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Transformation Rules in Tool Use

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Transformation Rules in Tool Use

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Chapter 1

Movement Selection in Tool Use

Δῶς μοι πᾶ στῶ καὶ τὰν γᾶν κινάσω
Give me a place to stand and with a lever
I will move the whole world
Archimedes

The quote by Archimedes impressively depicts the benefit people associate with tools. Tool use enables humans to achieve effects which would not be attained by simple hand movements. Still, the extension of one's own capacities by using a tool comes at a price: Actions become more complex because in addition to the own bodily effectors, a tool with a more or less complex structure has to be controlled. In order to achieve a desired effect in the environment, the actor has to adapt his or her operating movements to the mechanisms of the tool.

In Cognitive Psychology, the adaptation of action to external constraints has already been investigated in diverse experimental paradigms. In many of these, abstract stimuli and explicitly defined action rules are used to achieve a maximum of experimental control. For instance, participants are instructed to react with a same-side button press to a red triangle and with an opposite-side button press to a blue square appearing on the left or right on the computer screen. Paradigms of this kind reveal that the adaptation of action to external constraints can produce performance costs. Still, it is questionable whether these findings can simply be applied to the context of tool use. Presumably, a tool as an external constraint to action differs from some abstract stimulus in several aspects.

The aim of this thesis was to elucidate the cognitive processes which are involved in the selection of operating movements when people use simple mechanical tools in order to achieve desired effects. The knowledge about how a specific tool structure may influence the efficiency of people's actions can help to optimize tools, work environments, operational procedures, and it can help to avoid sources of errors.

In the following, I will start with the introduction and definition of tool use (section 1.1). An emphasis will be laid on the transformation between an operating movement and its effect at the distal tip of the tool. I will then present empirical support for the notion that operating movements in tool use are directly activated by effect anticipation or simply by the perception of a tool (section 1.2). These findings will be integrated with more general theories on action. Still, these approaches are not explicit about how the transformation between an operating movement and its distal effect is taken into account when people select their operating movements in tool use. Therefore I will then center on evidence that this transformation indeed plays a crucial role for movement selection (section 1.3). This evidence even suggests that the transformation between an operating movement and a distal effect might be realized in a similar manner as an explicit mapping rule (section 1.4). Based on these empirical findings and theoretical considerations, I will then present hypotheses about how the transformation is taken into account when people select their operating movements in the use of simple mechanical everyday tools (section 1.5). These hypotheses motivated the seven experiments which I will present in the empirical part of this thesis. For the experiments, simple mechanical tools were introduced into a classical experimental setup. Finally, in the General Discussion, I will discuss the most important findings of these experiments and their correspondence with existing theories, as well as their practical implications and limitations.

1.1 Introducing Tool-Use Actions

1.1.1 Instructions to Remove the Cork From the Bottleneck

A large part of human interaction with the external world is goal-oriented: It aims at changing the current state. For example, I first light a candle to illuminate the room. Then I open a bottle. After that, I pour wine into an empty glass. And finally, I lift the glass and taste the wine.

Usually people know which motor actions entail the action effects that will change the environment according to their current goals. However, the continual flow of motor actions and action effects may be interrupted if the problem is faced that one's own physical capacities are not sufficient to attain the desired effect in the external world. For instance, I fail pulling the cork out of the bottleneck by my fingers – I cannot grasp it. In such a case, one may look around searching for a tool which suits one's demands. If the problem has been faced by many people before, one can be sure that a tool exists that has been manufactured as a "standardized" solution to this problem (Baber, 2006). In most cases, tools of this kind are very efficient. Many people like drinking wine, so I can even choose among a number of more or less sophisticated corkscrews to remove the cork from the bottleneck. If one has already experienced the efficiency of a tool, next time one does not waste time trying to achieve the desired effect by help of the hands only, but one directly acts upon the tool. People do so because they know in advance that the tool will *transform* motor action into the desired action effect. For instance, the motor action of pushing down the lever of my corkscrew will be transformed into a much stronger upwards force on its screw which will finally cause the cork to pop out of the bottleneck. In other cases, one has to alienate an object for one's purpose because a standard tool is not at hand or has not been constructed yet. But also in this case, one will select an object that appears adequate to transform motor action into the desired effect.

Thus, in short, tool use can be defined as the *effect-oriented use of any object that is controlled by and functionally transforms body movements*.[1]

1.1.2 Introducing Tool-Associated Transformation Rules

Given the preceding reflections, it is an oversimplifying, but illustrative idea that in the course of evolution tool use has emerged with goals that could not be sufficiently attained by the help of claws, hands, a beak, or a mouth only. In any case, the first action effectively extending the limits of a pre-human or animal body by the help of an *external object* mark the beginning of tool-use behavior. Very simple tools are casually used by a variety of contemporary species (e.g., Anderson, 2002; Breuer, Ndoundou-Hockemba, & Fishlock, 2005) and probably have also been used in time past. However, the first graspable landmark in the evolution of doubtlessly effect-oriented tool-use behavior in human evolution dates about 2,000,000 years ago. It refers to the Stone Age, to the early Homo,

[1]Here and in the following, the terms "movement" and "motor action" are used as synonyms and refer to the motor act which leads to a desired or incidental effect.

and to the probably oldest tradition of tool-making. *Oldowan tools* (taking their name from Olduvai Gorge, Tanzania, the place where many of these tools have been discovered) are probably the first tools made out of stone. And – even more importantly – they are probably the first tools manufactured exactly for the purpose to attain a specific effect: They were made sharp-edged to be adequate for tasks like cutting, digging, or hammering – or for manufacturing new tools (Lancaster, 1968). Manufacturing adequate tools for a prescribed purpose requires causal reasoning about the kind of transformation the tool has to exert upon a motor action so that the desired effect will be attained (L. Wolpert, 2003). It has been proposed that this kind of causal reasoning is unique to humans and primates (Johnson-Frey, 2003, but see Taylor, Hunt, Medina, & Gray, 2009).

Knowledge about the transformation between an operating movement and its resulting effect is not only an essential prerequisite for manufacturing tools. It is also necessary for the selection of the correct operating movement in tool use. Basically, movement selection in tool use thus depends on two components: 1) The *effect* that the acting person wants to achieve in the environment by help of the tool; 2) The *transformation* by which a tool converts an operating movement into this desired effect (Lepper, Massen, & Prinz, 2008; Massen & Prinz, 2007b).

This transformation between an operating movement and an effect is a characteristic feature of tool-use actions and therefore deserves some further introduction. It is set up by the interface between the tool's handle and the tool's effective tip, namely by the tool body and can be described in a bidirectional manner. On the one hand and from the perspective of an observer, operating movements are transformed into effects at the tool's effective tip. On the other hand, from the perspective of the user, the desired effect at the tool's distal tip has to be transformed into the corresponding operating movement. Movement-effect and effect-movement transformations, that is, the implementation of a transformation rule by a tool and the application of a transformation rule by its user, are thus two sides of the same coin.

To give some examples of transformations, tools implement transformations of force (e.g., a nutcracker) or of accuracy (e.g., tweezers). These functional transformations are accompanied by *spatial* transformations. Operating movements at a tool's handle are spatially detached from the effect movements of the tool's distal tip by the tool body. Sometimes, operating movements are not only spatially detached, but even reversed by the tool (e.g., by a lever). That is, there is a *transformation rule* inherent in a tool, and this transformation rule defines the kind of spatial relation between operating movements and distal effect movements.[2] For illustration, imagine that you are using clothespins to hang out the washing. A clothespin reverses operating movements. If you are using it in a conventional manner you will first have to squeeze its handles between thumb and index finger (*movement 1*) in order to open its distal grippers (*effect 1*). Then, you will have to release its handles by thumb and index finger (*movement 2*) in order to close the distal grippers to fasten the clothes (*effect 2*). You will thus switch between the realization of two operating movements of opening and closing whose associated effects are determined by the transformation rule of a clothespin.

1.1.3 Types of Tool-Associated Transformation Rules

The transformation rule which determines the kind of transformation between operating movements and resulting effect movements at the tool's distal tip has to be realized (implicitly or explicitly) in order to operate a tool in a skillful manner. As it will be shown in this section, tool-associated transformation rules may adopt different levels of complexity depending on the tool at hand. This holds especially because tools have become fairly sophisticated since the early beginnings of tool use in human evolution. A fundamental distinction is the one between *transparent* and *opaque* transformation rules (Lepper et al., 2008).

A simple mechanical tool is the prototype of a tool with a transparent transformation rule: The kind of transformation between operating movements and their associated effects is obviously caused by the tool structure and follows simple physical laws. Examples are pliers or scissors. A very intelligent Stone Age man who is confronted with scissors for the first time (for instance on time travel), might admire their structure and their material, but at the same time, he should be able to understand even without any further advice that two sharp scissor blades are joined by a screw and that closing the two blades in order to cut will be achieved by closing the two handles that are attached. Conversely, electronic and electric tools are examples for tools with an opaque transformation rule: A finger movement on a touch pad is associated with a movement of the pointer on the screen, or a push of a button triggers a motor which in turn independently drives the tool's activity. Simply by analyzing the tool's structure, it is not easy to figure out the transformation between operating movements (e.g., some push or release of a button) and their associated effects. The intelligent Stone Age

[2] In this sense, in the following, the term "transformation rule" will be used to stress the specific kind of a spatial transformation between operating movements and effect movements. The term "movement-effect transformation" will be used to refer to a specific instance of a transformation between one movement and one effect.

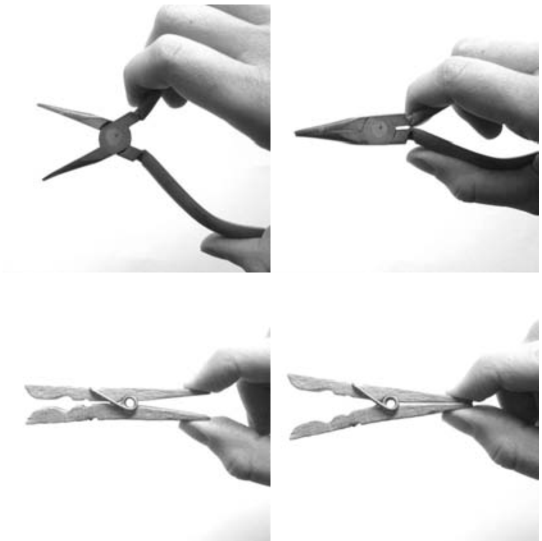

Figure 1.1: Examples for a tool with a compatible (pliers, top panel) and a tool with an incompatible (clothespin, bottom panel) transformation rule. Closing the handles of pliers by the fingers will cause the pliers' distal grippers to close as well. Conversely, closing the handles of a clothespin will open its distal grippers.

man might even believe in magic if he pushes the button of an electric mixer and this causes the stirring staffs to rotate.

Most relevant for the work at hand, tool-associated transformation rules can further be subdivided as regards the spatial correspondence between operating movements and their associated effect movements. Some tools are merely extensors of the bodily effectors: The effect movements at the functional end of the tool go into the same direction as the body movements by which the tool is operated. For instance, if you want to grip an object with pliers, you have to close the two handles by your fingers. This closing movement of the fingers will cause the two grippers to close as well. Tools of this kind incorporate *compatible transformation rules* with compatible movement-effect transformations. Other tools transform body movements into opposite effect movements. For instance, opening a clothespin will be achieved by closing your fingers at its handle. These tools incorporate *incompatible transformation rules*, that is, incompatible movement-effect transformations. Consequently, the same body movement (e.g., closing the fingers) may be transformed into different effects (e.g., closing or opening) depending on the tool-associated transformation rule (see Figure 1.1).

The central motivation of the present work was to elucidate how people represent and apply transparent compatible and incompatible transformation rules in order to select adequate operating movements when they use simple mechanical tools. In general, it has been proposed that there are two possible ways towards the identification of the movement (or response) which is adequate in a specific context: One way is automatic activation of this movement. The other way is more elaborate processing in terms of rule application, search, or table lookup (Kornblum, Hasbroucq, & Osman, 1990). Movement activation cannot be equated with movement selection (e.g., Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Hommel, 1998a). Still, movement activation facilitates the selection of this movement for execution.

Surprisingly, up to now, there is no comprehensive theory about how transformation rules in everyday tool use influence movement selection. Still, there are many empirical findings which suggest that operating movements in tool use are activated automatically and might thus easily be selected. These findings are helpful as well to derive hypothesis about transformation rule application for movement selection in tool use. In the following chapter, I will review these findings and I will present theoretical approaches which can be used for their explanation.

1.2 Direct Motor Activation in Tool Use

In this section, I will review two approaches which assume that operating movements in tool use are directly activated. This activation seems independent from the tool-associated transformation rule. In part 1.2.1, I will center on the role of the distal effect for the direct activation of an operating movement in tool use. In part 1.2.2, I will spotlight processes of direct motor activation by tool perception. For each approach, I will first review empirical findings. I will then outline in which way these findings from research on tool use can be related to more general theories on action.

1.2.1 Effect-Induced Motor Activation

1.2.1.1 The Relevance of Distal Action Effects

People execute tool-use actions mostly intentionally, that is, in order to achieve a certain action effect that will change the environment according to their current goal. Operating a tool means transferring the final action effect from the body's own effector to the distal tip of the tool: The tool thus virtually replaces the bodily effector as the critical effective organ, although it still requires manual input.

Indeed there is evidence that tool-use actions are represented mainly in terms of their distal effects at the tool's effective tip. "When pliers become fingers in the monkey motor system" Umiltà et al. (2008) ostentatiously title. They showed that neurons in the primary motor cortex (in F5 and F1) which typically discharge during hand grasping discharged in the same temporal pattern if trained macaques were using pliers for grasping food. Thereby, it did not matter whether the pliers' grippers exactly mirrored the movement of the operating hand (normal pliers with a compatible transformation rule) or moved into the direction opposite to the operating hand (reverse pliers with an incompatible transformation rule). The authors concluded that the desired effect (in this case: grasping an object) is the central element around which movements are organized. If a tool is used to achieve this effect, the tool is integrated into the action as an artificial hand and it is thus controlled in the same effect-oriented manner as the natural hand.

In humans, the relevance of distal effects for the successful use of mechanical tools has been impressively demonstrated in a patient study by Hayakawa, Yamadori, Fujii, Suzuki, and Tobita (2000). The authors report on a stroke patient with diverse lesions in the left temporal, occipital and parietal lobe. This patient had difficulties in demonstrating tool-use actions in the absence of information about the action goal. For instance, he was not able to correctly demonstrate the use of scissors which were placed on the desk in front of him. He did, however, correctly use them if a potential action goal, for instance a sheet of paper, was shown to him, even though he was not allowed to touch it. Presumably, the presentation of an action goal helped the patient to get an idea about the required action effects and therefore also helped to activate the corresponding motor action.

