between two poles separated by 25 cm, a slot (14x1 cm) in a panel (28x17.5 cm) could be adjusted to the participant’s wrist height with the arm at the side. Two small pins that could slide on a carriage behind the panel, stuck out of the slot. A small cube (of 1.5 cm) or a large cube (of 5.5
cm) could be attached to the pins. 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 screen; this ensured that the tip of the rod was used to displace the cube.

Table 1. Characteristics of the rods used in Experiment 1.

<table>
<thead>
<tr>
<th>Inner steel tube</th>
<th>Rod length</th>
<th>Rod mass</th>
<th>$l_1$</th>
<th>$l_2$</th>
<th>$l_3$</th>
<th>CP</th>
<th>Static moment</th>
<th>HPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm m g</td>
<td>kg m²*10³</td>
<td>kg m²*10³</td>
<td>kg m²*10³</td>
<td>m Nm kg² m⁴</td>
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<td></td>
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<td>16.06</td>
<td>0.122</td>
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<td>0.376</td>
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<td>97.89</td>
<td>0.520</td>
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<td>0.62</td>
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<td>17.76</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rods stood in a rack about three meters from the target. The participant grasped the rod designated by the experimenter and, with the rod at an angle of about 45° upward from the horizontal, walked towards the stand (see Figure 1). The participants’ task was to stop at a distance from the stand from which they could displace the cube most comfortably; then the cube was displaced approximately 14 cm to the left with the tip of a rod (the cube returned automatically to its original position because of the weight).
The approach, reach, and displacement were videotaped. A video digitizing system was used to determine the positions of the handle of the rod, tip of the rod, and various anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, and wrist) in a 2D plane at the moment the displacement of the object started.\footnote{We were aware that measuring the behavior at one moment in the action provided a snapshot view of the behavior. This might be at odds with our stated interest in the ‘dynamics of the body + rod system’. However, we were not so much interested in the process of unfolding of the reach but more in whether dynamic aspects of the system affected the foot distance in an anticipatory way and how the posture with which the object was displaced was adapted to changes in the dynamics. We believed that the adaptations in the actions according to the changes in the dynamics could be revealed in the snapshot manner as presented here.} We measured foot distance as the distance between the stand and the foot nearer to the stand.\footnote{In most trials the feet were closely aligned, but we always measured foot distance from the foot closest to the table.} Postural angles were computed from the positions of the joints.

Figure 1. Several stages in the unfolding of a trial.
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. This gave a total of 200 trials for each participant. For each cube, the first block was considered as practice and was not further analyzed. The order of cube size was balanced over participants.

Results and Discussion

We divide our results into three sections. First we examine the extent to which joint angles appear to reflect synergies. We do this first because any observed functional relations will be crucial to interpreting adaptations in posture and foot distance. We then turn attention to those adaptations.

Postural synergies

We expected that the posture would be organized in synergies to control the rod: one synergy organizing the arm and the other synergy organizing the trunk and legs. To examine the synergy in the arm we analyzed the relationship between shoulder angle and elbow angle. A regression analysis on all the raw data showed a good correspondence between these two angles: Shoulder angle = 0.76 * elbow angle – 96.69, $F(1, 2698) = 5443$, $p < .001$, $r^2 = .67$. This suggested that the joints in the arm were indeed organized as a synergy.

To examine whether all individual participants showed the existence of this arm synergy, we performed similar regression analyses on the individuals. As can be seen in Table 2, there were two participants who showed essentially no relation between the shoulder and elbow angle ($r^2$ smaller than .10). Of the remaining 16 participants, there were six who showed a weak relation ($r^2$ between .10 and .50) and ten who showed a strong correspondence ($r^2$ higher than .65). The upper arm tended to be put more forward when the elbow was more stretched. For the majority of the participants, then, the adjustments in the shoulder were related to the adaptations in the elbow and, therefore, seem to reflect a synergy.3

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3 As those results indicate, not all participants organized the posture similarly. Some individuals differed in the relations between the joints. However, paying attention to the details of the individual
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 angle. The analysis showed that the changes in the hip angle had only a weak correspondence to the changes in the arm posture: 

\[ \text{hip angle} = 5.40 -0.05 \times \text{elbow angle} + 0.25 \times \text{shoulder angle}, \]

\[ F(2, 2697) = 308, p < .001, R^2 = .19. \]

This pattern of a weak relationship was reiterated in the results of the individual participants; only Participant 5 had an explained variance larger than 50% (.53) and the other \( R^2 \)'s were all smaller than .30. Postural adaptations in the trunk (i.e., hip angle), it seems, are relatively uncoupled to adjustments in the arm (i.e., shoulder angle and elbow angle).

Table 2. The regression analyses for each individual participant with elbow angle as the independent variable and shoulder angle as the dependent variable.

<table>
<thead>
<tr>
<th>Participant</th>
<th>( r^2 )</th>
<th>( F )</th>
<th>( p )</th>
<th>constant</th>
<th>slope</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>1.09</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>1240.37</td>
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<td>-87.76</td>
<td>0.63</td>
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</table>

*Note.* For each of the regression analysis the \( df \)'s were (1, 148).
Table 3. The multiple regression analyses for each individual participant with hip angle as the dependent variable of Experiment 1.

<table>
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<tr>
<th>Participant</th>
<th>$r^2$</th>
<th>$F$</th>
<th>$p$</th>
<th>constant</th>
<th>slope ankle angle</th>
<th>slope knee angle</th>
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<td>136.84</td>
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<td>-1.18</td>
</tr>
<tr>
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<td>.09</td>
<td>6.99</td>
<td>.001</td>
<td>54.10</td>
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<td>-0.53</td>
</tr>
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<td>74.00</td>
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<td>-0.84</td>
</tr>
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<tr>
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Note. For each of the regression analysis the df’s were (2, 147).

To explore the angles that were important for the synergy in the trunk and leg, we performed a regression analysis with hip angle as the dependent variable, and ankle angle and knee angle as independent variables. The overall regression analysis (hip angle = 179.15 –1.90 * ankle angle -1.45 * knee angle, $F(2, 2697) = 2532$, $p < .001$, $R^2 = .65$) showed a relatively high correspondence among those angles. Analyses on the individuals’ data revealed that for all but three participants the relation varied over a continuum from weak to strong, see also Table 3. Some participants clearly adapted the ankle and knee in correspondence to the hip, which we take as evidence that, at least for those participants, the body posture was organized as a synergy. The analyses show 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.

To summarize, the regression analyses on the angles indicated that separate synergies were formed in the trunk and leg, and in the arm. The synergy in the arm showed that the upper arm was put more forward when the elbow was more extended. In addition, the trunk was more
forward when the leg was more stretched. We presume that the synergy in the trunk and leg (which we will refer to as the body synergy) provides a stable platform for the control of the arm (cf. Kaminiski et al., 1995). If we now assume that the two synergies provide for different functionality, different aspects of the task may affect them differently. For example, it is possible that higher precision requirements required adaptations in the body synergy whereas properties of the rod affected the organization of the arm. In other words, it might be that there is a division of ‘work’ between the two synergies. To test these propositions, we started off by analyzing the distance that each synergy provides.

Postural distances

The present concern was not so much with the adaptations in the angles per se but more 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, an arm length is produced by the shoulder-elbow synergy. The lengths of the synergies are important because we expect them to be anticipated in the chosen distance to the stand. Only when synergy length is anticipated can the displacement be performed with an optimal posture. Before we address this anticipatory aspect of the present task, we first examine whether the effective length of the two synergies varied with experimental manipulations.

To test the possible contributions of the lengths produced by the arm and body synergies, we computed the horizontal distances between the extreme joints of the two synergies. We used the horizontal distance because the selected distance to the stand could vary only in the horizontal direction. To compute the wrist-shoulder distance, we subtracted the wrist position from shoulder position (see Figure 2). This measure reflected contributions of the arm synergy and was larger when the arm was more extended. The shoulder-ankle distance was computed by subtracting the shoulder position from the ankle position. This distance reflects the contributions of the body synergy and is positive when the shoulder is in front of the ankle, so larger positive values represent the body’s leaning forward. To examine whether and how the posture was adapted, we analyzed the wrist-shoulder distance, and the shoulder-ankle distance in separate three-way multivariate ANOVAs with Cube Size (small (1.5x1.5x1.5 cm) and large (5.5x5.5x5.5 cm)), Rod Type (steel
diameter of 0.2, 0.4, 0.6, 0.8, 1.0 cm), and Rod Length (0.4, 0.5, 0.6, 0.7, 0.8 m) as within-subject factors. The analyses were performed on the averages for each participant over repetitions. To increase the power of the tests, we did not look at the omnibus test but only at the linear and quadratic contrasts.4

Figure 2. The effective distances for each of the synergies.

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 4). In addition, one of the interaction effects was significant: Cube Size X 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 this distance tended to decrease over weight for the large cubes (see Figure 3A).

4 Because the rod types and the rod length were varied in a gradual fashion, we expected a gradual adaptation in the dependent variables. The linear and quadratic contrasts test a linear and a quadratic relation between the independent and the dependent variables. Specifying those contrast a priori, increases the power of the test because only specific relations between the independent and the dependent variables are tested.
Table 4. Means (SD) for the rod length effects of Experiment 1.

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Wrist-shoulder distance (m)</th>
<th>Ankle-shoulder distance (m)</th>
<th>Foot distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.202 (0.065)</td>
<td>0.120 (0.038)</td>
<td>0.729 (0.087)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.201 (0.066)</td>
<td>0.113 (0.038)</td>
<td>0.820 (0.088)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.195 (0.067)</td>
<td>0.107 (0.035)</td>
<td>0.905 (0.087)</td>
</tr>
<tr>
<td>0.7</td>
<td>0.189 (0.068)</td>
<td>0.104 (0.035)</td>
<td>0.995 (0.086)</td>
</tr>
<tr>
<td>0.8</td>
<td>0.180 (0.068)</td>
<td>0.097 (0.035)</td>
<td>1.078 (0.086)</td>
</tr>
</tbody>
</table>

We had hypothesized that the small cube, the larger rods, and the lighter rods would all require better control and therefore would affect wrist-shoulder distance in the same way. Accuracy demands associated with cube size decreased the arm extension, suggesting that a smaller wrist-shoulder distance is more dexterous. Increasing rod length has 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 these effects imply better control with a shorter arm, the small effect of rod mass, which was only seen for the large cubes, is opposite; heavy rods, which we supposed were easier to control also yielded a shorter distance.