Highly compatible with the assumption that tool-use actions are primarily represented in terms of their distal effects are also the results from studies with healthy participants. For instance, a study by Rieger, Knoblich, and Prinz (2005) abstracts from concrete tool use for object manipulation and introduces opaque transformations between movements and effects. Participants had to draw straight and continuous strokes between two target lines on a writing pad. Effect movements were displayed on the screen and in some conditions, movement gain was changed. The authors could show that this gain change in the effect display influenced movement time for the drawing movements. Unconscious adaptation of body movements in response to transformed effect movements on the computer screen has been reported by other authors as well (e.g., Fourneret & Jeannerod, 1998; Knoblich & Kircher, 2004).

For concrete tool use, an attentional shift towards the effective tip of the tool can be observed (Berti & Frassinetti, 2000; Collins, Schicke, & Röder, 2008; Holmes, Calvert, & Spence, 2004; Longo & Lourenco, 2006; Pegna et al., 2001; Yue, Bischof, Zhou, Spence, & Röder, 2008). For instance, in the study by Collins et al. (2008) participants were seated at a table and had to perform two tasks at the same time. They had to move the tip of a triangular hand-held tool towards a target on the table. Concurrently, they had to discriminate visual stimuli which were displayed randomly at several locations on the table. Discrimination performance was enhanced when the visual stimuli were presented close to the target. To a lesser extent, it was enhanced at the motor endpoint which was defined as the position the fingers would reach in order to bring the tool tip towards the target. Discrimination performance however was not enhanced in intermediate locations, namely along the tool body which, as an interface between hand and tip, carried out the transformation between operating movement and distal tip. Most notably, attentional shifts towards the effective tip of a tool depend on the intention to use the tool. They do not occur if people simply hold the tool without the intention to achieve some effect (Witt, Proffitt, & Epstein, 2005).

In summary, these findings provide evidence, or are at least highly compatible with the assumption that tool-use actions are mainly represented in terms of their distal effects. Beyond that, some of the studies, for instance the patient study by Hayakawa et al. (2000), or the study with opaque transformations by Rieger et al. (2005), even suggest that a distal effect is actually responsible for activating the associated movement. Such an outstanding role of action effects not only for tool-use actions, but for human action in general has been postulated by the ideomotor principle and the theory of common coding which I will present now.

1.2.1.2 The Ideomotor Principle and Common Coding Theory

Central to the ideomotor principle is the idea of bidirectional associations between actions and their effects. It states that on the one hand, the execution of an action is accompanied by the expectation to perceive its sensorial effects. On the other hand, the anticipation of sensorial effects activates the action which entails these effects.

This idea has been raised by a group of British physiologists around William B. Carpenter (1813–1885) in order to explain motor reflexes, but similar suggestions have also been advanced by the German philosophers Johann Friedrich Herbart (1776–1841) and Rudolf Hermann Lotze (1817–1881) and the physiologist Emil Harless (1820–1862) to account for human voluntary action (for an historical overview see Stock & Stock, 2004). Both roots were integrated by William James in his Principles of Psychology from 1890 as a general account on everyday action: "Wherever movement follows unhesitatingly and immediately the notion of it in the mind, we have ideo-motor action." (James, 1890, p. 522). According to James (1890), this "notion" of an action means the anticipation of sensorial action effects which should directly activate the action which leads to these effects. Since, a huge amount of empirical evidence has been accumulated to support the notion of bidirectional associations between actions and their associated effects on the one hand, and the outstanding role of effect anticipation for the activation of motor action on the other hand (e.g., Elsner & Hommel, 2001; Greenwald, 1970; Hoffmann, 1993; Hoffmann, Sebald, & Stöcker, 2001; Hommel, 1996; Kunde, 2001; Stock & Hoffmann, 2002; Stöcker, Sebald, & Hoffmann, 2003; Ziessler & Nattkemper, 2001, 2002).

A tool-use action may well be regarded as the prototype of an effect-oriented action. However, in tool-use actions, there are two kinds of effects. One has to distinguish between the proximal sensorial consequences which reside in the movements of the operating hand, and the distal action effects at the tool's effective tip. Tool-use actions are generally executed in order to attain these distal effects. Already James (1890) pointed out that distal effects which are detached from the actual movement can be included into the ideomotor logic.

A newer theoretical approach which draws on the ideomotor principle and pursues the idea of action activation by effect anticipation is the common coding theory (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1990, 1992, 1997, submitted). Particularly, the common coding theory postulates that, on top of the classically assumed separate domains for the representation of action and perception, there is a common representational domain. In this domain, action and perception are coded in the same format, both referring to external events. Perception codes refer to perceived events in the external world and action codes refer to the perceived or anticipated external consequences of acting. Such a "common coding" of action and perception implicates that the perception or the anticipation of action effects directly activates the associated action. Again there is evidence that the abstractness or remoteness of perceived or anticipated action effects is no obstacle for the direct activation of action (Rieger, 2004). The only prerequisite is that reliable action-effect associations have been acquired previously (Hommel et al., 2001; Hommel, 2005).

The dissociation of proximal and distal action effects and the influence of distal effects on the activation of action have been tested in a meanwhile classical experiment by Hommel (1993). Participants had to press a left or right button in response to high- or low-pitched tones which were randomly presented to the left or to the right ear. Furthermore, a left-hand key press illuminated a light on the right-hand side; a right-hand key press illuminated a light on the left-hand side. A key press and its associated light were thus always on opposite sides. In one condition, participants were instructed to ignore the lights and a standard Simon effect was obtained: Reaction times (RTs) were lower if the sides of the stimulus tone and the response that was required by its pitch corresponded in comparison to non-corresponding stimulus-response locations. In another condition, the setup was exactly the same, but participants were explicitly instructed towards the distal effects. Their explicit task was to illuminate the left light or the right light, respectively, in response to the high- or low pitch tones via the button presses. In this case, it was not the correspondence between stimulus and response location, but the one between stimulus and distal effect location that produced lower RTs. Hommel (1993) concluded that the relative importance of proximal (i.e., the keypress) and distal (i.e., the light flashing) action effects for the activation of action can be manipulated by the participant's intention.

Obviously, the experimental setup used in this study by Hommel (1993) creates a sort of tool-use situation. A manual action (pressing a response key) is transformed into a distal effect (illumination of a remote light on the side opposite to the keypress). The results show that the action is represented in terms of this distal effect if participants intend to produce the effect. Closely related are the results of studies with an experimental setup that is even more similar to an actual tool-use situation. These are studies in which a steering wheel has been used to couple operating movements with distal effects (e.g., Guiard, 1983; Merz, Kalveram, & Huber, 1981; Proctor, Wang, & Pick, 2004; Wang, Proctor, & Pick, 2003). For instance, in the study by Proctor et al. (2004), a Simon-like task was applied as well: Participants had to respond to the pitch of a tone by moving a steering wheel in a clockwise or in a counterclockwise direction. The tone was randomly presented to the left or to the right ear. Participants had their hands on the lowest part of the steering wheel. Consequently, the steering wheel incorporated an incompatible transformation rule, and in order to move the wheel to the right, the operating hands had to be moved to the left. If the wheel rotation was depicted by visual feedback (a cursor on the screen that moved along the horizontal line of the screen to the right for clockwise, and to the left for counterclockwise rotation), participants coded their response in terms of this distal effect on the screen: Response facilitation was obtained by correspondence between the side of the stimulus tone and the direction of the cursor movement, despite the non-correspondence between the side of the stimulus tone and the direction of the hand movement.

Surprisingly, also the spatial non-correspondence between the direction of the operating movements (at the lowest part of the steering wheel) and the direction of the resulting effect movements of the cursor did not have a general detrimental effect on performance in this study – although it has often been reported that compatible movement-effect mappings are easier to implement than incompatible ones (Keller & Koch, 2006, 2008; Kunde, 2001, 2003; Kunde, Koch, & Hoffmann, 2004; Koch & Kunde, 2002; Stöcker et al., 2003). Merz et al. (1981) stated that the disadvantage of incompatibility is a cognitive phenomenon which is much reduced if the reason for incompatibility is transparent – for instance in the form of a steering wheel.

In sum, there is evidence that the perception or anticipation of remote effects directly activates the body movement that entails these effects. In this line, the activation of operating movements in tool use should primarily depend on the anticipation of distal effects at the tool's tip.

But how does the cognitive system meet the challenge that movement-effect transformations are variable and context-dependent? For instance, in the study by Umiltà et al. (2008) the distal effect of closing the pliers' tips could require an operating movement of closing or opening, depending on whether the normal pliers with the compatible transformation rule or the reverse pliers with the incompatible transformation rule were in use. A possible solution is provided by the finding that movement-effect associations are acquired context-specifically. In a study by Kiesel and Hoffmann (2004), reliable movement-effect mappings occurred in a horizontal context. In a vertical context the mapping between these same actions and their effects was reliably inverted. After a learning phase, the anticipation of one effect could evoke different actions depending on whether it occurred in the horizontal or in the vertical context. Presumably, a tool is a strong feature of context. It is thus possible that a tool activates those movement-effect associations which are required by its transformation rule – given that these associations have been learned in prior instances of manipulation.

The anticipation of action effects originating in the intention to act describes one way towards movement activation in tool use. However, operating movements in tool use can also be triggered externally. In the next section, I will review evidence for the activation of operating movements merely by tool perception.

1.2.2 Tool-Induced Motor Activation

1.2.2.1 The Relevance of Tool Perception

It seems that movements appropriate to operate a tool can also be activated independently of a person's explicit intention to attain a specific effect. Actually, the mere perception of a tool may directly activate adequate motor action.

An intelligent way to test object-induced motor activation in a behavioral paradigm has been applied by Tucker and Ellis (1998). In this paradigm, photos of graspable household objects and tools (e.g., a brush or a knife) were presented on the screen and participants had to judge via a left- or right-hand button press whether the object was depicted upright or inverted. The horizontal orientation of object presentation was manipulated, too. The object handle pointed either to the right side (optimal for a right-hand grip) or to the left side (optimal for a left-hand grip). Even though the handle position was irrelevant for the task, performance was facilitated when the hand of response was congruent with the orientation of the handle (e.g., a handle pointing to the right facilitated a right-hand button press). Similar congruency effects were obtained when the paradigm was slightly changed and a power or a precision grip was used for the main task, while objects on the screen were either small (usually grasped with a precision grip) or large (usually grasped with a power grip) (Ellis & Tucker, 2000). Object perception thus directly activated object-associated action even though there was no explicit intention to interact with the object. A related study could show that these kinds of compatibility effects are not only an online product of visual processing, but also arise if an object is retained in visual memory (Derbyshire, Ellis, & Tucker, 2006). The authors accordingly suggested that the motor action which is associated with a manipulable object forms part of the object's representation in the cognitive system.

Additionaly, there is neurophysiological evidence for motor activation by object perception. The findings by Tucker and collegues were complemented by data from a functional magnetic resonance imaging (fMRI) study using a similar paradigm with precision and power grips (Grèzes, Tucker, Armony, Ellis, &

Passingham, 2003). Across participants, activation in the left parietal, premotor and inferior frontal cortex increased as the RT difference between congruent and incongruent trials increased. This parieto-premotor network is involved in the execution of hand grasping movements (Dafotakis, Sparing, Eickhoff, Fink, & Nowak, 2008; Grol et al., 2007). The result thus speaks for the assumption that it was indeed motor activation which caused the competition between perceptual object properties and the response required by the explicit task.

Even for tasks that do not require any overt manual action at all, but involve naming or simply viewing tool pictures, left premotor cortex activation has consistently been reported (e.g., Creem-Regehr & Lee, 2005; Chao & Martin, 2000; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Grèzes & Decety, 2002; Martin, Wiggs, Ungerleider, & Haxby, 1996). Activation is located in an area of the premotor cortex that is also active for the imagination or execution of right hand movements (e.g., Grafton, Arbib, Fadiga, & Rizzolatti, 1996). It presumably mirrors the direct link between the perception of a tool picture and the activation of a specific operating movement. Most notably, this activation occurs without any subsequent movement and without any explicit intention to act.

Some effects of brain damage impressively illustrate the possible consequences of automatic motor activation by tool perception. Especially relevant are three disorders of Clinical Neuropsychology, namely utilization behavior, apraxia, and semantic dementia. Utilization behavior is sometimes exhibited following frontal lobe damage (Lhermitte, 1983). It becomes manifest in excessive motor responding to manipulable objects. These responses are instrumentally correct, but often exaggerated or inappropriate for that particular situation (Archibald, Mateer, & Kerns, 2001). There is obviously a failure to inhibit the operating movements which are automatically triggered by the perception of tools and other manipulable objects (Sumner & Husain, 2008). In a neuropsychological testing session, for instance, a patient with utilization behavior might pick up nail scissors that are placed on the table in front of him and he might cut his finger nails without being asked to do so. In some patients exhibiting utilization behavior, even explicitly formulated response instructions cannot be used to override the automatic motor associations which are elicited by object perception (Humphreys & Riddoch, 2000). The reason is an impairment of goal-directed and rule-based behavior which has been ascribed to the intact frontal cortex (e.g., Ridderinkhof, Wildenberg, Segalowitz, & Carter, 2004).

Whereas direct motor activation caused by the perception of a tool can be counterproductive in patients with utilization behavior, it can be helpful for patients with apraxia following left-brain damage. In these patients, the production of meaningful gestures, as well as gestures of pantomiming and actual tool use are often defective. One explanation is that explicit knowledge about the tool-use action cannot be retrieved from semantic memory (Goldenberg & Hagmann, 1998). Still many patients, though they are not able to pantomime the gestures of using a specific tool, perform significantly better if they are given a real tool to operate (Goldenberg, Hentze, & Hermsdörfer, 2004; Renzi, Faglioni, & Sorgato, 1982). It has been suggested that in actual tool use patients can rely on the shape and on the mechanical structure of the tool which both directly help to specify the appropriate operating movements (Goldenberg & Hagmann, 1998).

Similarly, automatic motor activation triggered by object perception can help patients with semantic dementia to accomplish everyday tasks including tool use. Semantic dementia is associated with temporal lobe atrophy which impairs the knowledge about object semantics, that is, about object meaning. However, there are reports about patients who correctly use everyday objects like tools even though knowledge about object semantics is lacking (e.g., Hodges, Spatt, & Patterson, 1999; Negri, Lunardelli, Reverberi, Gigli, & Rumiati, 2007, but see Bozeat, Ralph, Patterson, & Hodges, 2002, for different findings).

Remarkably, the adequate manipulation of tools is impossible solely on the basis of knowledge about object semantics (e.g., Buxbaum, Schwartz, & Carew, 1997).

To summarize, tools have obviously the capacity to directly activate adequate operating movements. One may also say that a tool *affords* these movements, and indeed, the theory of affordances (Gibson, 1979) is a classical and often cited account towards motor activation by object perception and will be presented in the following.