The shoulder-ankle distance (see Figure 2) depended, linearly, on the length of the rod, $F(1, 17) = 20.98, p < .001$. The means showed that this distance was smaller for longer rods (see Table 4). None of the other effects was significant.

![Figure 3](image-url)

Figure 3. The interaction between Cube Size and Rod Type of wrist-shoulder distance for (A) Experiment 1, and (B) Experiment 2.
Chapter 5

The relatively upright body posture seen with longer rods might stem 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 further outward (as happens with longer rods), the more the CM of the body + rod system will be displaced. The postural adaptation in the body might try to compensate for this shift. Note that adjustments of the body have a larger effect on the shift in CM than adjustments of arm posture. Such an upright body posture has also been found when individuals lift the arm to a horizontal position in front of the shoulder (cf. Massion, 1992; cf. 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.5

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 is adapted only to the change of length in the system while the arm also reflects both changes in kinetics of the body + rod system and precision requirements. The demonstration that these different postural synergies are affected by different aspects of the task raises the question of whether both are anticipated in the chosen distance to the object. That is, for example, does a need for a shorter arm distance mean that the participant will stop closer to the stand?

Foot distance

The foot distance, which was defined as the distance between the foot nearer to the stand and the stand, was analyzed by means of a three-way multivariate ANOVA with Cube Size, Rod Type, and Rod Length as within-subject factors. The analyses were performed on the averages of each participant in each condition. Again, we looked only at the linear and quadratic contrasts. 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 \( F(1, 17) = 1091.09, p < .001 \); participants selected a larger distance from the stand when they were to reach with longer rods (see Table 4). The linear contrast of Rod Type was marginally significant, \( F(1, 17) = 4.15, p < .06 \); the means show that participants tended to select a larger distance to the

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5 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.
stand with more massive rods (0.2 cm, 0.903 m [SD = 0.153]; 0.4 cm, 0.904 m [SD = 0.151]; 0.6 cm, 0.904 m [SD = 0.152]; 0.8 cm, 0.908 m [SD = 0.147]; 1.0 cm, 0.908 m [SD = 0.152]). None of the interaction effects was 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. The closer distance to the stand with a small cube was in agreement with the postural adaptation in the body and the arm; less arm extension was observed in situations in which better control of the rod was required. 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, a cube-size effect on distance demonstrates unequivocally that upcoming posture is prospectively reflected in the chosen distance.

Distance was also well accommodated to length of the rod, which also hints at anticipatory control; one must stop at the place that will leave room for the rod to be lowered. To determine the nature of that relation between stopping distance and rod length, we regressed foot distance on rod length. The results (foot distance = 0.38 + 0.87 * rod length, $F(1, 2698) = 5459, p < .001, r^2 = .67$) showed that length explained the vast majority of the variance in the selected distance. This corresponds with our earlier findings (Bongers et al., submitted-b).

But as is clear from the cube-size effect, it is not just length that was anticipated in the distance; the chosen distance had to leave the right amount of room for the posture needed to control the rod. Thus, other variables, such as mass, that could influence posture, should have an analogous effect on distance. Rod mass did have the hypothesized effect on distance—shorter distance when more control is required—but since it had had an opposite effect on posture, there can be no appeal to (postural) anticipation in this case.

We should also note that the rod-type effect, that is, a closer distance for lighter rods conflicts with our earlier findings (Bongers et al., submitted-b, Experiment 2). There we found that participants selected a closer distance when heavier rods were used. In fact, we have replicated both of these effects on different occasions. In our earlier setup, we found a shorter distance with heavier rods when the different rod types were presented on consecutive days (Bongers, Smitsman, & Michaels, 1998). Also the finding in the present experiment, shorter distance with lighter
rods, was replicated; in an experiment where adolescents performed the same task in an almost identical setup, we found that a closer distance was selected with rods of less (homogeneous) mass.\footnote{In this study, which is not published, 20 adolescents varying in age between 12 and 16 years displaced the small cube with rods varying in length from 0.3 to 0.7 m in 0.1-m steps. Two rod types were used, rods of wood and rods of steel (a subset of the rods used in Experiment 2 of Bongers et al., submitted-b). In this experiment a stand similar to the present stand, but of slightly different dimensions was used and adolescents displaced only the small cube (1.5x1.5x1.5 cm). They selected a larger distance to the table with the heavy (steel) rods than they did with the light rods.} Based on the fact that both effects have been observed on more than one occasion, there is a need to identify the circumstances that set the stage for each effect. An explanation of the variant found in this experiment, we believe, will help make those circumstances clear. In the General Discussion we further address the different findings in the different setups.

A possible explanation of why in the present experiment shorter distances were selected with lighter rods might be related to haptic information about rod length. Research into perception of length via dynamic touch has revealed that light rods that were held but not seen were perceived as shorter than heavy rods of equal length (Carello, Fitzpatrick, Flascher & Turvey, 1998; Fitzpatrick, Carello, & Turvey, 1994). Thus, if in our paradigm only haptic information determined perceived length, the observed effect is predicted—a closer distance to the stand is selected with lighter rods. In a series of experiments, Fitzpatrick, Carello and Turvey (1994) established the relation between \textit{haptic perceived length} (HPL) and rod properties (see Appendix). As can be seen in Table 1, HPL increases with increasing diameter of the inner steel rod (i.e., with heavier rods) and with longer rods. To evaluate whether the increase in HPL determined the selected distance, we plotted this relation (see Figure 4). The figure clearly shows five levels that represent the five rod lengths. The five points at each level represent the five rod types that differ in weight. The fact that there is little or no ascent within the clusters of five indicates that HPL was not related to foot distance. Therefore, we think that the haptic perceived length did not contribute to the selected distance in the present experiment. This implies that effects of mass cannot affect the distance directly. Instead, we argue that the effect of mass manipulation on distance stems from postural adjustments associated with rod control.
Before we further address the underlying basis of the postural adaptations, we first 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 variation in homogeneous mass. We expected that manipulations of mass distributions would provide insight in how the adaptations in foot distance and posture were related.

**Experiment 2**

Experiment 1 showed that both the distance to the stand and the posture depended primarily on cube size and length of the rod. Rod mass had some minor effects but they were not systematic in that 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 wieldableness (and concomitant controllability). 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.

One might expect that rods with mass at the tip would effect behavior in the same way as our heavier rods because both produce relatively larger torques and have more resistance to rotational acceleration (see Appendix). We expected that the larger inertia of those rods would improve the stability of the tip. Not finding effects of inertia in Experiment 1 may have resulted from the range over which wieldability could be manipulated with homogeneous rods. Varying mass distribution makes it possible to extend the range of the inertia of the rods. This should make it more likely that postural adjustments, and thus, adaptations in distance will occur as a function of mass manipulations. Moreover, extending this range allowed us to examine the relation between stability of the rod’s tip, presumably related to wieldability, and precision requirements in more detail.

An extra motivation to perform this manipulation is to follow up on a lead offered in Experiment 1. The observation that adaptations to heavy homogenous rods in Experiment 1 were similar to adaptations to rods with mass at the tip in our previous study (Bongers et al., submitted-b), suggests a possible resolution to the discrepant findings with homogeneous mass.

Method

The setup used in this experiment was similar to the setup of Experiment 1. The experiments differed only in the participants and the types of rods that were used. Participants ranged in ages from 20 to 26 years, nine were females and nine were males. The rods used in this experiment had the same range of lengths as those used in Experiment 1. To manipulate the mass distribution, a lead cylinder (diameter 1.9 cm, length 10 cm, with a mass of 345 g) was inserted inside the tube. For each of the five lengths, five rod types were constructed by inserting a weight at one of five evenly distributed rod positions from (but not including) the handle to the tip. Properties related to the controllability and wieldability of the rod are presented in Table 5 (see Appendix for the computation of the variables).
Table 5. Characteristics of the rods used in Experiment 2.

<table>
<thead>
<tr>
<th>Place inserted weight</th>
<th>Rod length</th>
<th>Rod mass</th>
<th>( I_1 ) (10^3 kgm²)</th>
<th>( I_2 ) (10^3 kgm²)</th>
<th>( I_3 ) (10^3 kgm²)</th>
<th>CP (Nm)</th>
<th>Static moment (kg m²)</th>
<th>HPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location m g</td>
<td>kgm²*</td>
<td>Place 1 (handle) 0.4</td>
<td>0.448</td>
<td>19.74</td>
<td>19.50</td>
<td>0.271</td>
<td>0.24</td>
<td>0.809</td>
</tr>
<tr>
<td>Place 1 (handle) 0.5</td>
<td>0.466</td>
<td>25.51</td>
<td>25.15</td>
<td>0.393</td>
<td>0.28</td>
<td>0.908</td>
<td>8.87</td>
<td></td>
</tr>
<tr>
<td>Place 1 (handle) 0.6</td>
<td>0.484</td>
<td>33.47</td>
<td>32.98</td>
<td>0.518</td>
<td>0.32</td>
<td>1.024</td>
<td>9.13</td>
<td></td>
</tr>
<tr>
<td>Place 1 (handle) 0.7</td>
<td>0.502</td>
<td>43.97</td>
<td>43.37</td>
<td>0.633</td>
<td>0.37</td>
<td>1.158</td>
<td>9.62</td>
<td></td>
</tr>
<tr>
<td>Place 1 (handle) 0.8</td>
<td>0.520</td>
<td>57.38</td>
<td>56.68</td>
<td>0.737</td>
<td>0.43</td>
<td>1.309</td>
<td>10.25</td>
<td></td>
</tr>
<tr>
<td>Place 2 0.4</td>
<td>0.448</td>
<td>30.57</td>
<td>30.45</td>
<td>0.152</td>
<td>0.28</td>
<td>1.071</td>
<td>12.72</td>
<td></td>
</tr>
<tr>
<td>Place 2 0.5</td>
<td>0.466</td>
<td>40.84</td>
<td>40.68</td>
<td>0.190</td>
<td>0.32</td>
<td>1.257</td>
<td>13.38</td>
<td></td>
</tr>
<tr>
<td>Place 2 0.6</td>
<td>0.484</td>
<td>53.75</td>
<td>53.55</td>
<td>0.232</td>
<td>0.36</td>
<td>1.461</td>
<td>14.12</td>
<td></td>
</tr>
<tr>
<td>Place 2 0.7</td>
<td>0.502</td>
<td>69.64</td>
<td>69.40</td>
<td>0.273</td>
<td>0.41</td>
<td>1.682</td>
<td>14.94</td>
<td></td>
</tr>
<tr>
<td>Place 2 0.8</td>
<td>0.520</td>
<td>88.89</td>
<td>88.61</td>
<td>0.314</td>
<td>0.45</td>
<td>1.921</td>
<td>15.83</td>
<td></td>
</tr>
<tr>
<td>Place 3 0.4</td>
<td>0.448</td>
<td>45.42</td>
<td>45.33</td>
<td>0.119</td>
<td>0.33</td>
<td>1.334</td>
<td>16.10</td>
<td></td>
</tr>
<tr>
<td>Place 3 0.5</td>
<td>0.466</td>
<td>63.31</td>
<td>63.20</td>
<td>0.137</td>
<td>0.39</td>
<td>1.607</td>
<td>17.69</td>
<td></td>
</tr>
<tr>
<td>Place 3 0.6</td>
<td>0.484</td>
<td>85.17</td>
<td>85.05</td>
<td>0.155</td>
<td>0.44</td>
<td>1.898</td>
<td>19.23</td>
<td></td>
</tr>
<tr>
<td>Place 3 0.7</td>
<td>0.502</td>
<td>111.36</td>
<td>111.22</td>
<td>0.175</td>
<td>0.50</td>
<td>2.207</td>
<td>20.72</td>
<td></td>
</tr>
<tr>
<td>Place 3 0.8</td>
<td>0.520</td>
<td>142.24</td>
<td>142.08</td>
<td>0.194</td>
<td>0.55</td>
<td>2.533</td>
<td>22.19</td>
<td></td>
</tr>
<tr>
<td>Place 4 0.4</td>
<td>0.448</td>
<td>64.27</td>
<td>64.18</td>
<td>0.118</td>
<td>0.40</td>
<td>1.596</td>
<td>18.58</td>
<td></td>
</tr>
<tr>
<td>Place 4 0.5</td>
<td>0.466</td>
<td>92.90</td>
<td>92.80</td>
<td>0.135</td>
<td>0.47</td>
<td>1.957</td>
<td>20.77</td>
<td></td>
</tr>
<tr>
<td>Place 4 0.6</td>
<td>0.484</td>
<td>127.73</td>
<td>127.61</td>
<td>0.153</td>
<td>0.54</td>
<td>2.336</td>
<td>22.82</td>
<td></td>
</tr>
<tr>
<td>Place 4 0.7</td>
<td>0.502</td>
<td>169.13</td>
<td>168.99</td>
<td>0.170</td>
<td>0.61</td>
<td>2.732</td>
<td>24.78</td>
<td></td>
</tr>
<tr>
<td>Place 4 0.8</td>
<td>0.520</td>
<td>217.43</td>
<td>217.28</td>
<td>0.188</td>
<td>0.68</td>
<td>3.145</td>
<td>26.65</td>
<td></td>
</tr>
<tr>
<td>Place 5 (tip) 0.4</td>
<td>0.448</td>
<td>87.13</td>
<td>87.03</td>
<td>0.129</td>
<td>0.46</td>
<td>1.858</td>
<td>20.51</td>
<td></td>
</tr>
<tr>
<td>Place 5 (tip) 0.5</td>
<td>0.466</td>
<td>129.63</td>
<td>129.51</td>
<td>0.150</td>
<td>0.55</td>
<td>2.307</td>
<td>23.06</td>
<td></td>
</tr>
<tr>
<td>Place 5 (tip) 0.6</td>
<td>0.484</td>
<td>181.44</td>
<td>181.30</td>
<td>0.172</td>
<td>0.64</td>
<td>2.773</td>
<td>25.42</td>
<td></td>
</tr>
<tr>
<td>Place 5 (tip) 0.7</td>
<td>0.502</td>
<td>242.94</td>
<td>242.78</td>
<td>0.194</td>
<td>0.73</td>
<td>3.256</td>
<td>27.64</td>
<td></td>
</tr>
<tr>
<td>Place 5 (tip) 0.8</td>
<td>0.520</td>
<td>314.47</td>
<td>314.29</td>
<td>0.216</td>
<td>0.82</td>
<td>3.757</td>
<td>29.76</td>
<td></td>
</tr>
</tbody>
</table>

Results and Discussion

As in Experiment 1 we start with examining the functional relations between the joints with which the posture is organized. Then we address the distances provided for by the synergies and how those distances were anticipated in the distance.

Postural synergies

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

A regression analysis on all the raw data showed a good correspondence between the shoulder and elbow angles: shoulder angle = 0.85 * elbow angle –109.71, $F(1, 2698) = 3906.66$, $p < .001$, $r^2 = .59$. This again suggested that the joints in the arm were indeed organized as a synergy. We regressed shoulder against elbow angle for each participant separately. The results are presented in Table 6 and showed that for most of the participants there existed a correspondence between the two angles of the arm. However, for some of the participants this relation was rather weak ($r^2$ of .19, .24, and .30). The explained variances of the other participants were scattered over the continuum from weak to strong. However, the explained variances in the arm were, in general, smaller in this experiment than they had been in Experiment 1. Still, for nine participants the explained variance was larger than 60% indicating that, at least for half the participants, the upper arm was more forward when the elbow was more extended.

Table 6. Regression analyses between shoulder and elbow for each participant separately.

<table>
<thead>
<tr>
<th>Participant</th>
<th>$r^2$</th>
<th>$F$</th>
<th>constant</th>
<th>slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.45</td>
<td>118.93</td>
<td>-49.37</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
<td>.68</td>
<td>311.48</td>
<td>-101.14</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>.43</td>
<td>111.69</td>
<td>-117.71</td>
<td>0.86</td>
</tr>
<tr>
<td>4</td>
<td>.63</td>
<td>250.15</td>
<td>-130.65</td>
<td>1.03</td>
</tr>
<tr>
<td>5</td>
<td>.48</td>
<td>134.84</td>
<td>-94.64</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>.65</td>
<td>269.16</td>
<td>-99.96</td>
<td>0.82</td>
</tr>
<tr>
<td>7</td>
<td>.30</td>
<td>64.12</td>
<td>-39.73</td>
<td>0.37</td>
</tr>
<tr>
<td>8</td>
<td>.36</td>
<td>84.79</td>
<td>-70.01</td>
<td>0.53</td>
</tr>
<tr>
<td>9</td>
<td>.65</td>
<td>276.60</td>
<td>-126.48</td>
<td>0.90</td>
</tr>
<tr>
<td>10</td>
<td>.24</td>
<td>46.63</td>
<td>-93.19</td>
<td>0.75</td>
</tr>
<tr>
<td>11</td>
<td>.63</td>
<td>252.83</td>
<td>-115.77</td>
<td>0.89</td>
</tr>
<tr>
<td>12</td>
<td>.52</td>
<td>158.71</td>
<td>-120.60</td>
<td>0.87</td>
</tr>
<tr>
<td>13</td>
<td>.75</td>
<td>432.41</td>
<td>-150.80</td>
<td>1.26</td>
</tr>
<tr>
<td>14</td>
<td>.62</td>
<td>241.50</td>
<td>-102.54</td>
<td>0.80</td>
</tr>
<tr>
<td>15</td>
<td>.50</td>
<td>145.31</td>
<td>-123.89</td>
<td>0.90</td>
</tr>
<tr>
<td>16</td>
<td>.69</td>
<td>329.16</td>
<td>-147.58</td>
<td>1.12</td>
</tr>
<tr>
<td>17</td>
<td>.19</td>
<td>34.65</td>
<td>-35.72</td>
<td>0.32</td>
</tr>
<tr>
<td>18</td>
<td>.66</td>
<td>290.93</td>
<td>-198.98</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Note. For each of the regression analysis the df's were (1, 148), $p < .001$. 

156
To evaluate how the adaptations in the arm were related to adjustments in the trunk we regressed the shoulder and elbow angle on the hip angle. The analysis showed that hip angle had a very weak correspondence to arm posture: hip angle = 31.89 –0.25 × elbow angle + 0.44 × shoulder angle, $F(2, 2697) = 721, p < .001, R^2 = .35$. The regression equations on the individual participants showed a similar pattern; only two had an explained variance larger than 70% and all the other $R^2$'s were smaller than .37. Those analyses show that postural adaptations in the trunk (i.e., hip angle) are relatively uncoupled to adjustments in the arm (i.e., shoulder angle and elbow angle). As in Experiment 1, we think that this analysis showed that hip and arm are controlled by separate synergies.

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, $F(1, 2698) = 1564.64, p < .001, R^2 = .54$. Regressions on the data of individual participants showed all but one participant had this relationship (see Table 7). For the other participants the explained variance varied from .38 to .85.

Table 7. The multiple regression analyses for each individual participant with hip angle as the dependent variable of Experiment 2.