1.2.2.2 Affordances and the Dorsal Processing Stream

Ecological psychology emphasizes the importance of the environment to explain human and animal behavior. In this field, the theory of affordances (Gibson, 1979) is a key concept and it is based on the notion that the environment is perceived in terms of potential action. Originally, this idea goes back to the Gestalt psychologists and to their proposition that objects possess a certain "Aufforderungscharakter" (Lewin, 1926) or "demand character" (Koffka, 1935) which is perceived as easily as the physical characteristics of this object, for instance color. The demand character is the perception of an object in terms of how acting upon it can satisfy the needs of the observer. For example, someone who is hungry and sitting down for lunch at a well-laid table will perceive his fork as the device that is adequate to pick up hot food and to transport it from the dish to his mouth. The demand character of an object will disappear with the satisfaction of the observer's needs (e.g., when the hunger is satisfied).

In a similar spirit, the term "affordance" has been created by Gibson (1977). He argues that the visual system generally does not perceive the properties of the environment, for instance size, shape, color and texture, as abstract physical qualities, but in terms of what information they entail about possible action. An affordance is thus "an invariant combination of variables" (Gibson, 1979, p. 134) which demands or invites appropriate behavior. Gibson emphasizes that affordances arise in the complementarity between the observer and the environment and thus are neither subjective nor objective in the common sense. In relation to the observer, affordances are stable, and they do not change with his current needs. For instance, the long handle and the pointed tines of a fork afford to pick something up, whether a person is hungry or not. Gibson himself noted that this independence of current needs is a critical difference to the related concepts proposed by the Gestalt psychologists. It is also relevant for the suggestion that the perception of a tool directly activates action devoid of any explicit intention to act (see 1.2.2.1).

The theory of affordances is a general approach to human and animal action and perception. Gibson (1979) has provided examples for the affordances that are entailed in substances (e.g., air or water), objects (e.g., tools or utensils) and other persons or animals. The particular relevance of this theory for tool use is based on the fact that tools are exclusively manufactured to be acted upon in a certain manner. They thus specify rather concrete affordances. In this regard, Neisser (1994) has even proposed to restrict the concept of affordances to the physical affordances which are entailed in objects.

Notably, in order to perceive the physical affordances of objects, knowledge about object semantics is not necessary. The concept of physical object affordances thus comes close to the concept of mechanical problem solving (Bozeat et al., 2002). Indeed, correct tool use in apraxic patients is positively correlated with their ability to solve mechanical problems and to use entirely new objects (Goldenberg & Hagmann, 1998). Also in healthy participants, operating movements adequate for tool use are evoked more easily if the task is to concentrate on object characteristics which obviously imply physical affordances, for instance the object's shape (Tipper, Paul, & Hayes, 2006).

It is thus not surprising that on a neuroanatomical basis, the activation of functional knowledge about object manipulation can be dissociated from the activation of knowledge about object semantics. The cornerstone for such a distinction has been laid by Ungerleider and Mishkin (1982) who reported about two processing streams starting in the primary visual cortex. They suggested that the *ventral stream*, leading to the inferotemporal cortex, is concerned with object identification ('what'), whereas the *dorsal stream*, leading to the posterior parietal cortex, is involved in spatial vision and thus plays a critical role in object localization ('where'). This distinction between a ventral and a dorsal stream has since been maintained, but its interpretation has been revised. Goodale and Milner emphasized the different processing goals which the two streams subserve, rather than the different types of information that they process (Goodale & Milner, 1992; Milner & Goodale, 1995): The ventral stream subserves the recognition of objects and the activation of associated semantic knowledge ('vision for perception'). The dorsal stream provides critical information about physical object characteristics like localization, size and shape, and thus mediates the visual control of object manipulation ('vision for action'). The dorsal stream might thus be regarded as the processing system where object affordances arise (Arbib, 1997; Goodale & Humphrey, 1998), and, in the framework of Gibson, activation of this stream should be sufficient to stimulate adequate action for object use.

There is, however, a limitation to this assumption. Without semantic processing, physical affordances may indeed direct, for instance, the grasp of a tool, but not necessarily in a manner that also supports its adequate use (Creem & Proffitt, 2001). For effective tool use, the ventral and the dorsal stream thus have to interact (Adamo & Ferber, 2008; Creem-Regehr & Lee, 2005). This interaction has been described by Goodale and Humphrey (1998) as follows: The desired action effect of a tool-use action is specified via the ventral stream, and the dorsal stream then activates the specific motor action which – given the physical affordances of the tool – will result in this effect. Information provided by the dorsal and by the ventral stream is presumably integrated in the left inferior parietal lobule (Frey, 2007).

To conclude, there is evidence and theoretical support for two ways of direct motor activation facilitating movement selection in tool use. One way is the direct activation of operating movements by tool perception. Activation of this kind seems unspecific as regards a concrete action goal. The other way is the activation of a *specific* operating movement by effect anticipation. This way is relevant for goal-oriented action. It furthermore may well be that in goal-oriented action, movement activation by effect anticipation can also benefit or even relies on unspecific motor activation which is caused by tool perception.

Unfortunately, these approaches which assume direct motor activation in tool use are not explicit about the role of the tool-associated transformation rule for movement activation and selection. As I stated before (1.1.3), depending on this rule, the transformation between a desired effect and the required operating movement can be more or less complex. Consequently, it is an interesting question whether transformation complexity may influence or even disturb the processes of motor activation and movement selection. And this question directs to the following chapter which is concerned with the influence of transformations between movements and effects.

1.3 Transformations between Movements and Effects

In this section, I will review research which suggests that that people somehow represent and apply a transformation rule when they use a tool. Surprisingly, the relevance of transformation rules for movement selection has not yet been investigated for the use of simple mechanical tools which are well-known from everyday life. Instead, movement-effect transformations have often been investigated in paradigms in which a computer mouse is used and implements an opaque transformation between movements and distal effects on the screen (e.g., Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003). The relevance of transparent transformation rules has been investigated in recent studies using different kinds of levers (e.g., Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2007b).

In the following, I will first discuss empirical and theoretical work on how opaque transformation rules influence movement selection, and I will then proceed to empirical findings on the influence of transparent transformation rules.

1.3.1 Opaque Transformations Between Movements and Effects

If people act without a tool, for instance with their hands only, they experience immediate temporal and spatial correspondence between their actions and the associated effects. Raising the hand means touching something above the head, exactly at the place that corresponds to the height of the hand. Closing the fingers which are holding an object means squeezing the object with exactly that amount of pressure that is exerted by the fingers. Movement-effect transformations of this kind are overlearned and they appear normal. However, even for these seemingly simple actions the physical properties of the bodily limbs define which movement-effect transformations can be realized. For instance, the movements of the arm's joints are transformed into specific positions of the arm's tip. For successful action, this kind of transformation has to be taken into account. Consequently, it has been suggested that even bodily limbs are controlled in a tool-like manner (e.g., Kalveram, 1993, 2004).

Yet, in tool use, an additional externally imposed transformation between body movements and their resulting effects is added.[3] It seems that in some cases humans can adapt quite well to such an additional movement-effect transformation. Perfect adaptation means that an external transformation does not even produce performance costs as compared to the performance for actions which are executed with the bodily limbs only. Most people, for instance, are able to skillfully operate a computer mouse on the table in order to produce the effect movement of the pointer in a different location, namely on the computer screen. Indeed, these operations performed with a computer mouse are even similarly efficient as if people were directly using their hands for reaching a target (Brenner & Smeets, 2003).

Many studies investigating how humans represent and apply transformation rules according to which body movements are associated with distal effects make use of paradigms which are similar to the setting of using a computer mouse. Participants have to move a pen or a computer mouse on a tablet, or they have to perform simple reaching movements with their hand. These movements are displayed by a cursor on a computer screen. Thus, body movements in one location are transformed into effect movements in a different location. Participants then have to conduct tracking movements in order to follow a moving target, or reaching movements in order to touch a stationary target on the screen. The advantage of these paradigms is that additional kinds of transformations between a body movement and a distal effect movement on the screen can be added relatively easily, for instance, movement rotation or changing movement gain (see Figure 1.2). A challenge is that these additional transformations are sometimes only distantly related to transformations exerted by simple mechanical tools. Still, work in this context has revealed several important findings which most likely apply as well to situations in which simple mechanical tools are used.

[3] In the following – as in the preceding chapters – the term "transformation" will be used to refer to such an externally imposed movement-effect transformation.

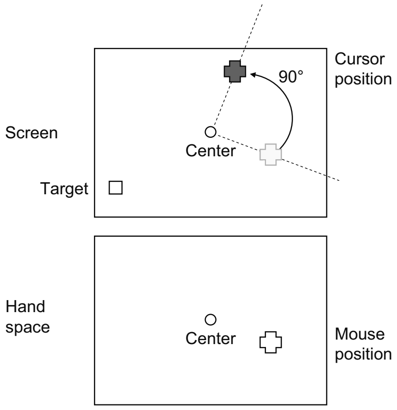

Figure 1.2: Example of a paradigm which implements an opaque transformation between movements and effects. Moving the computer mouse results in a movement of the cursor on the screen. This effect movement, however, is displayed transformed by 90°. The task is to move the cursor towards the target. Adapted from Imamizu et al. (2000).

Firstly, it has been shown that the kind of transformation rule determines whether perfect adaptation is easy, difficult, or even impossible. A rule of thumb seems to be that the more the spatial correspondence between movements and their associated effects is disrupted, the more difficult the adaptation and the more costs are produced in terms of inaccurate action. For instance, costs increase with increasing angle of rotation between hand movements and distal effect movements (e.g., rotation of the hand movement by 113° is more difficult than rotation by 45°, Cunningham, 1989). Similarly, simple linear transformations of movement gain (e.g., a small movement of the hand results in a bigger displacement of the cursor on the screen) are still relatively easy to learn (Bedford, 1994; Bock & Burghoff, 1997; Rieger et al., 2005), whereas transformations involving a nonlinear relationship between hand movement and effect movement produce substantial costs (Heuer & Hegele, 2007; Verwey & Heuer, 2007).

Secondly, once adaptation to a transformation rule has occurred, the return to non-transformed movement-effect relations is characterized by costs as well. These appear in a tendency to continue moving as if the preceding transformation rule was still active and they have therefore been termed aftereffects (e.g., Kagerer, Contreras-Vidal, & Stelmach, 1997; Rieger et al., 2005). It thus seems that the transformation rule is transiently adopted as the standard. Aftereffects can be used to estimate the quality of adaptation to a transformation rule: The greater the aftereffects the more perfect the adaptation has been (Kagerer et al., 1997).

Thirdly, explicit context information facilitates switching between different transformation rules. For instance, aftereffects are reduced when a discriminative stimulus is reliably coupled to the occurrence of a specific transformation rule (Imamizu, Sugimoto, et al., 2007). This holds although – at least in tracking and reaching tasks – a transformation between a movement and its effect is not always consciously realized (Cunningham & Welch, 1994). Participants are often not aware of whether or in which way their hand movements are transformed (Knoblich & Kircher, 2004; Rieger, Verwey, & Massen, 2008; Vetter & Wolpert, 2000; Verwey & Heuer, 2007).

A theory concentrating on how transformation rules are represented and taken into account for movement selection is the internal model approach. This theoretical work again draws upon research on opaque transformation rules in computer mouse paradigms, and it has been tested as well by computer simulations of sensorimotor control.

1.3.1.1 Internal Models of Opaque Transformations

The *internal model* approach has been inspired by research on how humans predict the consequences of their body movements (D. M. Wolpert & Flanagan, 2001). Von Holst (1954) proposed that once a motor action is executed, an image of the motor command is left in the central nervous system. This efference copy can be used to predict the effects of the motor action, for instance the sensory feedback, before actual feedback is available. Later, this idea of outcome prediction has been taken up to account for motor control (Kawato, Furukawa, & Suzuki, 1987; D. M. Wolpert, Ghahramani, & Jordan, 1995).

In the tradition of an approach in engineering, it has been proposed that motor control operates in two opposing directions: A *forward model* predicts the effects of an action on the basis of the efference copy. It estimates, for instance, how the arm will move in response to a motor command. Closely coupled with the forward model operates a so-called *inverse model*. It estimates which motor command will lead to a desired action effect. Thus, the forward and the inverse model are tightly coupled as functional units to form an internal model which simulates the movement-effect transformations which can be realized by the motor system (D. M. Wolpert et al., 1995). Most relevant for the context of tool use, internal models can also simulate the movement-effect transformations which are implemented by tools (Imamizu et al., 2000; D. M. Wolpert & Flanagan, 2001).

Neuronal activity associated with internal models has been located in the cerebellum (Miall, Weir, Wolpert, & Stein, 1993). More specifically, internal models simulating movement-effect transformations in tool use have been reported to activate the lateral and phylogenetically newer parts of the cerebellum (Imamizu et al., 2000).

Movement-effect transformations implemented by tools are diverse, but the possibilities to model these transformations do not seem to be restricted (Haruno, Wolpert, & Kawato, 2001). One version of the internal model approach, the MOSAIC theory (Modular Selection And Identification Controller), states that multiple pairs (modules) of forward and inverse models (predictors and controllers) are stored spatially segregated in the cerebellum and can be combined to realize any kind of transformation (D. Wolpert & Kawato, 1998). When a new tool has to be operated, the cerebellum is extensively activated and the models compete to learn the current transformation. All forward models predict in parallel the effect of a motor action. Predicted and actually observed effects are compared and for each model, a responsibility signal is calculated which reveals its probability of a correct prediction. On the basis of this signal, one inverse model or a combination of models gradually learn to control those situations for which their paired forward models have a high predictive value. As a result, after learning, only a distinct region of the cerebellum is activated while operating the tool. It represents the appropriate internal model whose inverse model reliably predicts the operating movement that will lead to a desired effect (Ghahramani & Wolpert, 1997; Imamizu et al., 2000; Imamizu, Higuchi, Toda, & Kawato, 2007; Imamizu, Kuroda, Yoshioka, & Kawato, 2004). This internal model thus seems to represent and apply the tool-associated transformation rule.

After a transformation rule has been learned, the adequate internal model can be selected even *before* motor action occurs (Imamizu & Kawato, 2008; Vetter & Wolpert, 2000). In this case, perceptual context information associated with this transformation rule directly activates the appropriate inverse model (Haruno et al., 2001; Imamizu, Sugimoto, et al., 2007). In the routine of everyday tool use, such a predictive switch to the adequate inverse model should be the most common way to select the adequate operating movement in order to achieve a desired effect. Luckily, most tools have characteristic shapes and structures and thus provide distinct visual context cues which can activate the adequate internal model.