<table>
<thead>
<tr>
<th>Participant</th>
<th>$r^2$</th>
<th>$F$</th>
<th>constant</th>
<th>slope ankle angle</th>
<th>slope knee angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.70</td>
<td>170.52</td>
<td>105.16</td>
<td>-1.13</td>
<td>-1.19</td>
</tr>
<tr>
<td>2</td>
<td>.66</td>
<td>145.57</td>
<td>129.10</td>
<td>-1.39</td>
<td>-1.29</td>
</tr>
<tr>
<td>3</td>
<td>.52</td>
<td>80.43</td>
<td>118.48</td>
<td>-1.32</td>
<td>-1.20</td>
</tr>
<tr>
<td>4</td>
<td>.38</td>
<td>45.40</td>
<td>69.79</td>
<td>-0.74</td>
<td>-0.70</td>
</tr>
<tr>
<td>5</td>
<td>.52</td>
<td>78.32</td>
<td>109.61</td>
<td>-1.18</td>
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<tr>
<td>6</td>
<td>.24</td>
<td>23.82</td>
<td>132.58</td>
<td>-1.38</td>
<td>0.14</td>
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<tr>
<td>7</td>
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<td>126.02</td>
<td>106.82</td>
<td>-1.09</td>
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<td>8</td>
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<td>420.13</td>
<td>107.38</td>
<td>-1.08</td>
<td>-0.98</td>
</tr>
<tr>
<td>9</td>
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<td>162.36</td>
<td>127.44</td>
<td>-1.39</td>
<td>-1.21</td>
</tr>
<tr>
<td>10</td>
<td>.54</td>
<td>86.88</td>
<td>107.10</td>
<td>-1.14</td>
<td>-1.11</td>
</tr>
<tr>
<td>11</td>
<td>.66</td>
<td>141.47</td>
<td>97.58</td>
<td>-1.04</td>
<td>-0.93</td>
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<td>12</td>
<td>.57</td>
<td>97.22</td>
<td>104.90</td>
<td>-1.18</td>
<td>-1.22</td>
</tr>
<tr>
<td>13</td>
<td>.39</td>
<td>46.39</td>
<td>234.77</td>
<td>-2.44</td>
<td>-0.96</td>
</tr>
<tr>
<td>14</td>
<td>.58</td>
<td>100.06</td>
<td>92.36</td>
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<td>-0.79</td>
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<tr>
<td>15</td>
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<td>71.73</td>
<td>-0.77</td>
<td>-0.85</td>
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<td>140.33</td>
<td>68.67</td>
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<td>-0.94</td>
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<td>290.43</td>
<td>111.05</td>
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<td>18</td>
<td>.43</td>
<td>55.72</td>
<td>147.45</td>
<td>-1.51</td>
<td>-0.75</td>
</tr>
</tbody>
</table>

Note. For each of the regression analysis the df's were (2, 147), $p < .001$. 

157
In general, then, the regression lines showed that participants adapted the ankle and knee in correspondence to the hip, which indicated that the body posture was organized as a synergy. The analyses show that the hip bends more forward when the knee extends more and the shank is more upright.

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

**Postural distances**

As in Experiment 1, we subtracted wrist position from shoulder position (i.e., the wrist-shoulder distance, reflecting contributions of the arm synergy), and shoulder position from ankle position (i.e., the shoulder-ankle distance, reflecting contributions of the body synergy) to compute the effective length of each of the synergies. 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 (small and large), Rod Type (weight attached at place 1 (the handle), place 2, place 3 (the middle), place 4, and place 5 (the tip)), and Rod Length (0.4, 0.5, 0.6, 0.7, 0.8 m) as within-subject factors. The analyses were performed on the averages for each participant for each condition. Again, to increase the power we did not look at the omnibus test but only at the linear and quadratic contrasts.

The *wrist-shoulder distance* was adapted according to size of the cube, $F(1, 17) = 7.99, p = .01$, and was smaller for the small cube (small = 0.188 m, large = 0.207 m). This effect shows that precision requirements affect the postural control of the rod. The linear contrast of Rod Length was significant ($F(1, 17) = 4.96, p < .05$), showing that the wrist-shoulder distance was shorter for longer rods (see Table 8). 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 this distance was larger (see Figure 3B).

We had expected that better control was required both by longer rods (because small movements at the wrist could result in large movements of the tip) and by small cubes. Because both conditions yielded a smaller wrist-shoulder distance, one would 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 it had to displace a small cube. Before we further interpret this finding we first present the analysis on the body synergy.

Table 8. Means (SD) for the conditions of Experiment 2.

<table>
<thead>
<tr>
<th>Rod length (m)</th>
<th>Wrist-shoulder distance (m)</th>
<th>Ankle-shoulder distance (m)</th>
<th>Foot distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.202 (0.057)</td>
<td>0.115 (0.047)</td>
<td>0.729 (0.081)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.205 (0.056)</td>
<td>0.115 (0.044)</td>
<td>0.830 (0.079)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.199 (0.064)</td>
<td>0.108 (0.043)</td>
<td>0.915 (0.084)</td>
</tr>
<tr>
<td>0.7</td>
<td>0.193 (0.067)</td>
<td>0.104 (0.044)</td>
<td>1.004 (0.092)</td>
</tr>
<tr>
<td>0.8</td>
<td>0.188 (0.069)</td>
<td>0.104 (0.042)</td>
<td>1.095 (0.095)</td>
</tr>
</tbody>
</table>

Rod type

| Place 1 (handle) | 0.108 (0.044) | 0.910 (0.154) |
| Place 2         | 0.108 (0.044) | 0.912 (0.154) |
| Place 3         | 0.108 (0.043) | 0.913 (0.155) |
| Place 4         | 0.109 (0.044) | 0.917 (0.155) |
| Place 5 (tip)   | 0.112 (0.045) | 0.921 (0.156) |

For the shoulder-ankle distance the main effect of Rod Length was significant, $F(1, 17) = 5.02, p < .05$. The means showed that the shoulder-ankle distance was smaller for longer rods (see Table 8). 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 was significant. In short, in conditions where the rod required better control the body did not lean as far forward as it did when less control was required. This suggests that a more upright body provided for more stability. However, the body was only affected by variations of the rod, not by variations in object size.

In sum, the effective lengths of both the arm synergy and the body synergy were affected by our experimental manipulations. It seemed that
in conditions were the rod had to be better controlled, the arm was less extended and the body was more upright. We now ask whether those adaptations in the posture are anticipated in the chosen distance.

Foot distance

The foot distance was analyzed by means of a three-way multivariate ANOVA with Cube Size, Rod Type, and Rod Length as within-subject factors. The analyses were performed on the averages for each participant for each condition. Again, we only looked at the linear and quadratic contrasts. Participants selected a considerably smaller distance to the stand with the small cube than 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 8). The linear trend of Rod Type was significant, $F(1, 17) = 12.65; p < .005$. As the means in Table 8 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 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 a similar distance to the stand for all rod types; however, with the small cube, the distance to the stand tended to be larger for rods weighted at the tip (see Figure 5). Finally, the interaction between the quadratic trends of Rod Type and Rod Length was significant, $F(1, 17) = 10.64; p = .005$. This significance seemed to result from a single condition, the longest rod with weight at the tip, in which the foot was slightly larger than other rod types.

As in Experiment 1, rod length explained most of the variance in the distance. To examine this relation we computed the regression line for the raw data pooled over participants (foot distance = 0.37 + 0.91 * rod length, $F(1, 2698) = 5943; p < .001; r^2 = .69$). The analysis showed that the correspondence between rod length and the distance to the stand is comparable to the regression line in Experiment 1 (in Experiment 1 we found a slope of 0.87 and a $r^2$ of .67).
In this experiment the foot distance depended on length, mass distribution, and cube size. With a smaller cube, shorter rods, and rods weighted at the handle, participants selected a shorter distance. The combined effect of a rod with weight at the handle and a small cube size led to an especially short reaching distance. We had expected rods with weight at the handle to be noisier at the tip than rods weighted at the tip. All in all, these effects show that closer distances are selected when better control is required.

How is this conclusion related to the length adaptations of the postural synergies? The adaptations in the chosen distance were in agreement with the adjustments in the postural synergies. The arm was less extended when rods with mass in the handle were used to displace a small cube and the body also leaned less forward in some of those conditions.

**General Discussion**

In the present study we were interested in how properties of task and tool affected actions, in particular, using the tip of a hand-held rod to displace an object. We measured chosen distance to the object and posture at the moment the object was displaced. In two experiments we varied length,
mass, and mass distribution of the rod and size of the to-be-displaced cube. Rod length was expected to determine geometrics of the body + rod system and should thereby affect the chosen distance directly. The mass and cube manipulations were expected to influence the posture required to control the rod, which should also prospectively affect the chosen distance. The details of this prospective control were to be investigated by relating adaptations in distance to adjustments in different parts of the posture. The two experiments used the same manipulations of rod length and cube size; only their mass manipulations differed.

In Experiment 1, rod mass was distributed homogeneously and the weight of the rod was varied. 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 only to rod length, whereas the arm synergy was adapted to length, 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, where increased control was associated with smaller cube size and longer rods. However, decreased weight had also been expected to require more control, but light rods gave rise to greater arm extension, at least with the large cube. Of critical interest was whether postural adjustments would be reflected in the chosen distance, and we found that they were; the selected distance was relatively shorter for the smaller cube and the longer rods. The shorter distance with lighter rods, on the other hand, had no parallel in posture. Because parallels between posture and distance can reflect either the distance affecting posture or the posture affecting distance, effects such as those of rod length are ambiguous. However, because effects of cube size on distance could result only from postural adjustment stemming from differences in required control, we concluded that at least some postural adjustments are prospectively reflected in the chosen distance. Our attempt to find an anticipation of mass-related posture was hampered by the small range of wieldability. To enlarge this range, mass distribution of the rods was varied in Experiment 2.

In Experiment 2, we varied mass distribution in order to extend the range of the rod’s resistance to movement, and, thus, its required control. The results again showed that posture was organized in an arm synergy and a body synergy. The arm was less extended and the body was more
upright for conditions in which the rod required better control. Moreover, both of these accommodations were reflected in the distance. Note that we had not found such striking parallels in Experiment 1; the body synergy had been adapted only to rod length. It might have been that the larger range of controllability in Experiment 2 put more constraints on arm posture, which, in turn, put more stringent requirements on where one could stand. The stringent requirements might have led to overshoot in the adaptation in the foot distance (i.e., stopping too close when rods were weighted at the handle). Ending up too close may require the body posture to compensate, so that the arm can meet those stringent constraints. Although this explanation is highly speculative, it illustrates how different synergies could function flexibly to make this goal-directed act possible.

How do the results of the present study, in which properties of both tool and task were varied, relate to our earlier findings when only properties of the tool were varied? Some of the results conflict with our earlier findings; Bongers et al., (submitted-b) reported that when mass was varied homogeneously, a shorter distance was selected with heavier rods. However, in the present Experiment 1, we found that a longer distance was selected with heavier rods. As stated before, we believe that both findings were reliable because both were replicated in other experiments (see also footnote 4). Two things had changed with respect to our earlier experiments (Bongers et al., submitted-b): (a) the rods in the earlier experiments were made of one material throughout whereas the rods presently used are compound, and (b) in the earlier setup the to-be-displaced object was a cylinder sitting on a table, whereas in the present experiment the cube was 'hanging in the air', unsupported by a surface. We do not believe that rod composition was the critical factor, because we have found (in the unpublished experiment described in footnote 4) the present results—a farther distance was selected with heavier rods—using the old rods but the new stand (i.e., the to-be-displaced cube was hanging in the air). From this, we inferred that the difference lay in the difference between the to-be-displaced objects or between the stand and the tabletop. The object that was used in the earlier experiment was comparable in size to the large cube used in the present study (diameter cylinder was 5 cm, height 6 cm vs. a cube of 5.5x5.5x5.5 cm) so size does not seem the likely cause of the difference. We are left with the difference between sliding an object over a table (including instructions not to touch
the table) vs. pushing a cube through the air. Whether this is the origin of the difference would require a new experiment.

However, both our current and the earlier (Bongers et al., submitted-b) results agree about an important point: the postural adaptations did not minimize the torques in the joints. Torque in the arm joints increases with increasing arm extension—wrist more in front of the shoulder (cf. Bongers et al., submitted-b). In all the trials of the present study, the wrist was in front of the shoulder and the arm was more extended both with Experiment 1’s heavier rods and with Experiment 2’s rods weighted at the tip. These rod types produce greater torques than lighter rods and rods weighted at the handle, respectively, indicating that torque in the arm increased as a combined effect of the posture and the torque produced by the rods. Minimizing the torques, of course, would require a less extended arm. From this we conclude that the posture was not adapted to minimize the torque in the arm joints, again in accordance with our earlier article (Bongers et al.) for which we computed the torques in the arm and found no signs of minimization. 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, thus, how action possibilities change with tools.

The search for variables that determine the action possibilities with a tool might also be guided by our finding that the postural synergies emerging in this task are similar to those found during reaches without a rod. Investigations into postural synergies employed when reaching with the hand to a target has revealed that one synergy controls the trunk, independent from the motion of the hand, while 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). The resemblance between those synergies and the synergies revealed in the present study indicates that reaching with a rod and reaching with just the hand share underlying control and coordination processes. More particularly, the synergy in the arm was affected by variations in rod length and mass, and precision requirements; the arm was organized to control the rod. We speculated in Experiment 2 that the body synergy compensated the selected distance to the object and the required arm posture. This corresponds with the idea that 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 (Kaminiski et al., 1995; Martin et al., 2000; Saling et al., 1996).

How the rod should be controlled was shown to be dependent not only on properties of the rod itself, but also on accuracy constraints of the task that had to be performed. Our results showed that differences in accuracy constraints affected the posture controlling the rod and the selected distance to the object. Because the effects of accuracy constraints are common in the motor-control literature, our finding of accuracy effects again emphasizes the similarity in processes underlying actions with and without tools. It is obvious that one grasps tiny objects in a different way than larger objects (using a precision grip rather than a power grip), and the approach phase anticipates the grip that is employed. A variety of studies make clear that the kinematics of reaches are adapted to accuracy constraints (cf. MacKenzie et al., 1987; cf. Bootsma et al., 1998; cf. Soechting, 1984). Changes in kinematics according to accuracy constraints have also been revealed in a very different tool-using task; Van der Kamp and Steenbergen (1999) found different arm trajectories when adults used a spoon for eating two types of food that differed in viscosity. Differences in viscosity can be regarded as variations in accuracy constraints, as Van der Kamp and Steenbergen argued. Our results go beyond those of Van der Kamp and Steenbergen in demonstrating the anticipatory nature of the changes in actions with a tool under variations in accuracy constraints.

Adaptations in actions are expected to reflect changes in action possibilities; the characteristics of actions depend on the behavioral patterns that are possible with a tool. The fact that properties of tool and task affected the actions in the current experiment demonstrates that action possibilities are conjointly determined by properties of the environment and properties of the body + tool system. In other words, possibilities for action with a tool depend on the relation between characteristics of the body + tool system and the constraints of the task. For example, we showed that the reaching range with a rod depends not on the dynamics of the rod or the size of the cube but on their relation. Such a finding provides a useful general lesson for students of tool use. We think it illustrates the value of an action-approach to tool use over the more common cognitive perspective. The literature on the development of tool use, in particular, has emphasized children's cognitive skills in constructing an action plan for tool use (cf. Connolly & Dalgleish, 1989; cf.
McCarty et al., 1999). However, such an interest in cognitive abilities easily neglects the changes in action possibilities that tools bring about (cf. Smitsman, 1997; Smitsman & Bongers, 2000).

Acknowledgements

The authors would like to thank Roelof Schellingerhout for helpful discussions. We wish to express our gratitude to Jules van Horen for drawing Figure 1.
Appendix

In our earlier study (cf. Bongers et al., submitted-b), we tested a series of variables that might be determine distance and posture in displacement-with-a-rod. Those variables can be divided into three categories, variables related to: (a) rod control (moments of inertia), (b) the force required to manipulate the rod (static moment), and (c) the haptic perceived length. In the following paragraphs we explain how those measures were computed. In Tables 1 and 5 are the values for each of the rods presented for Experiment 1 and Experiment 2, respectively.

The motion of a rod is best described as a rotation in three dimensions about axes through the wrist. The center of mass of the rod remains at a fixed distance from the wrist, independent of the wielding. The rod’s resistance to rotational acceleration depends not only on the rod’s constituent masses but also on how far they are from the axes of rotation. A mass farther away from the axis of rotation has a larger resistance to rotational acceleration about that axis than a mass closer by. A rod’s moment of inertia is the sum of all of its masses multiplied by their squared distances from the axis. The resistance to rotational acceleration a rod possesses in 3D is represented by the inertia tensor. The three elements in the diagonalized form of the inertia tensor reflect the object’s resistance to rotational acceleration around its principal axes of inertia, or symmetry axes. Those three elements of the diagonalized form are called the (principal) moments of inertia or eigenvalues. We computed the moments of inertia of the rod with the rotation point in the wrist (to simplify the computations we did not use the mass of the hand). $I_1$, $I_2$, and $I_3$ refer to the eigenvalues (with 1, 2, and 3 corresponding to largest, intermediate and smallest). The rods we use were almost symmetrical in two directions (i.e., an up-down and a left-right movement) and the only asymmetry is related to the point of rotation that is not in the rod but in the wrist. In our case the largest moment of inertia reflects the resistance to movements in the up-down direction. The middle moment of inertia reflects the resistance to sideward movement. The magnitudes of $I_1$ and $I_2$ are nearly identical. The smallest moment of inertia reflects resistance to rotations around an axis through the wrist but to parallel the longitudinal axis of the rod.
Dynamic touch experiments have revealed that individuals have an awareness of the linear dimensions of object through wielding them (for an overview see Turvey & Carello, 1995). Several studies revealed the importance of the moments of inertia for the perception of length of an object that is held but not seen. Based on the combined data of several experiments, Fitzpatrick, Carello, and Turvey (1994) presented a formula to compute haptic perceived length: $HPL = 3.8 \cdot I_1^{0.41} \cdot I_3^{-0.30}$.

The force required to hold an object depends on the torque such an object produces in the wrist. This torque depends on the distance between the CM of the held object and point of rotation and this distance varies with the angle under which the object is held, and, thus with movement. To provide for an invariant under movement of the object we computed the static moment, which is the invariant part of the static torque (cf. Kingma, Beek, & Van Dieën, submitted). It was computed as the distance between the wrist and the CM of the rod multiplied by the gravitational acceleration and the mass of the rod.
Introduction

Picking up a tool changes the activities one can engage in. Those changes have been examined here from a novel perspective—an action perspective—that takes the action as a starting point for studying tool use (cf. Smitsman & Bongers, 2000). Four sets of experiments examined whether and how different properties of tools affected an action. The primary focus was on how properties of tools determined action possibilities for adults and young children. In this Epilogue the results of the studies will be discussed with regard to three main questions: First, do tools affect affordances, and do individuals perceive those new action possibilities? Second, what is the nature of the development of tool use? The question of development was deemed especially interesting because adapting to bodily growth might be analogous to using a tool. And, third, if tools do affect affordances, what information provides the basis for perceiving the new action possibilities? This Epilogue will conclude with a set of proposed research questions to further study tool use and its development from an action perspective.
Chapter 6

Affordances

The action perspective used in the present thesis was grounded in the Ecological approach to perception, and in the dynamic systems theory approach to action development (see Chapter 1). One of the cornerstones of the ecological approach to perception is the concept of affordances and this section discusses how this concept relates to tool use.

Remember that affordances are defined as the possibilities for behavior provided to a given organism by an environmental layout (J.J. Gibson, 1979). Perceiving affordances is perceiving the action possibilities in the environment; or in other words, perceiving the environment in relation to the actor’s capabilities for action. Tools change the action possibilities of an actor; for instance, holding a rod brings formerly out-of-reach objects within reach. I argued that if an actor prospectively adapts the action when using a tool, then the actor has perceived the changed affordances with that tool. To test whether actions were prospectively adapted in the current experiments, I employed a variety of manipulations on a single experimental paradigm. While carrying a rod, adults or children approached an object and chose a position from which to displace that object with the rod’s tip. Length and mass properties of the rod and size of the to-be-displaced object were varied. Adults clearly adapted the distance to the object; children adapted the distance, too, but they also adapted the strategies during the approach phase. That both children and adults prospectively adapted their actions to the changes in action capabilities brought about by the tool was taken as evidence that they perceive the new affordances tools engender.

This finding has implications for understanding tool use: The present findings show that both body and tool determine the new affordances. In other words, the end-effector to which affordances refer is formed by body + tool. This idea is not new; similar ideas were put forward by Smitsman (1997) who suggested that body + tool function as a single system (cf. J.J. Gibson, 1979; cf. Loomis & Lederman, 1986). The current thesis elaborated on Smitsman’s ideas and provided a step toward grounding the claim that body + tool function as a single system. One finding supporting this claim was that the postural synergies were similar independent of whether a tool is used. Chapter 4 and 5 show that the posture was organized into two synergies; one synergy coordinating the shoulder and elbow, and another synergy coordinating the ankle, knee,
and hip. Those synergies showed strong similarities with synergies found when reaches with just the hand were studied (Kaminiski, Bock, & Gentile, 1995; Ma & Feldman, 1995; Martin, Teasdale, Simonea, Corbeil & Bourdin, 2000; Saling, Stelmach, Mescheriakov, & Berger, 1996; Wang & Stelmach, 1998). This similarity suggests that the underlying processes of controlling and coordinating the degrees of freedom in the neuromotor system do not depend on whether a tool is used. In short, from the viewpoint of the underlying control processes, body + tool behave as one.