In computer simulations, the internal model of a transformation associated with a specific object shows generalization to novel objects with similar transformations (Haruno et al., 2001). An internal model thus seems to be represented as an independent entity which is not exclusively associated with one specific context of application. Consequently, it is likely that one internal model is not specific for one tool, but more general for a specific kind of transformation rule.

Interestingly and despite the fact that the internal model approach towards tool use has been derived from motor control theories, the activation of internal models in order to apply an opaque transformation rule seems to be primarily a cognitive, though not necessarily a conscious process (Imamizu et al., 2003, 2004). The neural correlates of tool models in the cerebellum are located bilaterally in the posterior lobe – although one should expect ipsilateral correspondence between cerebellar activity and sensorimotor control of the operating hand. In many other studies, bilateral activation in the posterior lobe has been related to higher cognitive function. For instance, it has been associated with the mental simulation of motor acts (e.g., in mental rotation tasks, Vingerhoets, Lange, Vandemaele, Deblaere, & Achten, 2002), or with updating the associations between stimuli and simple button press responses (Bischoff-Grethe, Ivry, & Grafton, 2002).

To summarize, it has been proposed that internal models simulating the movement-effect transformations of a tool represent the tool-associated transformation rule and predict the adequate operating movement to achieve a desired effect. Despite the notion that internal model activation underlies actual tool use in everyday life (Imamizu, Higuchi, et al., 2007), empirical data mainly rely on the application of opaque transformation rules or on computer simulations. Still, in an fMRI study by Higuchi, Imamizu, and Kawato (2007) the manipulation of different simple tools like a screwdriver or scissors indeed activated distinct cerebellar locations. This distributed activity presumably mirrored the different kinds of movement-effect transformations of these tools which were realized by different internal models.

However, as I will outline in the subsequent section, systematic research on transparent transformation rules which are coupled to a concrete tool body has only been taken up very recently and has not yet been consistently integrated into a theoretical context.

1.3.2 Transparent Transformations Between Movements and Effects

Opaque transformations and transparent transformations which are exerted by simple mechanical tools seem to influence the process of movement selection in a similar manner.

For instance, also for simple mechanical tools, performance is impaired if the spatial correspondence between movements and effects is disrupted. Mechanical tools often entail incompatible transformation rules and thus implement a reversal between operating movements and effect movements. Potential dangers of such a reversal become evident in research on minimally invasive or laparoscopic surgery. This method allows entering the body through a very small incision by a surgical instrument while visual feedback is provided via a camera and a monitor. The technique is complicated by the fact that the point where the surgical instrument enters the body forms a mechanical *fulcrum*: The hand movement at the proximal end of the instrument is transformed into a reversed effect movement of the tool's tip. Studies have shown that this reversal significantly increases the rate of operative injuries in comparison to classical open surgery with unreversed movement-effect transformations (Ostrzenski, Radolinski, & Ostrzenska, 2003; Parpala-Spårman, Paananen, Santala, Ohtonen, & Hellström, 2008; Savader et al., 1997). In a study assessing the psychomotor skills of experienced laparoscopic surgeons about 10% of the participants showed very poor performance in a virtual reality task of laparoscopic surgery (Gallagher et al., 2003). Fortunately, the majority of surgeons have automated to the incompatible transformation between movements and effects (Crothers, Gallagher, McClure, James, & McGuigan, 1999). Still, novices perform significantly better if inversed visual feedback is provided on the monitor and the direction of the hand movement and of the perceived effect movement are thus compatible as in classical open surgery (Gallagher, McClure, McGuigan, Ritchie, & Sheehy, 1998).

Kunde et al. (2007) have investigated compatibility effects in the use of simple mechanical tools in a purely experimental context. Participants had to operate a lever handle in order to move the tip of the lever to the left or to the right in response to the color of a stimulus. Notably, they found two kinds of compatibility effects: On the one hand, responding was faster when stimulus location and movement direction of the lever's distal tip corresponded then when they did not correspond. This effect was independent of the movement direction of the hand which operated the lever. On the other hand, performance costs in terms of slower RTs were reported when the lever was constructed to implement an

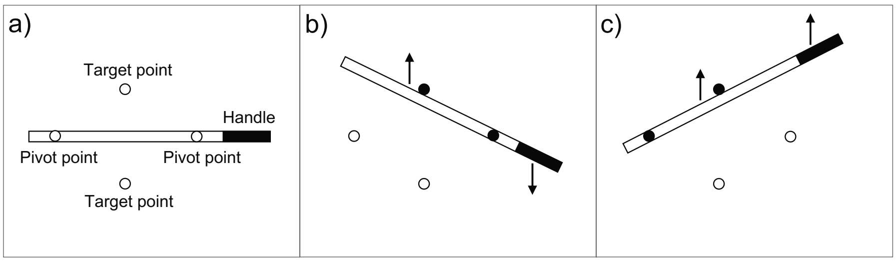

Figure 1.3: a) Schematic illustration of the lever paradigm by Massen and Prinz (2007b). In each trial, one of the two pivot points was activated and one of the two target points had to be touched. b) When the right pivot point was active, the transformation between hand movement and lever movement was incompatible. c) When the left pivot point was active, the transformation was compatible.

incompatible transformation rule and its tip thus moved into the direction opposite rather than corresponding to its handle. In another study, Müsseler, Kunde, Gausepohl, and Heuer (2008) could show that participants' reactions were fastest when the relations between all task elements (including the operating movement, the movement of the lever's effective tip and the stimulus location) were compatible. Both studies thus provided evidence that an incompatible transformation rule which is incorporated in a lever can have a detrimental effect on the speed of movement selection.

Additionally, the pre-specification of a transparent transformation rule facilitates performance. This has been shown by Massen and Prinz (2007b) who used a lever paradigm as well. Participants had to operate a lever for which the location of the pivot point could change. The lever was either movable around a pivot point close to the operating hand, or it was movable around a pivot point located at the opposite end of the lever. In the first case, the transformation between operating movement and lever movement was an incompatible one, in the second case it was a compatible one. In each trial, participants had to touch one of two targets by the lever. This target, as well as the active pivot point were cued by illumination (see Figure 1.3). With this paradigm, apart from the replication of the compatibility effect, a large performance benefit was obtained for trials starting with a precue for the valid pivot point. The knowledge about the kind of transformation between operating movement and resulting lever movement obviously facilitated performance, although the relevant target was specified later. This result is reminiscent of the finding that prespecification of explicit context information allows for predictive switches between opaque transformation rules (e.g., Imamizu & Kawato, 2008; see 1.3.1). Most notably, however, transparent transformation rules in the study by Massen and Prinz (2007b) even seemed to play the leading role in movement selection: There was no significant benefit for precuing the target that had to be touched, as long as the relevant transformation rule was unknown.

Costs have been reported for switching between transparent transformation rules in relation to a benefit when the rule remains the same.[4] In another study by Massen and Prinz (Massen & Prinz, 2007a) participants had higher RTs and made more errors if the pivot point switched between trial $n-1$ and trial n (but the target point was repeated), as compared to rule repetition trials (in which the target point changed). These switch costs seem distantly related to the aftereffects which impair performance when people have to switch to an opaque transformation rule, or back to non-transformed movements (e.g., Kagerer et al., 1997; see 1.3.1). Surprisingly, in the study by Massen and Prinz (2007a), rule switch costs were even obtained when two participants took turns in operating the lever.

Finally, Herwig and Massen (in press) provided evidence for tool-independent representations of transformation rules. In their study, participants again had to operate the lever with two possible pivot points, but this time, the lever had two handles, one on the left- and one on the right-hand side. In each trial, the target point, the pivot point and the handle were specified. With this setup, not the active pivot point, but the specific combination of lever handle and pivot point determined whether the transformation between an operating movement and a lever movement was compatible or incompatible: For instance, if in trial $n-1$ the right handle had to be used and the active pivot point was also on the right-hand side (i.e., close to the active handle), the transformation rule was an incompatible one. If then in trial n the left handle had to be used, but again the active pivot point was located on the right-hand side, the transformation rule was an compatible one. In this case, the tool mechanics remained the same, but the transformation rule changed from trial $n-1$ to trial n. Results showed that in hand switch trials, there were greater costs for changing the transformation rule (but repeating the tool mechanics) as compared to repeating the transformation rule (but changing the tool mechanics).

[4]Due to the lack of a baseline indicating inhibition or facilitation, both, the terms "switch costs" and "repetition benefit", will be used in this work, and they will be used complementarily to each other. They refer to empirical phenomena associated with the effects of transformation rule repetitions and switches and do not imply the detailed theoretical background assumptions which have, for instance, been expressed for switch costs in task-switching studies (e.g., Meiran, 1996).

These are intriguing data which suggest that a transformation rule which is incorporated in a simple mechanical tool has an independent representation in the cognitive system and is somehow applied for movement selection. Furthermore, especially the costs that are associated with an incompatible transformation rule or with switching between different transformation rules are crucial findings. It is likely that they affect the efficiency with which people operate and switch between tools in everyday life.

1.3.2.1 Considerations about the Representation and Application of Transparent Transformation Rules

It seems relevant to ask how transparent transformation rules are represented and applied for movement selection when people use simple mechanical tools. Approaches which assume direct motor activation in tool use (see 1.2.1 and 1.2.2) do not entail much information about transformation rule application for movement selection. On the contrary, in the internal model approach, the representation and application of tool-associated transformation rules is explained in detail in terms of forward and inverse models which are not necessarily consciously represented (see 1.3.1.1). However, the internal model approach mainly relies on data about transformation rules which are not coupled to a concrete tool body. For instance, for opaque movement-effect transformations in computer mouse paradigms the hand is typically not guided, but it is free to test innumerable movements that might or might not produce the desired effect movement. Participants can thus gradually adapt their movements to the transformation rule. In contrast, transparent transformation rules which are incorporated in simple mechanical tools often define a few distinct spatial movement-effect transformations. For instance, the handles of scissors can only either be opened or closed, and in response to this, the distal blades will likewise either open or close; the realization of further movement-effect transformations is not possible. Similar restrictions for movement selection apply to the lever paradigms reviewed above. For instance, in the study by Massen and Prinz (2007b), the lever could either be moved towards or away from the body, and likewise, its distal tip moved towards or away from the body.

For these simple mechanical tools, gradual and maybe even unconscious online adaptation to a transformation rule as described in the internal model approach should therefore play a minor role for correct movement selection. Instead, transformation rules of simple mechanical tools might even be represented explicitly in the cognitive system, defining a set of distinct movement-effect pairs.

Indeed, it has been proposed that people turn to the deduction and application of formal rules to predict the behavior of mechanical systems like tools as soon as they get acquainted with the system properties (Schwartz & Black, 1996; Schwartz & Martin, 2002). Such an application of explicit transformation rules – instead of being an unconscious process as described in the internal model approach – should require "controlled" processing. Controlled processing is classically characterized as effortful and intention-driven and it is furthermore susceptible to interference (e.g., Logan, 1988; Posner & Snyder, 1975; Shiffrin, 1977).

The controlled application of explicit rules reminds of conventional stimulus-response paradigms used in Experimental Psychology to investigate processes of action selection. In the following section, I will outline in which way these paradigms might be relevant to explain transformation rule application for movement selection in tool use.

1.4 Movement Selection According to Explicit Mapping Rules

Transformation rules inherent in simple mechanical tools define which operating movement will lead to a desired effect movement. In many conventional paradigms which are used in Experimental Psychology, not a tool body, but an explicitly instructed rule specifies the mapping between actions and external events. For instance, an explicit mapping rule might specify that participants always have to react with an opposite-side button press to the appearance of a stimulus on the left- or right-hand side of the screen. Such a mapping rule thus specifies an explicit transformation rule for the relation between stimuli and responses. Indeed, some authors speak of *stimulus-response transformations* (e.g., R. de Jong, 1995; Ragot & Guiard, 1992; Stoffels, 1996).

At this point, a short excursus towards a conceptual clarification is required. Transformation rules in tool use define movement-effect transformations. On the contrary, most work on the application of explicit mapping rules has been conducted in a stimulus-response (S-R) context. This has theoretical and practical reasons: On the one hand, S-R paradigms origin in the tradition of the classical sensorimotor view according to which actions are regarded as reactions upon external stimuli. On the other hand, it seems difficult to manipulate a participant's intention to produce a specific effect. Yet, stimuli provoking action on the one hand, and action effects on the other hand are similar to some extent: Firstly, both refer to sensorially perceivable events in the external world. Secondly and most important for the present work, external stimuli as well as anticipated action effects play a functional role for triggering action (e.g. Hoffmann et al., 2001; Kunde, 2001). Thirdly, anticipated action effects influence action selection as if they were already sensorially present (Kunde, 2001). The one and main difference seems to be that a stimulus is externally presented, whereas a response effect is anticipated endogeneously. But even this distinction is sometimes not clear-cut, as it happens that external events trigger the anticipation of action effects.

To conclude, both, S-R mapping rules and tool-associated transformation rules, specify the relation between (anticipated or displayed) external events provoking action on the one hand and the corresponding action on the other hand. Consequently, the comparison between tool-associated transformation rules and explicit S-R mapping rules seems to be justified on a conceptual basis.

On an empirical basis, the compatibility effect, switching costs, and the precuing benefit which have been observed for the use of simple mechanical tools (see 1.3.2) are well known phenomena from research on explicit S-R mapping rules. In this context, they have already been extensively investigated, and they have been described in detail on a theoretical basis as well. So if transparent transformation rules in tool use were represented and applied in the same way as explicit mapping rules, one could simply apply the diverse results and theoretical assumptions which have been reported for explicit mapping rules to the context of movement selection in tool use.

There are two fields of research which seem especially relevant for the supposition that transparent transformation rules in tool use are applied in a similar manner as explicit mapping rules. These are research on S-R compatibility on the one hand, and research on sequential effects when participants switch between S-R mapping rules on the other hand. In the following, both fields will shortly be presented along with ways to explain movement selection in tool use in terms of explicit rule application.

1.4.1 Compatibility Effects

As it has been described above, an incompatible transformation rule in tool use results in considerable performance costs in terms of RTs and error rates (Kunde et al., 2007; Massen & Prinz, 2007b; Müsseler et al., 2008). Similar costs have also been reported in numerous studies on S-R compatibility (e.g., Dassonville, Lewis, Foster, & Ashe, 1999; Dutta & Proctor, 1992; Fitts & Seeger, 1953; Hommel, 1996; Proctor & Reeve, 1990; Stins & Michaels, 2000). In a very simple S-R compatibility paradigm, an abstract stimulus (e.g., a square) is presented to the left or to the right of a fixation point on the computer screen. Depending on the explicit mapping rule, participants have to react as fast as possible with a left- or right-hand button press (e.g., Dutta & Proctor, 1992). Typically, responding is easier (in terms of lower RTs and higher accuracy) if the explicit mapping rule is a compatible one and thus defines spatially corresponding S-R associations in comparison to an incompatible mapping rule. That is, in response to a stimulus on the right, a right-hand button press is typically executed faster than a left-hand button press.