The claim that body + tool operate as a single unit has interesting consequences for adopting a proper approach to study tool use. As I maintained in Chapter 1, earlier approaches to tool use focussed on the cognitive abilities required to use a tool. Those approaches started from the tentative assumption that tool use comprised a higher cognitive level than the perceptions and actions required controlling the tool. However, the present findings suggest that action possibilities with tools can be understood in much the same way as acting without a tool, implying that no additional steps in explanatory models of tool use need to be introduced (see also, Lockman, 2000). Although I believe the present findings support this viewpoint, it is a radical hypothesis; more experimental support and corroboration are needed. The viewpoint presented here is supported by findings in the dynamic touch paradigm; several studies showed that a tool can be conceived of as an extension of the haptic perceptual system (Burton, 1993). For instance, environmental properties can be perceived by probing with a tool (Barac-Cikoja & Turvey, 1991, 1993, 1995; Burton, 1992, 1993, 1994). Other corroboration of the viewpoint presented here comes from research in the fields of neurophysiology and neuropsychology. To strengthen the viewpoints presented in this thesis, I will present those findings in more detail in the following.

The argument that body + tool operate as a single unit has also received support from recent studies in neurophysiology and neuropsychology (Aglioti, Smania, Manfredi & Berlucchi, 1996; Berti & Frassinetti, 2000; Iriki, Tanaka & Iwamura, 1996). Iriki et al. (1996) studied brain activity of a monkey that used a rake to reach for objects. They found that the neurons that code the visual receptive field of the hand altered during tool use; the hand’s receptive field came to include the tool’s length or the augmented available reaching space. The results were interpreted as that the neural schema of the hand was adapted to
incorporate the tool. Similar conclusions were drawn from a different line of research. Berti and Frassinetti (2000) concentrated on adaptations of neural representations of “near” and “far” space when using a tool, with the former referring to the space reachable by the arm alone and the latter requiring locomotion. They reasoned that if the representation of the body schema can be adapted by using a tool, the phenomena observed in the near space should also be observed for events in the far space when a tool is used, because the far space comes within reach with a tool. This idea was tested using a patient who showed dissociation between the near and far space in the manifestation of neglect after a right hemisphere stroke (Berti & Frassinetti, 2000). The patient performed a line-bisection task under different conditions: (a) the patient showed neglect bisecting a line with a laser pointer in near space but not in far space, (b) the patient showed neglect when bisecting a line with the hand in near space, and, the cool part, (c) the patient also showed neglect when bisecting a line in far space with a hand-held rod. The investigators interpret the findings as that the “peripersonal space was expanded to include the far space reachable by the tool. The reaching of ‘far’ space with a tool determined a switch between spatial representations, so that the representation of near space was now activated.” (Berti & Frassinetti, 2000, pp. 418). To conclude, findings from several research lines (i.e., actual measurement of neural activity in monkey’s brains and behavioral measures of a patient suffering from a neurological disorder) were interpreted as that the neural representation of the body was adapted to include the tool that was used. However, the results so far should be treated with caution; for example, in the study of Berti and Frassinetti it is unclear why the so-called body schema is extended by a rod and not by a laser-pointer.

In sum, findings in neurophysiology and neuropsychology provide tentative additional support for one of the conclusions of the present thesis, that body + tool function as a single unit (see also, Smitsman, 1997, and, Smitsman & Bongers, 2000). The idea that the new end-effector consists of body and tool forms the basis for my argument that tools determine affordances. Because new affordances emerge according to properties of the tool, a developmental viewpoint seems appropriate to study tool use. The next section will address developmental aspects in the present study of tool use.
Development

In the present section I will characterize some developmental aspects of an action perspective on tool use. To do this, I start by giving the reader an impression of the phenomena one would expect from a more traditional, cognitive approach to the development of tool use. Examining how the results differ from those expectations gives me the opportunity to illustrate how development can be studied from an action perspective.

In the more cognitive approaches, different types of tool use are often associated with different levels of cognition (cf. Brown, 1990; cf. Parker & K.R. Gibson, 1977). Inherent in those approaches is the tentative assumption that a certain maturation of the cognitive system is required for the different types of tool use to emerge, that is, cognitive abilities are supposed to be the rate-limiting factors. From such an approach, one would expect that the set of tool-properties that affect the actions increase with age—i.e., when the cognitive system reached a certain level of maturation. This implies that older children, or children with a higher level of skill, would adapt their actions to more properties of the tool than younger children. Do our data confirm this prediction?

To understand the set of tool properties to which actions are adapted, it is helpful to distinguish what remains invariant and what changes as a function of age. The present findings showed invariance in the performance related to the task goal: The relation between the tip of the end-effector and the object remained controlled, independent of age. However, there were changes in the way in which the relation between the tip and the object was regulated; adults prospectively adapted the distance while children prospectively adapted not only the distance but also the strategies. Adults adapted the distance according to all manipulations (i.e., length and mass of the rod, and size of to-be-displaced object). Children adapted the distance only to length and the strategies to length, mass, and size. The results show that all the variables affected the behavior at all ages but that the way in which the variables affected the behavior differed with age. To put it another way, the set of tool-properties to which the actions were adapted did not differ over age, but the manner in which properties affected the action depended on the age. This indicates that the cognitive abilities by themselves do not determine the behavior because the actions depend on all tool-properties in different phases of development. In other words, the cognitive system
is not functioning as a rate-limiting factor; instead, other processes determine the level of skill. This conclusion contradicts the predictions from a cognitive approach to tool use development. In the following paragraphs I will argue that the findings are in agreement with predictions derived from an action perspective to tool use.

What is the underlying structure of the behavior at the different ages? The present findings show that the behavior of the participants was goal-directed, independent of the level of skill: The goal of the present task was to control the relation between the rod’s tip and the object and the actions served to control this relation. Adults chose a distance that accommodated the length of the rod and a posture with which the rod could be appropriately controlled. Children adapted both the distance and the strategies to control the relation between the tip and the object. I argued that children used strategies outside the task boundaries to create information about the new action possibilities. Based on this information, the relation between the tip and the object was controlled. For instance, the younger children lowered the longer rods early in the approach phase, thereby producing information about the relation between the (distant) tip and the object. To conclude, at all ages the actions were goal-directed and aimed at picking up information to control the relation between tip and object.

This behavior is in agreement with what would be expected from an action perspective on tool use, which is inspired, in part, by ecological psychology. Within an ecological approach the generally accepted view holds that young children must learn to pick up the information that specifies the affordance (cf. Adolph, 1997; cf. Adolph, Eppler, & E.J. Gibson, 1993). In other words, the young actor must learn to differentiate information that specifies an affordance. The present results show that children with a tool adapt their actions to create information about their action possibilities; by lowering the rod, the children create information about where to stop. The action is goal-directed; the adaptations take place to control the relation between the rod’s tip and the object. The way the children adapt their action depends on the level of skill.

The current findings suggest that one learns which information has to be picked up to control the relation between the rod’s tip and the object. This conclusion raises the question of which information guides the action? The results of the present studies show that rod length was the most important variable for the adaptations in the actions and that
adaptations to other variables (i.e., related to mass properties of the rod and size of to-be-displaced object) were relatively small. In the next section I will discuss candidate variables that are affected by the experimental manipulations and that guide the behavior.

**Informational basis**

What might be the origin of the information guiding the behavior? Earlier I established that the body + tool system determine affordances which implies that it is not just the rod that must be anticipated in the distance but also the posture with which the rod is controlled. This is confirmed by a demonstration that the distance is adapted to a manipulation that can affect only the posture. This is what I found: The results of Chapter 5 showed that the distance was adapted to changes in the size of the to-be-displaced object. Variations in object size should only affect the required control of the rod, which determines the posture. The adaptations in the distance according to variations in object size were taken as evidence that the distance was prospectively adapted according to postural adaptations. Thus, it is the posture that is controlled and the distance is prospectively adapted to this posture.

This interpretation of the results was corroborated by other results: The relation between properties of the rod and selected distance expected on the basis of a perceived length was not found. Studies in the dynamic touch paradigm have determined the haptic perceived length of a rod that is held but not seen (for an overview see, Turvey and Carello, 1995). However, in the present studies adaptations in the distances were not in agreement with predictions stemming from the haptic perceived length. This finding, together with the effect of object size on distance, led me to conclude that the distance was prospectively adapted to the posture with which the object was displaced.

Because the posture seems to be a behavioral characteristic that is controlled, postural adaptations should reveal the physical basis on which the actions were adapted; the physical basis points in the direction of the informational basis. The results showed that the arm was less extended for the conditions in which more control of the rod was required, and this effect was largest when both the rod’s mass distribution and the object were manipulated. The selected distance to the object was shorter in those conditions to provide for the change in arm
posture. One possibility is that the postural adaptations follow from the forces and torques that counteract the load produced by the rod. More precisely, it is possible that participants used a posture in which the forces and torques were small, that is, a strategy to minimize the effects of biomechanical constraints. However, the results of both Chapters 4 and 5 show that participants did not adapt the posture to minimize the torques in the joints, at least not during the displacement. This implies that the load produced by a tool is not the limiting factor for the handling of the tool.

The results of Chapter 4 revealed that a complex set of variables in addition to length seemed to explain variation in the selected distance (i.e., arm length and body height, and static moment, center of percussion, and wieldability of the rod). Those variables were all related to how the rod should be controlled during object displacement, which was in agreement with my earlier conclusion that information about both posture and rod determine the distance. This implies that the available length in the body + tool system was not just a metric length depending on rod properties, but a dynamic length depending on properties of organism, environment, and tool. Therefore, the possibilities for action with a tool are action-scaled instead of metric-scaled (cf. Konczak, Meeuwsen, & Cress, 1992; cf. Oudejans, Michaels, Bakker, & Dolné, 1996).

The present studies were conducted to reveal the informational basis that determined actions with a tool. However, on the basis of the present findings the variable or set of variables that control the behavior can not be distinguished. But it can be concluded that tools scale the action possibilities. On the basis of this conclusion future questions to determine the informational basis can be framed. In the last section of this thesis I will propose new directions in which the study of tool use can develop.

Future directions for studying tool use and its development

In my view, future directions in the study of tool use and its development should also take an action perspective as the departure point. In this section I will present some themes around which future investigations can be organized. This section starts with future directions that find their origins in limitations and restrictions of the experiments that were conducted. This list is far from being exhaustive but is meant to give an
impression of what alternatives would be feasible from an action perspective.

An important restriction of the experiments with children was that they were asked to execute the task in a predetermined way. I believe that for the questions addressed in the current thesis, this approach was appropriate. One of the original aims of the project was to make a model of the body + tool system that could predict which distance an adult or a child should select, given a certain rod. Developing and validating such a model requires clear-cut experimental data. However, as Chapter 2 and 3 showed, it was not always easy for the children to behave according to the explicit task demands. It might be interesting in future research to remove the shackles. The results of Chapter 3, in particular, indicate the potentiality of studying children’s behavior when it is not restricted. One option is to study tool-using behavior of children in free play sessions. Such a study could open doors to how children explore the tool to discover how it can enhance action possibilities. In addition, in a free play session the importance of social interaction for the emergence of tool use can be investigated.

In most of the studies conducted in this thesis, only one moment in the performance was analyzed. Chapter 3 was the exception; the behavior was scored at different moments in a trial, but note that in that chapter no information was gathered about the kinematics of the action. Fixating on one moment might prohibit finding the information that guides the behavior. It is likely that sampling the kinematics of the body and rod at more instances in the performance would reveal more details of how children and adults prospectively adapted their actions. It is interesting to ask at what moment the action starts to be adapted to the new action possibilities—answering this question might help find the information that guides the behavior. For example, one can ask whether it is just the last step that is modulated to end up at the preferred distance to the object or whether the modulation occurs over a larger range (cf. Lee, Lishman, & Thomson, 1982). Adapting the length of more steps would indicate that the changes in action possibilities are perceived at an early stage in the performance.

The experiments in the current thesis are also limited in the properties of the body + tool system that were manipulated. One of the conclusions was that body + tool function as one system; however, a better test of this claim would be to vary properties of the action system independent of the
tool. This can be done in several ways: One option is to attach weights to the arms of the participants. Another option is to use participants with distinct bodily characteristics. For instance, two groups of participants, one group with short or light limbs and another group with long or heavy limbs, can be compared (for a similar strategy see Warren, 1984). Investigating how bodily characteristics interact with properties of tools would help in understanding the processes by which body + tool function as one system; that is, exactly what does the "+" mean?

As noted earlier, it follows from the conclusion that body + tool function as one system that tools change affordances. Tools allow for a systematic variation of the action system and, therefore, they make it possible to investigate how new affordances emerge when the action system changes. Tool use provides a way to study the development of affordances; it offers the opportunity to examine the pick-up of information under changes of the action system. More precisely, children’s exploratory actions to pick up information about the new possibilities for action can be studied.

Studying the development of tool use might also be helpful in understanding adolescents cope with the growth spurt. The growth spurt takes place at the beginning of adolescence and is characterized by rapid changes in physical maturation and bodily growth (Gabbard, 2000; Payne & Isaacs, 1995). Note that the growth spurt is more distinguishable for boys than for girls. Poor coordination of action and clumsiness is often reported for boys during this period. It already seems clear that adolescent boys in the growth spurt have difficulty in perceiving the changed action possibilities when their body has grown (Heffernan & Thomson, 1999). Heffernan and Thomson showed, for example, that boys in the growth spurt overestimated their maximum reaching distance with a rod more than boys of the same age but not in the growth spurt. There is a peculiarity about this phenomenon; boys from about ten years old can use tools dexterously (i.e., they can use pencils for writing and drawing, use eating utensils according to etiquette (in principle), and perform well in different sports in which implements are used). This means that those boys perceive the sudden change in action possibilities engendered by tools. It is strange why those boys have difficulty perceiving the changes in action possibilities due to rapid bodily growth. In other words, why can boys re-scale their actions to tools before the growth spurt but not to the rapid growth of their body? This suggests that the coordination
problems are not due to length and mass changes per se. Studying tool use in and around the growth spurt might be helpful in further pinning down adaptation processes at work during the growth spurt.

Another direction in which an action approach to tool use could develop is to disentangle the information about action possibilities that is picked up through vision and through dynamic touch. By varying mass properties of tools it is possible to manipulate the information that is picked up through dynamic touch (cf. Turvey & Carello, 1995). This is particularly interesting because a manipulation of properties of tool can vary the information for dynamic touch independent from the visual information (i.e., inserting weights in hollow tubing as is done in the current experiments). In this way the effects of the different modalities on the perception of action possibilities can be investigated.

An issue that deserves more attention in future studies is the interaction between findings at the behavioral level and findings at the neural level. As explained earlier, recent findings show that body + tool function as one in the neuromotor system (Aglioti, Smania, Manfredi & Berlucchi, 1996; Berti & Frassinetti, 2000; Iriki, Tanaka & Iwamura, 1996). Some of those studies showed that it was not simply a body schema that was represented in the activity of neural cells but that the activity of neural cells changed according to the new action possibilities with a tool. In other words, the neural activity changed according to the changes in affordances. Measuring neural activity during tool use could shed light on the mechanisms by which the information about the new action possibilities is picked up. This would be helpful in distinguishing the informational basis that determines action possibilities with a tool.


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Summary

The current thesis took the changes in action possibilities brought about by tools as the departure point for understanding tool use and developmental processes related to it. Typically, studies of tool use have examined whether children understand how a tool can augment their capacities for action. A different route was taken in the present thesis. Both children and adults were clearly instructed how to use a tool, and experiments tried to determine whether and how participants adapted their actions to properties of the tool. The experiments were set up to search for variables that determined action possibilities with a tool.

Chapter 1 started with an overview of earlier approaches to the study of tool use. This overview led me to conclude that most of those approaches focussed on cognitive abilities required to use a tool. However, a focus on cognitive abilities makes it easy to overlook the alteration in action possibilities due to tools. To study those alterations, the current thesis adopted an action perspective—a combined perspective of ecological psychology and the dynamic-systems-theory approach to the development of action (cf. Lockman, 2000; Smitsman, 1997; Smitsman & Bongers, 2000). Issues regarding tool use that were relevant from an action perspective were presented; these included the relation between tool use and affordances and the analogy between the change in action possibilities with tools and with bodily growth. At the end of Chapter 1, the experimental manipulations of the subsequent chapters were presented.

To test whether and how tools affected the action possibilities, I employed a variety of manipulations on a single experimental paradigm. While carrying a rod pointing upward, adults or young children approached an object. They stopped, lowered the rod, and displaced the object sideward with the tip of the rod. For the participant to displace the object with the rod’s tip, the selected distance to the object should accommodate the length of the rod as well as the posture needed to
control the rod. Length, mass, and mass distribution of the rod, and size of the to-be-displaced object were varied. All four manipulations were expected to affect control of the rod. For instance, a smaller to-be-displaced object requires more movement precision. The posture required to control the rod should affect actions prospectively, and such anticipatory adaptations reflect whether action possibilities with a tool have been perceived. In the various studies I examined whether and how the properties of rod and object affected the selected distance, the posture during displacement, or other parts of the performance.

In Chapter 2, children aged two to four performed the task. In three experiments, length, mass, and mass distribution of the rods were varied (the object was kept constant in this study). Two groups of children with different levels of skill were distinguished. This was done to examine how variables determining action possibilities with a tool, become important as the skill was mastered. The results showed that children adapted their selected distance only to rod length, not to changes in mass or mass distribution. Posture adopted while displacing the object, on the other hand, depended on length, mass, and mass distribution. Note that not all changes in the posture were prospectively reflected in the selected distance. No differences between the groups of children with different skill were found. Based on these findings it was concluded that children prospectively changed their actions to changes in length of the tool but that children needed to discover how the required control of the rod (as affected by mass manipulations) determined the action possibilities.

Chapter 3 extended the findings of Chapter 2 in several ways: in addition to length and mass of the rod, the size of the to-be-displaced object was also varied. I also measured different dependent variables: deviations from the task instruction were tallied at different phases of the act (approach, distance selection, and rod grip). Deviations from task instructions should reflect children’s functional adaptations in actions. This chapter examined whether the actions varied with properties of the rod and the object and whether those adaptations were anticipatory. The criterion for accepting an adaptation as anticipatory was that it had to be effective before the rod was lowered. Younger children lowered longer rods early, during the approach. Also, when displacing a smaller object, often two hands were used to hold the rod. Rod mass affected the fine-tuning of the distance just before or during the displacement. The latter two effects did not vary with age. The alterations in actions were
functional with regard to the experimental manipulation, and the rod-lowering created information about action possibilities with the tool. Thus, children prospectively adapted their actions to perform the task according to changes in the action possibilities engendered by the tool and the object, and for some changes this varied with age.

Chapter 4 and 5 report experiments that were performed with adults; the goal was to find variables that guided relatively expert tool users. Length, mass, and mass distribution of the rod were varied in three experiments, in Chapter 4. Length determined most of the variation in the selected distance and in the posture with which the object was displaced. Small but reliable adjustments in both distance and posture were made as a function of mass properties of the rod. Postural adaptations took place only in the arm, which appeared to be organized as a synergy. Chosen distance anticipated not only changes in rod length but also postural adaptations that were needed to control the rod. The results were interpreted as showing that adults prospectively adapted the distance to the object according to action possibilities with the tool.

In Chapter 5, the size of the to-be-displaced object was varied, together with length and mass properties of the rods. The size of the object was manipulated to examine how precision requirements affected the distance and the posture. Displacement posture appeared to be organized into two synergies; one comprising the arm, and one comprising legs and trunk. The lower-body synergy provided a stable platform for the displacement. The arm was less extended for small objects, longer rods, and handle-weighted rods, conditions in which better control of the rod would be required. Chosen distance also reflected postural adaptations. Because the effects of object size on distance could only result from postural adjustments related to required control, we concluded that postural adjustments were prospectively reflected in the chosen distance.