Although the majority of studies centers on S-R compatibility, compatibility effects have as well been reported for corresponding versus non-corresponding R-E mappings (Ansorge, 2002; Keller & Koch, 2006, 2008; Koch & Kunde, 2002; Kunde, 2001, 2003; Kunde et al., 2004; Stöcker et al., 2003). In the study by Kunde (2001), participants had to respond to the color of a centrally presented stimulus. Response keys were horizontally aligned and a key press was followed by the appearance of a box either above the currently relevant response key, or above a currently irrelevant key. Participants were faster in their reaction in blocks in which the position of this box corresponded to the currently relevant response key.

Models accounting for these compatibility effects mostly center on the advantage produced by dimensional overlap between external events and associated actions. An influential and comprehensive model is the dimensional overlap account by Kornblum and colleagues (Kornblum et al., 1990; Kornblum, 1992; Kornblum & Lee, 1995). It assumes that – given dimensional overlap between a set of stimuli and a set of responses – the perception of a stimulus triggers two routes of response activation: On the one hand, the compatible response which shares a common feature or dimension with the stimulus is activated automatically. On the other hand, the response which is actually required by the valid mapping rule is retrieved in a controlled process. The responses identified by both routes are compared, and in the case of a match, response execution is fast and accurate. This match occurs if the valid mapping rule requires the compatible response. In the case of a mismatch, the rule-dependent response has to be executed, but this process takes relatively long and is error-prone due to interference from the automatically activated compatible response which has to be aborted. Such a mismatch occurs if the mapping rule requires an incompatible response.

Consequently, compatibility effects in the use of simple mechanical tools could be explained as follows: A tool-use action is initiated by the anticipation of the distal effect. Upon effect anticipation, the operating movement which is spatially compatible to this effect is always activated automatically. However, for movement selection, also the tool-associated transformation rule is needed and it is represented as an explicit rule and applied in a controlled process. If it defines the compatible operating movement as well, movement selection is facilitated. If it defines an operating movement that is spatially incompatible to the anticipated effect, movement selection is delayed and error-prone.

Yet there remains the question why there were no costs associated with an incompatible transformation between movements and effects in the studies using a steering wheel (e.g., Proctor et al., 2004). However it has been speculated that the dimensional overlap between operating movements (rotating the steering wheel) and distal effects (a cursor movement to the left or to the right) was not strong enough to create a significant compatibility effect (Kunde et al., 2007).

1.4.2 Sequential Effects

There are furthermore some hints that a tool-associated transformation rule holds an independent representation, which is not bound to specific tool mechanics, in the cognitive system: Precuing the transformation rule, as well as a transformation rule repetition in comparison to a rule switch facilitate movement selection (Herwig & Massen, in press; Massen & Prinz, 2007b, 2007a). These findings agree with the results of paradigms in which not tools, but abstract cues signal the valid mapping between actions and external events.

For instance, in a study by Shaffer (1965) a variable S-R mapping was introduced. In each trial, a symbol representing a rule signified whether the spatially corresponding or the opposite button should be pressed in response to a stimulus light appearing on the left- or on the right-hand side. Precuing the rule led to shorter RTs than precuing the stimulus or presenting both components at the same time. Additionally, RTs in rule repetition trials were faster than in rule switch trials.

Similar to these findings are the results of so-called task-switching paradigms (Jersild, 1927). In these, participants have to switch between two (or more) tasks (e.g., “Attend to stimulus color” or “Attend to stimulus form”) that both refer to the same set of stimuli (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; Meiran, 1996). Thus, switching between tasks means switching between task-defined S-R mappings (e.g., depending on the current task, a red triangle may require a left button press to indicate its red color, or a right button press to indicate its triangular form). In each trial, a cue (e.g., a letter) signals which task to execute. With this setup, there is a precuing benefit if the relevant task cue is presented before stimulus presentation (Meiran, 1996). Furthermore, participants are faster in trial n when the task from trial $n - 1$ is repeated than when there is a task switch (e.g., Mayr & Kliegl, 2003; Monsell & Mizon, 2006). Notably, this holds even if two different cues are used for one and the same task (Altmann, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). The task thus seems to be represented in the cognitive system as a set of S-R mappings which is not necessarily bound to one perceptual cue.

It is a common view that the task-related associations between stimuli and responses are established in a controlled process (e.g., Monsell, Sumner, & Waters, 2003). It is assumed that the task set including all relevant S-R mappings is loaded from long-term memory into working memory in response to the task cue. Then the specific mapping that matches the stimulus is selected and applied (Mayr & Kliegl, 2003, for a different view see Logan & Bundesen, 2003). In this approach, switch costs are due to updating the relevant task set. The precuing benefit can be explained by the fact that task set retrieval can already take place before stimulus presentation.

Of course, switching between tool-associated transformation rules cannot simply be equated with task switching. The reason is that different tasks explicitly signal different goals (Rubinstein, Meyer, & Evans, 2001), for instance number specification or color specification. Different transformation rules, in contrast, define different means that may be even appropriate to achieve one and the same goal (e.g., touching a target point with a lever incorporating a compatible or an incompatible transformation rule). Still, there might be a way to explain the costs of switching between tool-associated transformation rules and the benefit for precuing a transformation rule in a similar way as it has been done in task-switching paradigms. It could be assumed that a tool is a cue for the controlled retrieval of a mental set which, similar to a task set, is applied in order to choose an adequate operating movement to achieve a desired effect (Massen & Prinz, 2007b). Such a mental set might include all movement-effect transformations which are relevant for using a tool with a specific transformation rule.

1.4.3 Controlled Processing

As evident from the preceding statements, the perception of a stimulus in a conventional experimental setting leads to controlled processing: A response is selected by the application of an explicit mapping rule. Furthermore, in the preceding section it has been demonstrated that there are potential ways to explain movement selection in tool use in terms of explicit rule application. Such an explanation implicates that a controlled route of processing is the main way towards the operating movement which is required to achieve a desired effect. To sum it up, one could assume that the relevant transformation rule is cued by the tool, loaded from long-term memory into working memory and then used to select the specific operating movement which will be transformed into the desired effect. Automatic and direct activation of an operating movement (presumably the operating movement which is spatially compatible to the desired effect) might only modulate this controlled process by facilitation or interference (Kornblum et al., 1990).

Notably, a further factor should influence movement selection if transformation rules in tool use were indeed applied in such a controlled process. This factor is the transformation between a movement and an effect in a preceding action. It has been repeatedly shown that performance in a current trial n is strongly influenced by the association between task elements in the preceding trial $n-1$. Typically, performance is facilitated if all task elements from the preceding trial are completely repeated or completely change (e.g., a stimulus/stimulus category is repeated and it furthermore requires the same response as in the preceding trial). Conflict is created for partial repetitions (e.g., only the response has to be repeated, but it is triggered by a different stimulus than in the preceding trial) (e.g., Hommel, 2004). For instance, in task-switching paradigms response repetitions are especially beneficial in task repetition trials: In these trials, a response-relevant stimulus category is repeated and it requires the same response as in the preceding trial. On the contrary, response repetitions are detrimental in task switch trials: In these, the response-relevant stimulus category changes, but still the response remains the same, though it has a different meaning now. Consequently, the task repetition benefit mainly relies on response repetition trials (e.g., Kleinsorge, 1999; Meiran, 2000; Rogers & Monsell, 1995; Schuch & Koch, 2004).

These findings are often explained by the *event file hypothesis* which assumes that acting in a specific context automatically results in a binding process that integrates the action and this specific context in an event file (Hommel, 1998b, 2004, 2005; Hommel et al., 2001). It is assumed that such an integration in trial $n-1$ may strongly influence action selection in trial n: Typically, any encounter of an element overlap reactivates the recently created event file, facilitating action if the event file can be repeated completely, but creating conflict if the overlap is only partial. That is, the associations between task elements which have been established according to a mapping rule in one trial are “sticky” (Hommel, 2005, p. 8) and influence movement selection in the next trial.

Notably, however, the association between task elements in a preceding trial has a selective impact on situations in which action selection in the current trial depends on controlled processing (Waszak, Hommel, & Allport, 2005; B. Hommel, personal communication, December 4, 2007). For instance, naming a stimulus picture requires a higher amount of controlled processing than reading a stimulus word (e.g., MacLeod, 1991). An influence of the stimulus-response mapping in trial $n-1$ on trial n can be observed for the former task, but not for the latter (Waszak et al., 2005).

Consequently, if movement selection in tool use depended on controlled rule application, it should be influenced by movement-effect transformations in preceding action. For instance, if one first uses normal pliers to squeeze an object (compatible movement-effect transformation) and directly afterwards uses reverse pliers to squeeze an object (incompatible movement-effect transformation) this is a partial repetition (squeezing is repeated, but the body movement is a different one). If movement selection depended on controlled rule application, this partial repetition should create conflict and thus complicate movement selection for using the reverse pliers. Such an influence might be relevant for situations in which people have to switch between different tools which incorporate the same or different transformation rules and thus implement similar or different movement-effect transformations. However, there are yet no data for tool use centering on this question.

To summarize, on a conceptual basis it is possible to explain movement selection in tool use as resulting from a controlled process of explicit rule application. However, there are also arguments for the notion that transformation rule application for movement selection in tool use differs from the application of explicit mapping rules in important aspects, and these arguments will be presented in the following section.

1.5 On Tools and Explicit Rules

Explicit S-R mappings are used in conventional compatibility or task-switching paradigms first and foremost in order to achieve a maximum of experimental control. Furthermore, responses like button presses and stimuli on the computer screen are often held as simple as possible. Still, many authors start their research articles with examples from everyday life which involve much more complex perceptual events and motor actions. They claim that their findings from the experimental context, for instance from S-R compatibility paradigms, can be generalized to many instances of action in everyday life (e.g., Proctor, Vu, & Pick, 2005).

This might be true in many cases. But still, there is an important objection against unrestrained generalizability. For the acting person, the relation between a stimulus and a mapping rule is typically meaningless and exchangeable in the context of conventional S-R paradigms. Therefore, this relation has to be defined in the instructions, it has to be learned and mapping rules are then applied in a controlled process (Kornblum et al., 1990; Monsell et al., 2003): Response selection is based on explicit knowledge about the relevant mapping rule which has to be loaded from long-term memory into working memory. Some rules are at least very easy to implement, for instance, when the S-R association is a compatible one (e.g., "in response to a light on the left-hand side press the left button"). But even such a compatible mapping rule is easily exchangeable in the sense that in the same context, it may be replaced by an incompatible one (i.e., for the participants, there is no transparent reason why they should react with a left- or with a right-hand button press to the stimulus light). Therefore, the direct and automatic activation of compatible responses can only be used when the mappings for all possible stimuli are known to be compatible; otherwise, response selection has to occur via explicit rule retrieval (Ehrenstein & Proctor, 1998). To sum it up, stimuli in conventional S-R mapping paradigms "are often abstract and therefore not associated with a set of real-world actions. There is nothing that a colored letter affords" (Ellis & Tucker, 2000, p. 467). On the contrary, tool-associated transformation rules might hold a special status, and in the following, I will present some arguments for this assumption which refer to tool-induced and effect-induced motor activation in tool use.

In contrast to the above-mentioned colored letter, a simple mechanical tool is a meaningful stimulus which people strongly associate with motor action. As outlined in detail in section 1.2.2, the operating movements which are physically afforded by a tool are automatically activated simply by visually perceiving the tool. This notion of physical affordances which are visually perceived can be extended to the tool-associated transformation rule: The structure of a simple mechanical tool does not only specify adequate operating movements, but based on everyday experience with mechanical devices, people can easily imagine which operating movement will result in which effect at the tool's distal tip. In other words, a tool affords its transformation rule. As a consequence, the adequate operating movement to achieve a desired effect can easily be revealed by anticipating this desired effect along with imagining the respective tool movement.

In the following, I will refer to this process as *visuomotor imagery*. This term was chosen because it can be distinguished from the concept of motor imagery which refers solely to the mental rehearsal of body movements (Jeannerod, 1994). It takes into account that the imagination of movement refers to an external object which extends the body. To give a concrete example, for using a clothespin, one might anticipate the effect of opening the distal grippers along with the respective closing movement of the clothespin's handles. Such a process of visuomotor imagery could specify the adequate handling movement.

If visuomotor imagery was involved, it could be hypothesized that – depending on the complexity of the tool's structure – movement selection according to the tool-associated transformation rule is not necessarily based on automatic movement activation alone. However, automaticity is not an all-or-non phenomenon and there are intermediate levels between truly automatic and strongly controlled processing (J. D. Cohen, Servan-Schreiber, & McClelland, 1992). One could assume that the amount of controlled processing for visuomotor imagery is reduced as compared to the amount of controlled processing which is required for the application of an explicit mapping rule: Visuomotor imagery is not necessarily a conscious process and at least no explicit rule definition and no retrieval of this explicit rule from long-term memory are required. Instead, the information needed for movement selection could be derived directly from the tool. That is, transformation rule application for movement selection in tool use should be an on-line process which is based on visual information and a lifelong experience with mechanical devices, and not primarily a process based on the retrieval of explicit knowledge.

Notably, visuomotor imagery relates to the internal model approach. It can be described as a process of simulating the movement-effect transformations of the tool – a process which is backed up by the imagination of the moving tool. One might say that the perception of a tool does not only activate a predictive switch to the adequate inverse model as it has already been postulated (Imamizu & Kawato, 2008), but additionally is helpful for the actual simulation process. Admittedly, visuomotor imagery abstracts from the original notion of an internal model which is concerned with the late processes of basal motor control and movement adaptation (e.g., D. M. Wolpert et al., 1995). Instead, it refers to the earlier and primarily cognitive antecedents of movement selection. However, on the basis of neuronal activation data already Imamizu and collegues state that internal models of tool transformations "are for cognitive functions rather than basic sensory-motor transformations" (Imamizu et al., 2003, p. 5466). Interestingly, even for opaque transformations, internal model activity in the cerebellum is located bilaterally in areas which are involved in the imagination of movement (Vingerhoets et al., 2002). However, this kind of imagery is presumably not based on additional visual information.

In addition, there is a further argument that transformation rule application for movement selection in tool use differs from the controlled application of an explicit rule. This argument refers specifically to simple mechanical tools which implement compatible transformations between movements and effects. As it will be explained in the following, this compatibility between movements and their associated effects might have a specific impact. To begin with, there is evidence that motor action in tool use is activated by effect anticipation. In the common coding theory this activation is explained by the assumption that actions and their associated effects are both represented in a common representational domain (see 1.2.1). It has been shown that movement activation by effect anticipation is typically easier if the movement and the effect overlap, for instance on the spatial dimension (this is the ordinary compatibility effect, see, e.g., Kunde, 2001). Sometimes, however, an action and the event that triggers this action do not only overlap, but the action is even almost identical with the event provoking it. A classical example is a task which requires verbally repeating an auditorily presented stimulus word. In this case, there is *high ideomotor compatibility* (Greenwald, 1972). In terms of the common coding approach (Prinz, 1990), both, actions and effects, refer to exactly the same codes in the cognitive system. For these kinds of tasks, the requirements for response selection are minimal (Brass, Bekkering, Wohlschläger, & Prinz, 2000; Greenwald, 1972; Hunt & Klein, 2002): Actions are automatically activated upon effect anticipation. Action selection then is a fast and effortless process, it is very efficient and does not require controlled processing.

High ideomotor compatibility exists if people act with their hands only in order to achieve certain effects. In the case of successful action, the anticipated effect which served to activate the action (e.g., the anticipation of the sensory effects of grasping an object) and the action itself (e.g., actually grasping the object) are identical. Consequently, natural reaching or grasping movements are activated automatically upon effect anticipation and the requirements of response selection in terms of controlled processing are minimal. This is shown, for instance, by the finding that for natural reaching movements the number of possible targets and therefore of movement alternatives does not influence the time needed for movement selection (Favilla, 1996). Most notably, high ideo-motor compatibility also exists in tool use, when the operating movement is identical with the anticipated and the actually achieved distal effect movement at the tool's tip. This is the case for simple mechanical tools which incorporate a compatible transformation rule. For instance, when one uses pliers, the spatial direction of the finger's grasping movement by which the pliers' handles are operated is identical to the spatial direction of the grasping movement of the distal grippers. For these tools, it is especially unlikely that the transformation rule is applied in a controlled process. Instead, the required operating movement should be activated automatically upon effect anticipation. It should then be selected with minimal requirements of controlled processing: The compatible transformation is immediately apparent by visually perceiving that the tool simply extends the effectors. That is, despite the spatial segregation between movements and effects, movement selection could even take place as if an effect was achieved by the hand only, without the involvement of a tool. This is why movement selection could rely on what I will call *default associations* between movements and effects: It could be assumed that movements are directly activated upon effect anticipation and that subsequent movement selection requires no or at least only a minimal amount of controlled processing.

In the following, before I will give way to the empirical part of this work, I will briefly summarize the main points which have been made in this chapter.

The starting point was the statement that spatial transformations between desired effects and the required operating movements are a characteristic feature of tool-use actions (see 1.1). Nevertheless, there is evidence for the direct activation of operating movements in tool use (see 1.2). On the one hand, the correct operating movement can be activated by effect anticipation. On the other hand, already tool perception results in motor activity. However, there is also evidence that the transformation between desired effects and required operating movements can substantially influence the processes of movement selection (see 1.3). On a conceptual basis, it is even possible to explain movement selection in tool use in terms of the controlled application of an explicit mapping rule (see 1.4). However, there are two reasons why it might be inadequate to put transformation rules of simple mechanical tools on equal footing with explicit mapping rules (see 1.5). First, tool-associated transformation rules are afforded by the tool's structure. Consequently, it can be hypothesized that transformation rule application means that the correct operating movement to achieve a desired effect is derived from the tool in a process of visuomotor imagery. If this was true, less controlled processing should be required for transformation rule application in tool use than for the retrieval of an explicit mapping rule from long-term memory. Second, for tools that incorporate a compatible transformation rule and simply extend the bodily effectors, the operating movement entails high ideomotor compatibility with the distal effect. The operating movement thus might even be activated automatically upon effect anticipation and then might be selected as the default movement.

These theoretical considerations motivated the experiments which will be presented in the following chapters.

1.6 Outline of Experiments

The preceding section comprised theoretical considerations, but so far, there is not much empirical evidence about how transformation rules are represented and applied when people select their operating movement to achieve desired effects in the use of simple mechanical everyday tools. In the paradigm which was applied in the present work, in each trial the picture of a simple mechanical tool appeared on the screen (e.g., pliers or a clothespin). Participants had to operate this tool via a response device (see Figure 2.1 on page 42). They had to perform the same operating movement as if they were directly handling the tool. Tools incorporated either a compatible or an incompatible transformation rule. Reaction times, error rates and functional imaging data for operating movements were collected.

Our research centered on three main issues: The first was to figure out whether transformation rules incorporated in simple mechanical everyday tools hold an independent representation in the cognitive system. The second was to investigate potential differences between the application of compatible and incompatible transformation rules. The third was to specify whether the application of transformation rules which are afforded by simple mechanical tools differs from explicit rule application.

The representation and application of compatible and incompatible tool-associated transformation rules, as well as their differences, were investigated in Experiments 1–4. In Experiment 1, the rule repetition benefit in relation to rule switch costs was studied while people had to switch between tools that incorporated either the same or different transformation rules. A potential rule repetition benefit should indicate that transformation rules hold an action-relevant representation in the cognitive system, although they do not necessarily rely on an explicit definition. A further concern of Experiment 1 and also of Experiment 2 was to elucidate the differences between the application of compatible and incompatible transformation rules in terms of controlled processing. Specifically, it was hypothesized that compatible movement-effect transformations can rely on default associations between movements and effects because they entail high ideomotor compatibility and are evidently afforded by the tool. Consequently, they should thus require a minimal amount of controlled processing. Following the event file logic (Hommel, 2004; Waszak et al., 2005), the influence of complete and partial repetitions of movement-effect transformations from trial $n-1$ on movement selection in trial n was taken as a measure of controlled processing.

In Experiment 3 and 4 it was investigated whether there are ways to reduce the differences between the application of compatible and incompatible tool-associated transformation rules, or even to establish incompatible movement-effect transformations as default associations by manipulating rule probability (Experiment 3) or by training (Experiment 4).

Experiments 5 and 6 aimed at investigating whether transformation rules which are afforded by simple tools hold a special status. In Experiment 5 it was asked whether the application of transformation rules for movement selection in response to tool pictures differs from the application of explicitly defined rules in terms of reduced controlled processing. With the same aim, in Experiment 6, transformation rule application in response to tool pictures was contrasted with transformation rule application in response to written tool names. It was proposed that in tool use, the correct operating movement to achieve a desired effect is derived from the tool in a process of visuomotor imagery and that movement selection thus requires less controlled processing than movement selection in response to an explicit mapping rule. Again, the influence of complete and partial repetitions of movement-effect transformations from trial $n-1$ on movement selection in trial n was taken as a measure of controlled processing.

Finally, Experiment 7 aimed at describing the application of transformation rules in tool use in terms of their neuronal correlates. Crucial questions were the differences between the application of compatible and incompatible transformation rules on the one hand, as well as process of switching between tool-associated transformation rules, on the other hand.

Chapter 2

Transformation Rules and High Ideomotor Compatibility

The aim of the present study was to improve the understanding of how people represent and apply transformation rules which are incorporated in simple mechanical tools. It was therefore required to isolate the tool-associated transformation rule as an independent component of the action. To this end, a paradigm was established which combines the advantages of a controlled experimental setting with tool stimuli known from everyday life which afford a certain action. In the following, this paradigm and its rationale as well as the starting hypotheses will be presented.

2.1 Paradigm and Predictions

One way to investigate the relevance of transformation rules in tool use is to analyze sequential effects when people switch between tool-use actions for which the tools incorporate either the same or different transformation rules. We therefore developed a tool-switching paradigm by which we could dissociate the repetition of transformation rules from the repetition of specific tools. In the basic form of this paradigm (see Figure 2.1), in each trial, one of four different tools was presented on the computer screen. Two of the four tools incorporated a compatible transformation rule (pliers and tweezers, also referred to as ‘compatible tools’); the other two incorporated an incompatible transformation rule (clothespin and clip, also referred to as ‘incompatible tools’). A common feature of these four tools is that with each of them, one can squeeze or release objects. With compatible tools, squeezing an object is achieved by closing and releasing the object

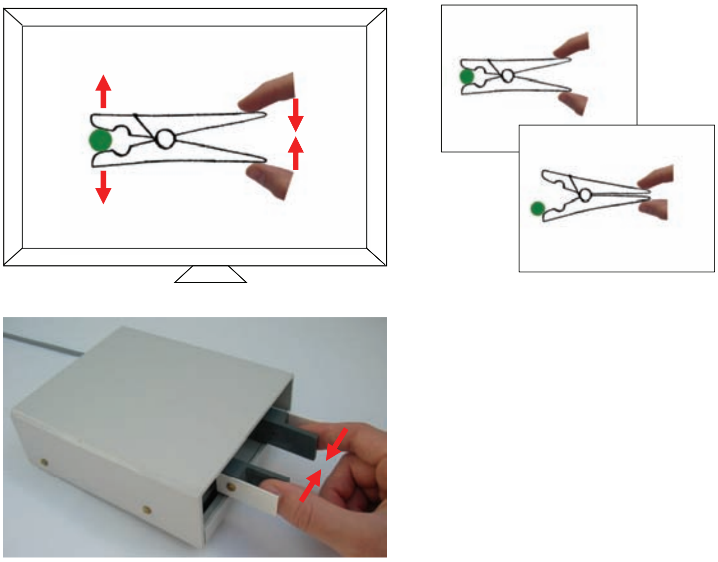

Figure 2.1: Experimental setup of the tool-switching paradigm. In each trial, a tool picture appeared on the computer screen and a red or green ball in its distal grippers indicated whether to open or to close the tool. The correct operating movement had to be executed in the response device as if the tool was directly handled and it was immediately followed by the appearance of the effect picture on the screen. Arrows illustrate the required movement direction for this example, but were not displayed during the experiment.

by opening the fingers which are holding the handles. For incompatible tools, squeezing is achieved by opening and releasing by closing the fingers.

In the experiment, a green or red ball in the grippers of each tool served as an effect cue signaling which operation (squeezing or releasing) to execute. Participants then had to conduct the correct operating movement which was ensued by the movement-contingent effect appearing on the screen (e.g., a closed tool that squeezed the ball). This paradigm should approach real tool-use actions: Movement selection followed upon effect anticipation (which was externally cued by the colored ball) and – given the execution of the correct operating movement – the anticipated effect was realized.

We could tap the relevance of a tool-associated transformation rule by comparing trials in which the tool changed from trial $n-1$ to trial n, but the transformation rule remained the same (e.g., switching between tweezers and pliers), with trials in which the tool and also the transformation rule changed (e.g., switching between tweezers and the clothespin). With some modifications, this paradigm was used in all the experiments presented here. In the following, our starting predictions will be outlined.

Previous research on opaque transformation rules in computer mouse paradigms and computer simulations (e.g., Haruno et al., 2001; Imamizu et al., 2003), or on transparent transformation rules in lever paradigms (e.g., Massen & Prinz, 2007b; Herwig & Massen, in press) has provided evidence that a transformation rule is a functionally relevant component of the action and represented independently from a specific tool. It was therefore expected that a transformation rule which is incorporated in a simple mechanical tool holds an independent and functionally relevant representation in the cognitive system as well. Consequently, faster RTs and lower error rates were expected in trials in which the tool changed, but the transformation rule was repeated from trial $n-1$ to trial n as compared to rule switch trials, thus resulting in a rule repetition benefit (in relation to rule switch costs).

We were furthermore interested in a potential compatibility effect induced by the tool-associated transformation rule. In accordance with the results of studies using a lever paradigm (Kunde et al., 2007; Massen & Prinz, 2007b; Müsseler et al., 2008) we hypothesized that the selection of the operating movement to achieve a desired effect would generally be easier for compatible than for incompatible tools.

Based on the hypothesis of a compatibility effect, the processing mechanisms which are involved in movement selection when people use compatible or incompatible tools to achieve required effects were in the center of our interest. We started with the following predictions: In section 1.5, we stated that a compatible transformation rule which is afforded by a simple mechanical tool obviously defines movement-effect transformations of high ideomotor compatibility (Greenwald, 1972). According to the common coding approach (Prinz, 1990), movements and effects of high ideomotor compatibility refer to identical codes in the cognitive system. We therefore hypothesized that for compatible tools, the movement to achieve a required effect should be activated automatically upon effect anticipation. Furthermore, for simple mechanical tools, compatible movement-effect transformations are obviously afforded by the tool: The tool simply extends the moving limbs. The requirements for movement selection in terms of controlled processing should thus be minimal. Despite the spatial segregation between movements and effects, movement selection could even take place as if the effect was achieved by the hands only. It was thus assumed that the

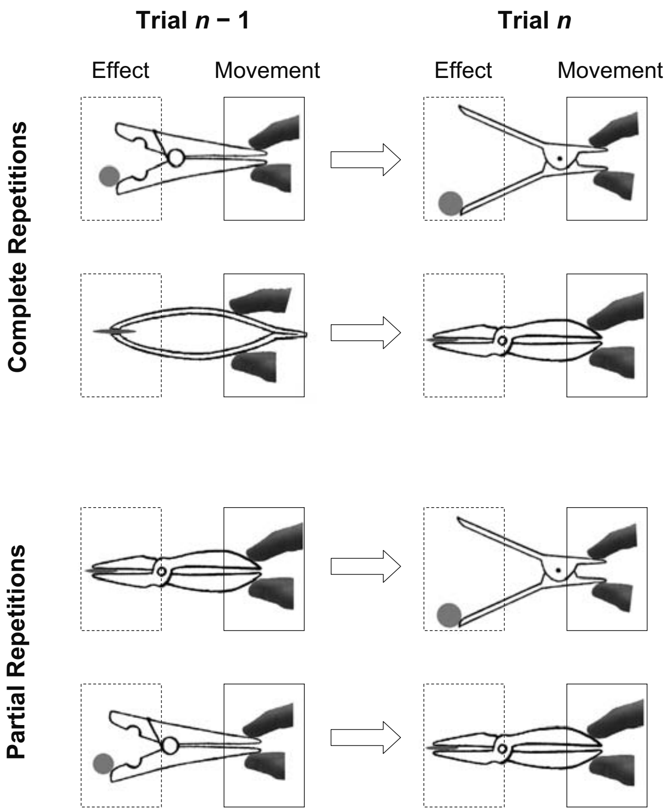

Figure 2.2: Movement repetition trials with complete and partial repetitions of movement-effect transformations. Complete repetitions occur only in rule repetition trials and should strengthen a potential rule repetition advantage. Only the effect pictures are displayed to illustrate the required movement direction. In these examples, the correct operating movement was always a closing movement.

realization of compatible movement-effect transformations can rely on default associations between movements and effects.

In contrast, an incompatible transformation rule which is afforded by a simple mechanical tool implements movement-effect transformations which conflict ideomotor compatibility. The (anticipated and actual) effect movement is incompatible to its associated operating movement. For incompatible tools, the amount of controlled processing required for movement selection should thus be considerably higher than for compatible tools. A measure to uncover the amount of controlled processing necessary for movement selection was provided by the detailed analysis of sequential effects. In the following, I will shortly outline the rationale behind this analysis.