Finally, in Chapter 6 the findings of all the experiments were summarized and discussed. I argued that body + tool functioned as one system and that affordances change as properties of a tool change. These conclusions were corroborated by recent findings from neurophysiology and neuropsychology. In addition, I presented the processes according to which tool use could develop. The variables that could determine action possibilities with a tool were discussed. The thesis ended with a brief overview of future questions that could be addressed from an action perspective to tool use.
Samenvatting

Een werktuig kan gedefinieerd worden als een voorwerp dat opgepakt wordt om handelingsmogelijkheden te veranderen. In het onderhavige proefschrift werden deze veranderingen bestudeerd om werktuiggebruik en ontwikkelingsprocessen die daar aan gerelateerd zijn te begrijpen. Eerdere onderzoeken naar werktuiggebruik bestudeerden vooral of een kind begreep hoe een werktuig de handelingsmogelijkheden kon vergroten. Het huidige proefschrift hanteerde een andere methode; kinderen en volwassenen werden duidelijk geïnstrueerd hoe ze een werktuig moesten gebruiken en de experimenten richtten zich op de aanpassingen in de handelingen als functie van de eigenschappen van het werktuig. Op deze manier werd gezocht naar de variabelen die de handelingsmogelijkheden met een werktuig bepaalden.

In Hoofdstuk 1 werd een overzicht gepresenteerd van eerdere studies naar werktuiggebruik. Uit dit overzicht bleek dat de meeste van deze vroegere benaderingen zich vooral richtten op cognitieve vermogens die nodig waren om een werktuig te kunnen gebruiken. Echter, als gevolg van de aandacht op cognitieve vermogens bleven de veranderingen in handelingsmogelijkheden buiten beschouwing. Om deze veranderingen te bestuderen werd in het huidige proefschrift een handelingsperspectief gebruikt—een combinatie van inzichten uit de ecologische psychologie en de dynamische systeem theorie op motorische ontwikkeling (zie ook Lockman, 2000; Smitsman, 1997; en Smitsman & Bongers, 2000). Aandachtspunten die relevant waren vanuit een handelingsperspectief, zoals de relatie tussen werktuiggebruik en affordances en de analogie tussen veranderingen in handelingsmogelijkheden als gevolg van werktuiggebruik en lichamelijke groei, werden gepresenteerd in Hoofdstuk 1. Dit hoofdstuk eindigde met een overzicht van de experimentele manipulaties van de studies in dit proefschrift.
De experimentele opzet die gebruikt werd om te bestuderen welke variabelen de handelingsmogelijkheden met een werktuig bepalen was hetzelfde in alle studies. Volwassenen of jonge kinderen naderden een voorwerp terwijl ze een stok vasthielden die omhoog wees, ze stopten, bewogen de stok naar beneden en verplaatsten het voorwerp zijwaarts met de punt van de stok. Om het voorwerp te kunnen verplaatsen met de punt van de stok, dient de gekozen afstand tot het voorwerp niet alleen overeen te stemmen met de lengte van de stok maar ook met de houding waarmee de stok gecontroleerd kan worden tijdens de verplaatsing van het voorwerp. Lengte, massa en massaverdeling van de stok en grootte van het te verplaatsen voorwerp werden gevarieerd. Alle vier de manipulaties bepaalden de vereiste controle van de stok. Bijvoorbeeld, een klein voorwerp vereist meer precisie aan de punt dan een groot voorwerp. De verwachting was dat de houding afhankelijk is van de benodigde controle over de stok en dat de gekozen afstand tot het voorwerp aangepast werd aan deze houdingsaanpassing. Deze, prospectieve, aanpassing van de afstand geeft weer of de veranderingen in handelingsmogelijkheden waargenomen worden. In verschillende studies heb ik onderzocht hoe variaties in eigenschappen van stok en voorwerp de gekozen afstand, de houding tijdens de verplaatsing of een ander deel van de uitvoering bepaalden.

In Hoofdstuk 2 voerden kinderen in de leeftijd van twee tot vier jaar de taak uit. In verschillende experimenten werd de lengte, massa en massaverdeling van de stok gevarieerd (de grootte van het voorwerp bleef constant in deze experimenten). De kinderen werden ingedeeld in twee groepen van verschillend vaardigheidsniveau. Dit werd gedaan om te onderzoeken hoe variabelen, die handelingsmogelijkheden met een stok bepalen, belangrijk worden als de vaardigheid toeneemt. Tegen de verwachting in bleek dat de resultaten niet verschilden voor de twee groepen. Uit de resultaten bleek dat kinderen de afstand alleen aanpasten bij veranderingen in lengte van de stok en niet bij veranderingen in massa en massaverdeling. Let op, veranderingen in de gekozen afstand geven prospectieve aanpassingen als gevolg van veranderingen in handelingsmogelijkheden weer. De houding waarmee het voorwerp werd verplaatst was afhankelijk van de lengte, massa en massaverdeling van de stok. De bevindingen lieten zien dat niet alle aanpassingen in de houdingen terugkwamen in de afstand. Geconcludeerd werd dat kinderen prospectief hun handelingen aanpasten aan de lengte van de
Hoofdstuk 3 was een uitbreiding van Hoofdstuk 2: er werd niet alleen lengte en massa van de stok gevarieerd maar ook de grootte van het te verplaatsen voorwerp. Tevens werden andere afhankelijke variabelen gemeten: afwijkingen van de taakinstructies werden gescoord in verschillende fasen van de uitvoering (bijvoorbeeld, tijdens de nadering, het selecteren van de afstand, en hoe de stok werd vastgepakt). De verwachting was dat de afwijkingen van taakinstructies functionele aanpassingen in de handelingen representeren. Er werd onderzocht of de aanpassingen van kinderen met eigenschappen van de stok en met eigenschappen van het te verplaatsen voorwerp en of deze aanpassingen prospectief waren. Het criterium om een aanpassing als prospectief te kenmerken was dat deze plaatsvond voordat de afstand tot het voorwerp werd gekozen. Jongere kinderen lieten de stok in een vroege fase, tijdens de nadering, al naar beneden. Tevens werden, vroeg in een trial, vaker twee handen gebruikt bij de verplaatsing van een klein voorwerp. De massa van de stok beïnvloedde kleine aanpassingen in de gekozen afstand net voor of gedurende de verplaatsing. Deze laatste twee effecten waren niet leeftijdsafhankelijk. De aanpassingen in de handelingen waren functioneel in het licht van de manipulaties en het laten zakken van de punt creëerde informatie over de handelingsmogelijkheden met de stok. Dus, wanneer eigenschappen van de stok en het voorwerp veranderden pasten kinderen hun handelingen prospectief aan overeenkomstig de nieuwe handelingsmogelijkheden en sommige aanpassingen varieerden met de leeftijd.

Om inzicht te krijgen in de variabelen die het gedrag sturen van relatief ervaren werktuiggebruikers, voerden volwassenen dezelfde taak uit als de kinderen. Deze bevindingen werden in Hoofdstuk 4 en 5 gerapporteerd. In de experimenten beschreven in Hoofdstuk 4 werden de lengte, massa en de massaverdeling van de stokken gemanipuleerd. Lengte bepaalde de meeste variatie in de gekozen afstand en in de houding. Massa-eigenschappen van de stok leidden tot kleine maar betrouwbare aanpassingen in de afstand en de houding. Van de houding werd alleen de arm aangepast, deze werd georganiseerd als een synergie. De gekozen afstand anticipeerde niet alleen veranderingen in stok lengte maar ook houdingsveranderingen die nodig waren om de stok te
De resultaten ondersteunden de gedachte dat volwassenen prospectief hun afstand tot het voorwerp aanpasten in overeenstemming met de handelingsmogelijkheden met het werktuig.

In Hoofdstuk 5, werd naast de lengte en massa-eigenschappen van de stok ook de grootte van het te verplaatsen object gevarieerd. Voorwerpgrootte werd gevarieerd om te onderzoeken hoe precisievereist de gekozen afstand en de houding bepaalden. De houding tijdens verplaatsen was georganiseerd in twee synergieën: een synergie omspande de arm en de andere synergie omspande de benen en de romp. De synergie in de benen en de romp zorgde voor een stabiel platform op basis waarvan het voorwerp verplaatst kon worden met de stok. De arm werd minder uitgestrekt voor kleinere voorwerpen, langere stokken en stokken met gewicht in het handvat; condities waar een verbeterde controle van de stok was vereist. De gekozen afstand werd aangepast aan de houdingsadaptaties. Omdat de effecten van de grootte van het voorwerp op de gekozen afstand alleen het resultaat konden zijn van houdingsaanpassingen die gerelateerd waren aan de vereiste controle over de stok werd geconcludeerd dat de gekozen afstand anticipeerde op de noodzakelijke houdingsaanpassingen.

Tenslotte, in Hoofdstuk 6 werden de bevindingen van alle hoofdstukken samengevat en bediscussieerd. Uit de bevindingen werd geconcludeerd dat lichaam + werktuig als een systeem functioneren en dat affordances veranderen afhankelijk van eigenschappen van het werktuig. Deze conclusies werden ondersteund door recente bevindingen uit de neurofysiologie en de neuropsychologie. Tevens werd besproken volgens welke processen werktuiggebruik zich kan ontwikkelen. De mogelijke variabelen die de handelingsmogelijkheden met een werktuig bepalen werden bediscussieerd. Het proefschrift eindigt met een kort overzicht van nieuwe onderzoeksvragen die gesteld kunnen worden vanuit een handelingsperspectief op werktuiggebruik.
Hoewel alleen ik verantwoordelijk ben voor de inhoud, zijn er veel mensen die bijgedragen hebben aan dit proefschrift. Misschien hadden sommige mensen zelfs het idee dat ze als werktuig gebruikt werden de afgelopen vier jaar. Graag wil ik iedereen die op een of ander manier meegewerkt heeft aan dit proefschrift bedanken. Enkele personen verdienen daarbij bijzondere aandacht.

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Op 1 september 2000 is Raoul gestart als postdoc bij de afdeling Bewegingsgedrag van de Faculteit der Bewegingswetenschappen (VU Amsterdam). Zijn project maakt deel uit van het aandachtsgebied ‘Fysische wetmatigheden als basis voor handelingsstrategieën’. Het onderzoek maakt deel uit van de onderzoekslijn C5; ‘Coördinatie van discrete bewegingen’. Raoul is in het onderwijs actief binnen de afstudeerrichting Bewegingscoördinatie.