In subsection 1.4.3 it was already depicted that performance in a current trial n is typically influenced by the association between task elements in the preceding trial $n-1$ (Hommel, 1998b, 2004; Hommel et al., 2001). Complete repetitions of associations are beneficial, whereas partial repetitions have a detrimental effect. Most interestingly for our issue, these sequential effects are the stronger the more performance depends on controlled processing (Waszak et al., 2005). Also in the tool-switching paradigm, we have complete and partial repetitions, namely of movement-effect transformations (see Figure 2.2). *Complete repetitions* occur in *transformation rule repetition trials* in the case that also the specific finger movement to achieve a required effect is repeated from trial $n-1$ to trial n (e.g., if in trial $n-1$ participants have to *close* their fingers to *close* tweezers, and in trial n they have to *close* their fingers to *close* pliers). *Partial repetitions* occur in *transformation rule switch trials*, for instance when the finger movement is repeated, but is associated with a different effect due to the rule switch (e.g., if in trial $n-1$, participants have to *close* their fingers to *open* a clothespin, and in trial n they have to *close* the fingers again but this time to *close* pliers). Consequently, movement repetitions should be beneficial in rule repetition trials (complete repetition of a movement-effect transformation), and they should be detrimental in rule switch trials (partial repetition of a movement-effect transformation). This way, movement repetitions should strengthen any potential rule repetition benefit. The rule repetition benefit should, in contrast, be less pronounced for movement shift trials for which the beneficial complete repetitions of movement-effect transformations cannot occur.[1] The crucial point

[1]Note that in our paradigm, we do not have complete changes which have been reported to be similarly beneficial as complete repetitions (e.g., Hommel, 2005). One element (either the transformation rule, or the movement, or the effect) is always repeated from trial $n-1$ to trial n).

however is, that this influence of the movement-effect transformations from trial $n-1$ on trial n, and therefore also the modulation of the rule repetition benefit by movement repetition should increase the more movement selection depends on controlled processing (Waszak et al., 2005). The choice to concentrate on movement repetition and shift trials in the analysis of complete and partial repetitions, and not, for instance, on effect repetition and shift trials was motivated by the results of task-switching paradigms. In these, movement/response repetitions have typically a strong advantage in task repetition, but not in task-switch trials (e.g., Kleinsorge, 1999; Rogers & Monsell, 1995; Meiran, 2000; Schuch & Koch, 2004; see also 1.4.3).

Sequential effects were thus analyzed with the starting hypothesis that for incompatible, but not for compatible tools, there would be a modulation of the rule repetition advantage by movement repetition. Only for the former, but not for the latter, we expected controlled processing for movement selection.

2.2 Experiment 1

In order to investigate how people represent and apply compatible and incompatible transformation rules when they have to switch between simple mechanical tools, the basic form of the tool-switching paradigm was applied. On the one hand, we were interested in whether transformations rules obtain an independent and functionally relevant representation in the cognitive system. On the other hand, we wanted to elucidate the differences between compatible and incompatible transformation rule application for movement selection in terms of controlled processing. Based on the logic outlined above, we expected a benefit for transformation rule repetitions, a compatibility effect, as well as a modulation of the rule repetition benefit by movement repetition for incompatible, but not for compatible tools.

2.2.1 Method

Participants. Sixteen right-handed participants (9 women and 7 men) took part in the experiment. Their mean age was 22.5 years, and in this and in the following experiments they were paid 7 € for their participation in one experimental session.

Apparatus and Stimuli. Stimuli were presented at the center of a 17-in. color monitor connected to an IBM-compatible PC. The response device was connected to the PC via serial port. This response device is illustrated in the bottom part of Figure 2.1. Parallelly to each other in the horizontal dimension, two bars protruded out of a box that was open to this side and closed to the other three sides. Each of the two bars was connected to one gearwheel fixed in the box. The two gearwheels were interlocked: Moving one bar thus resulted in a mirror-symmetric movement of the second bar. The visible part of each bar (protruding out of the box) had a length of 3 cm, a width of 1.5 cm and a height of 2 cm. Each bar ended with an indentation of 2.5 cm depth into which a finger could be inserted. In the experiment, participants had to insert thumb and index finger of their right hand into the indentations. Thus, finger movements were transformed into bar movements. The two bars snapped in a middle position, in which they were parallel to each other with a distance of 4 cm. They could however be "opened" by moving the fingers apart with a maximal aperture of 8 cm. Likewise, they could be "closed" by moving the fingers together till the ends of the two bars touched each other. The two bars did not move back to the middle position automatically but had to be moved until they snapped. This response device enabled us to register the beginning of a closing or an opening motion starting from the middle position, as well as the arrival at the point of maximal aperture or closing. It stood on the table in front of the computer screen; from the participant's point of view the two bars pointed to the right side.

In each trial, the schematic picture of a tool appeared in the center of the screen. The tool was held in a half-opened position at its handles by thumb and index finger. The handles were pointing to the right side and the distal grippers were pointing to the left side. The tool picture could represent either pliers, or tweezers, or a clothespin, or a clip (see Figure 2.3). The contours of each tool were drawn in black on a white background. Contours were held as simple as possible and did not include any decorating details. Color photos of thumb and index finger were added. The picture as a whole subtended a visual angle of approximately $10°$ in height and $16°$ in length. In each trial, a red or a green ball subtending a visual angle of $2.1°$ was hold by the distal grippers of the tool, serving as a cue whether to open or to close the tool. We thus had eight different tool-cue combinations.

Directly following a correct response, an effect picture appeared on the screen: Depending on the current trial, the picture of the half-opened tool was replaced by a picture of the tool being closed by the two fingers thus squeezing the ball, or a picture of the tool being opened thus releasing the ball. The effect pic-

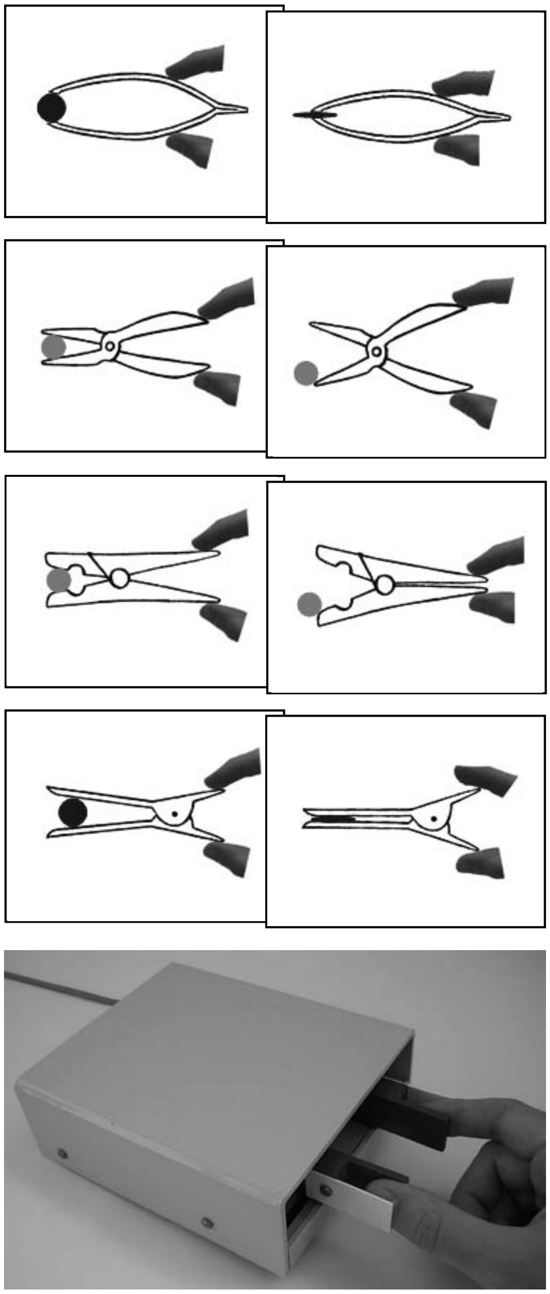

Figure 2.3: An example for a sequence of four trials in Experiment 1. Stimulus pictures are displayed in the picture column on the left side. Effect pictures following the correct operating movement are displayed in the picture column on the right side.

ture appeared without any start delay in response to the correct finger movement and exactly at the same position as the stimulus picture, thus producing an illusionary opening or closing movement. Stimulus presentation and recording of the responses were carried out with the software package Presentation (www.neurobs.com).

Procedure. The experiment was run in a single session with one participant at a time. Participants were first informed that they were required to execute tool-use actions with four different tools.

Pliers, tweezers, a clothespin, and a clip were shown to the participants as real tools. For each tool in turn, they were asked to hold it in a half-opened position, and then to open or to close its distal grippers by moving thumb and index finger of their right hand. Then, participants were informed that in each trial of the experiment, a tool picture would appear on the screen. They had to insert their right thumb and index finger into the indentations of the two bars of the response device and should thus imagine touching the handles of the tool appearing on the screen. Starting from the middle position, they had to conduct opening and clothing movements as if they were directly handling the tool. For half of the participants, the red ball was a cue for closing the distal grippers of the tool ("Squeeze the ball!"), and the green ball was a cue for opening the distal grippers ("Release the ball!"); for the other half, the reverse assignment was applied. As with the real tools, the pictures of tweezers and pliers required that the finger movement in the response device was the same as the desired effect (e.g., releasing the ball = opening the fingers). The pictures of clothespin and clip required that the finger movement was antagonistic to the required effect (e.g., releasing the ball = closing the fingers). Participants were only instructed towards the distal effect (closing or opening the distal grippers).

Each trial started with a blank screen for 1000 ms. Then the stimulus picture with the tool and the red or green effect cue appeared on the screen. It stayed there until the bars of the response device were maximally closed or opened. If this movement was the correct one, it was directly followed by the appearance of the effect picture. In the case of an error, the word "Fehler" (the German word for "error") appeared. The effect picture / error feedback remained visible on the screen until the two bars were brought back into the middle position (this took on average 500 ms) and then still another 500 ms. Subsequently the next trial began. The time from stimulus presentation to the initiation of an opening or a closing motion of the fingers in the response device was measured as RT.

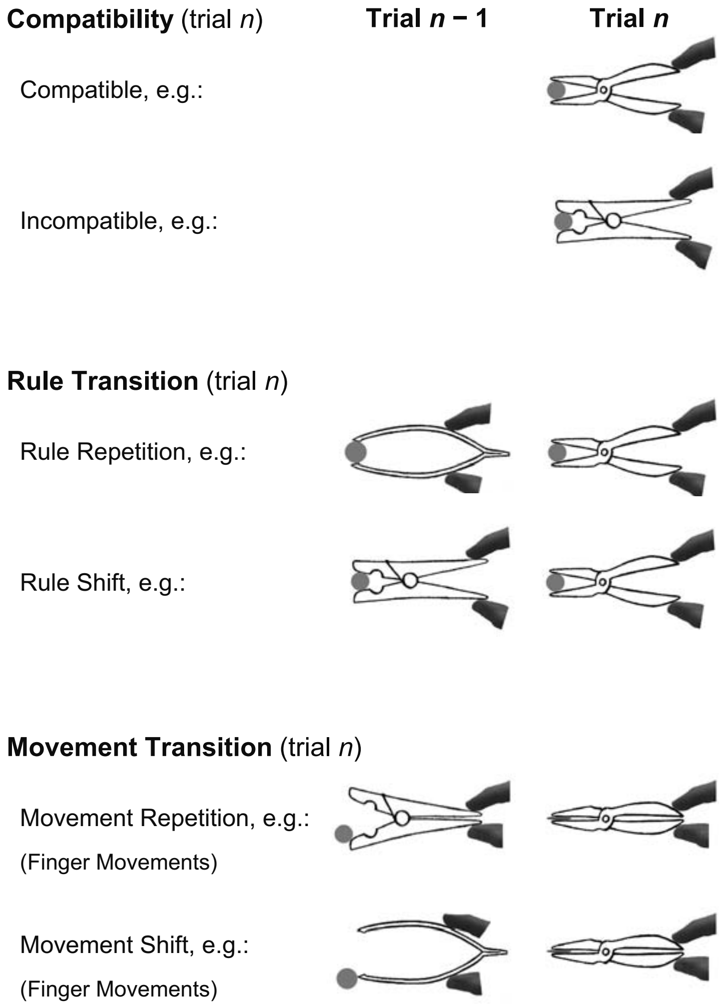

Figure 2.4: Design of Experiment 1. Compatibility, rule transition and movement transition were within-participant variables. Each variable had two levels. Examples of stimulus pictures for each level are displayed (only for the variable of movement transition the effect pictures are displayed in order to better illustrate movement direction).

Participants became acquainted with the task in a practice phase consisting of 48 trials. Then the test phase with 386 trials (two blocks of 193 trials each) started. Between the two blocks, participants were offered a little rest of about 20 s. The experiment took approximately 25 minutes.

Design. Each trial type (i.e., each of the eight tool-effect cue combinations) and each possible transition between two trials occurred equally often within a block. Three independent variables were varied within participants. The first was compatibility in trial n (compatible vs. incompatible transformation rule). The second was rule transition. We were especially interested in two types of rule transitions: 1) the tool changed but the transformation rule remained the same from trial $n-1$ to trial n (rule repetition trial); 2) the tool changed and also the transformation rule changed from trial $n-1$ to trial n (rule switch trial). The third variable was movement transition (finger movement repetition vs. shift) from trial $n-1$ to trial n (see Figure 2.4). RTs and error rates were measured as dependent variables and always refer to trial n.

2.2.2 Results

For each participant, median RTs and error rates were computed in dependence of compatibility, rule transition, and movement transition (see Figure 2.5). In this and in all the following experiments in which the switching paradimg was used, tool repetition trials were excluded from the analysis. For RT analysis, we furthermore excluded all errors and all trials that followed an error (15.6 % averaged over both blocks). For error rates, we excluded the trials that followed an error (8.4 %). This is a common practice in the analysis of sequential effects (e.g., Mayr & Kliegl, 2003; Kiesel, Kunde, & Hoffmann, 2006). In this and in the following experiments, significance was tested at the alpha level of 0.05.

RT Data. Median RTs were entered into a 2 × 2 × 2 analysis of variance (ANOVA). Compatibility (compatible vs. incompatible transformation rule), rule transition (transformation rule repetition vs. rule switch), and movement transition (finger movement repetition vs. movement shift) were within-participant variables.

There was a significant main effect of compatibility ($F(1,15) = 66.5$, $MSE = 49011.4$; $p < 0.001$): In trials, in which participants had to handle a compatible tool, movements were initiated 319 ms faster than in trials with an incompatible tool. Furthermore, there was a significant main effect of rule transition

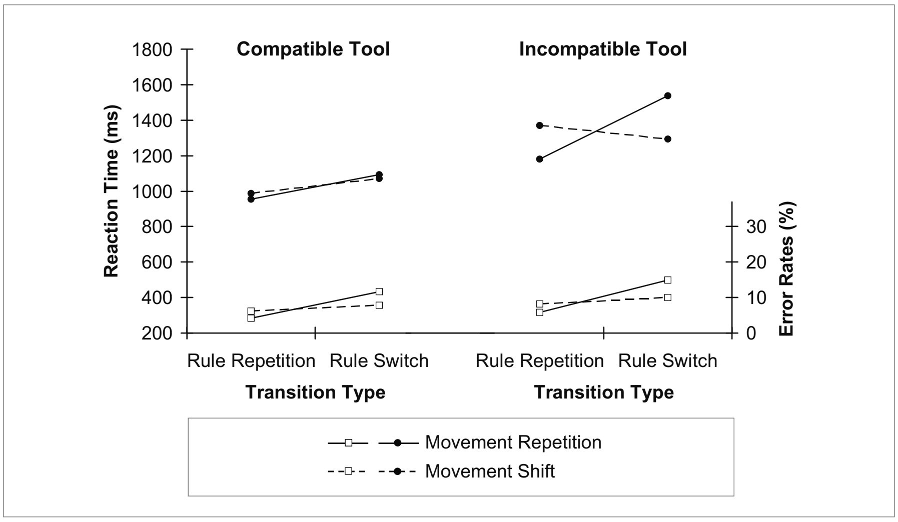

Figure 2.5: Mean RTs (filled circles) and error rates (open squares) for compatible (left) and incompatible (right) trials in Experiment 1 as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts).

($F(1, 15) = 25.0$, $MSE = 19943.8$; $p < 0.001$): With a mean difference of 124 ms, participants were faster in trial n if the transformation rule from trial $n-1$ was repeated than when it changed.

This effect of rule transition was modulated by movement transition, but only if the tool in trial n incorporated an incompatible transformation rule, and not, if the tool in trial n incorporated a compatible transformation rule ($F(1, 15) = 10.9$, $MSE = 26225.9$; $p < 0.01$ for the three-way interaction between compatibility, rule transition and movement transition). In detail, this means that if the tool in trial n was a compatible one, a rule repetition was beneficial for both, movement repetition as well as movement shift trials (ps < 0.05), and the interaction between rule transition and movement transition did not reach significance ($F(1, 15) = 1.4$, $MSE = 8958.0$). In contrast, if the tool in trial n was an incompatible one, there was a strong rule repetition benefit only if also the movement was repeated ($F(1, 15) = 11.9$, $MSE = 84862.1$; $p < 0.01$); for movement shift trials, there was even a tendency for repetition costs with rule switches being faster than rule repetitions ($F(1, 15) = 4.3$, $MSE = 11640.2$; $p = 0.056$); accordingly, for incompatible tools the interaction between rule transition and movement transition was significant ($F(1, 15) = 12.2$, $MSE = 62046.1$; $p < 0.01$).

Entering tool identity as an additional variable did not qualify any of these effects.

Error Rates. Descriptively, error data did not counteract RT data. Significant was the effect of compatibility ($F(1, 15) = 5.1$, $MSE = 31.7$; $p < 0.05$), as well as the effect of rule transition ($F(1, 15) = 22.6$, $MSE = 35.0$; $p < 0.001$). Participants made less errors with compatible than with incompatible tools, and they made less errors in rule repetition than in rule switch trials. RTs and error rates are summarized in Figure 2.5.

2.2.3 Discussion

The data of Experiment 1 revealed three main findings. The first was a compatibility effect. The second was a benefit for transformation rule repetitions as compared to switches. The third was an influence of the preceding movement-effect transformations on movement selection in trial n only if the tool in trial n was an incompatible, but not if it was a compatible one.

The compatibility effect replicates the findings from preceding studies on transformation rules in tool use (e.g., Kunde et al., 2007). Movement selection in order to achieve a required effect was faster and more accurate with compatible tools than with incompatible tools. Evidently, compatibility between anticipated effects and required operating movements is beneficial for movement selection even if the transformation between movements and effects is a transparent one and evidently required by the tool.

The crucial characteristic of the transformation rule repetition benefit was that did not depend on tool repetitions: In trials in which the tool changed but the tool-associated transformation rule remained the same, movements were initiated faster and more accurately than in trials in which the tool changed and the tool-associated transformation rule also changed. Such a rule repetition benefit was obtained for compatible as well as for incorporating tools. It was taken as evidence that compatible and incompatible transformation rules which are incorporated in simple mechanical tools hold an independent and functionally relevant representation in the cognitive system.

However, this rule repetition benefit relied on a different basis for compatible and incompatible tools. For an incompatible tool in trial n, there was an effect of the movement-effect transformation in trial $n - 1$ on movement selection in trial n: The rule repetition benefit depended on movement repetition trials. In contrast, if the tool in trial n was a compatible one, the movement-effect transformation in trial $n-1$ exerted only a minor influence on movement selection in trial n and the rule repetition benefit was thus not significantly modulated by movement repetition. These sequential effects were interpreted on the basis of the finding that sequential effects caused by complete and partial repetitions of task elements are the stronger the more movement selection depends on controlled processing (Waszak et al., 2005). We thus concluded that the amount of controlled processing required for movement selection differed between compatible and incompatible tools. Most notably, there was no evidence of controlled processing for tools with a compatible transformation rule. In contrast, controlled processing was evidently required for tools with an incompatible transformation rule. The results are thus in line with the hypothesis that the realization of compatible movement-effect transformations which are afforded by a simple mechanical tool can rely on default associations between movements and effects, although movements and effects are spatially detached from each other.

Interestingly, tool identity had no effect, that is, the results were the same for pliers and tweezers on the one hand, or the clothespin and the clip on the other hand. That is, only the kind of transformation between movements and effects, but not more elaborate differences in the tool structure, as obvious particularly between tweezers and pliers, mattered.

For incompatible tools, we even found *costs* in RT if the rule was repeated but a movement different from the one in trial $n-1$ was required. This result might be explained by the assumption that in a given trial, the incompatible transformation rule was strongly associated with the specific incompatible movement-effect transformation which had to be realized. In this case, one should expect costs if, in the following trial, the rule was repeated but the movement and the effect were different ones (e.g., trial $n-1$: incompatible tool, closing the fingers to squeeze the ball; trial n: incompatible tool: opening the fingers to release the ball). This interpretation is consistent with the finding that a task context (in this case the transformation rule) does not only provide an instructional frame for response selection but becomes an integrated part of action representation (e.g., Kiesel & Hoffmann, 2004; Mayr & Bryck, 2005). For the compatible transformation rule, the complete lack of rule repetition costs in movement shift trials supports the notion of compatible default associations. The activation of the compatible transformation rule resulting from the preceding trial faciliated movement selection whether or not the specific movement-effect transformation from this trial had to be repeated.

Interestingly, for incompatible tools, movement repetitions in rule and effect switch trials were the most difficult of all types of partial repetitions (see Figure 2.5). Conversely, partial repetitions of movement-effect transformations which contained an effect repetition were not associated with strong costs. We had not predicted such a differential influence, and several explanations might be possible. One plausible explanation relates to the fact that the transformation rule as well as the effect were cued on the screen whereas the operating movement had to be selected on the basis of this information, but without any direct cue. The presentation of two task elements (tool type and effect) which were different from the preceding trial could have induced a strong tendency towards a movement shift, though a movement repetition was required – thus producing strong costs. An alternative explanation might be that for incompatible tools the movement was actually irrelevant, but partial repetitions were especially detrimental when they contained an effect switch. As movement repetition/shifts and effect repetition/shifts were confounded in the present paradigm, there was no way to decide between both explanations. Most importantly, however, there was no such effect for movement selection in order to achieve a required effect with compatible tools, again corroborating the hypothesis of default associations for this tool type.

To summarize, the findings speak for the notion that transformation rules inherent in simple mechanical tools obtain an independent and functionally relevant representation in the cognitive system. Furthermore, they are in line with the assumption that compatible movement-effect transformations require a minimal amount of controlled processing and might even be provided as default associations.

At this point, we wanted to ask whether controlled processing was just reduced for operating compatible as compared to incompatible tools, or whether the realization of movement-effect transformations for compatible tools could indeed rely on default associations. Therefore, in Experiment 2, task difficulty was enhanced and it was asked whether the requirements for movement selection in terms of controlled processing would still be minimal for operating compatible tools. One should expect such a result if, for compatible tools, the selection of operating movements to achieve a required effect could rely on default associations between movements and effects.

2.3 Experiment 2

The aim of Experiment 2 was to justify the claim that for incompatible tools, movement selection in order to achieve a required effect could rely on default associations between movements and effects. To this end, we augmented the number of movement alternatives by implementing switches between spatial dimensions. The tool-switching paradigm we introduced in Experiment 1 was used again with two modifications: On the one hand, tool stimuli could appear in the horizontal as well as in the vertical dimension. On the other hand, there were two response sets with two response alternatives each. One response set corresponded to the horizontal and one to the vertical dimension. Participants had to conduct tool-use actions, this time not only switching between tools, but also switching between spatial dimensions and therefore between response sets.[2]

For trials in which the stimulus dimension and the response set did not switch from trial $n-1$ to trial n we expected to replicate the findings from Experiment 1. Moreover, the setup allowed for a stronger test of whether compatible movement-effect transformations were provided as default associations. This test concerned the interaction between a transformation rule repetition and a response set switch. If transformation rule application for movement selection in tool use was a controlled process, one should expect that switching between response sets reduces the rule repetition benefit. The reason is that similarity between rule repetition trials within a response set is evidently much higher than between response sets. One could even say that for a response set switch, in any case a new transformation rule has to be selected. At least, a simple binary coding of movement alternatives in terms movements and opposing movements as it could be used for rule repetition trials within a response set was not valid for response set switch trials. These assumptions are backed up by the results from task-switching paradigms in which response selection is assumed to rely on controlled processing: The ordinary task repetition benefit typically increases as a function of response set overlap. On the contrary, for switching between response sets, the task repetition benefit declines as if new mapping rules had to be selected (e.g., Cooper & Marí-Beffa, 2008; Mayr, 2001).

On the basis of Experiment 1, we assumed controlled processing for operating tools with an incompatible transformation rule. Consequently, we hypothesized that for incompatible tools, the advantage of a transformation rule repetition would be much reduced or even absent in response set switch trials. Notably,

[2] In the following, when we speak of a response set switch, this implies that the spatial dimension of the tool stimulus changes as well from trial $n-1$ to trial n.

however, this should not apply to compatible tools. If compatible movement-effect transformations had a default status, repetitions of the compatible transformation rule should be beneficial in response set repetition *as well as* in response set switch trials without any significant difference: In either case, the requirements for movement selection in terms of controlled processing should be minimal.

2.3.1 Method

Participants. Twenty right-handed participants (12 women and 8 men) took part in the experiment. Their mean age was 24.0 years.

Apparatus and Stimuli. Stimulus pictures and effect pictures were the same as in Experiment 1, only that this time, each tool could appear in the horizontal or vertical dimension (see Figure 2.6). There was a small gray bar at the underside of each tool, representing a table on which the tool was placed in the horizontal condition, or a wall against which the tool was pressed in the vertical dimension. Only the index finger was shown, pressing the tool against this gray bar in a half opened position. We had 16 different pictures, realizing all possible combinations of tools, effect cues, and spatial dimension. Participants responded on an external response pad that was connected to the PC via parallel port. On the response pad, five keys were aligned in a cross-like manner: The home key was located in the middle of four response keys, two of them arranged in the vertical dimension and the remaining two arranged in the horizontal dimension. Keys measured approximately 1.2×1.2 cm each and were spatially separated by 0.5 cm.

Procedure and Design. Procedure and Design were the same as in Experiment 1 except for the following modifications: In the instruction phase, participants were asked to press each tool in a half opened position horizontally on the table or vertically against the wall by their index finger. They thus could open or close the distal grippers of the tool by moving their index finger. During the experiment, participants had to respond to the stimulus pictures using the response pad. They were instructed to start each trial by pressing the home key with their index finger and to imagine that they were thus touching the upper / right handle of the tool that subsequently appeared. They were then instructed to handle the tool by moving their index finger – releasing the home key – into the same direction into which they would move it if they were directly

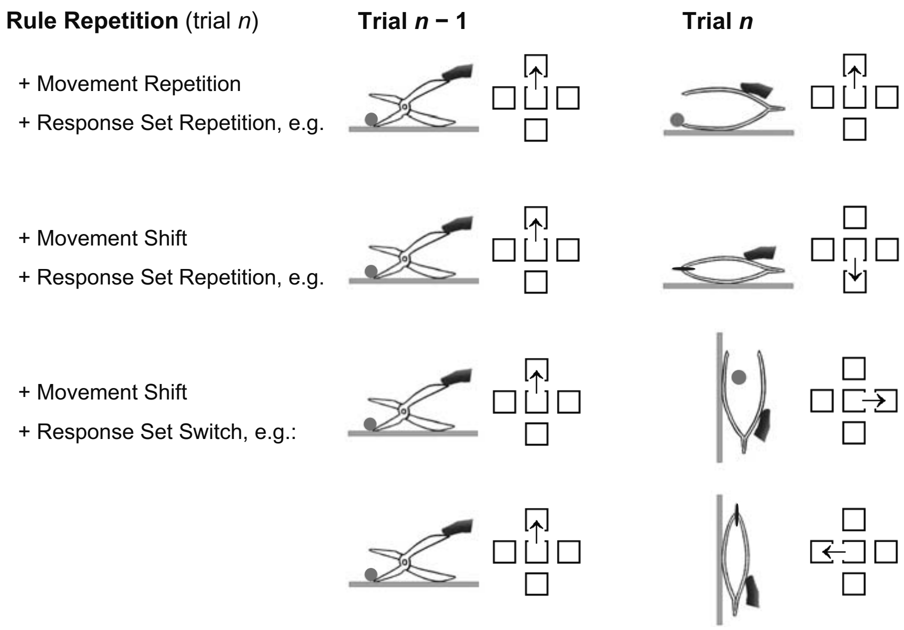

Figure 2.6: Examples for stimulus pictures and transition types in Experiment 2. This example depicts transformation rule repetitions in dependence of movement repetition, movement shift and response set switch. Starting from the home key in the middle, participants had to move their index finger to the upper or lower key to handle horizontally presented tools, and to the left or right key to handle vertically presented tools. The arrows illustrate the required movement direction in these examples.

touching the tool. For tools presented in the vertical position, they thus had to use the horizontal response set. For tools presented in the horizontal position, they had to use the vertical response set. For instance, if they wanted to open vertically presented pliers, they had to move their index finger to the right. If they wanted to open horizontally presented pliers, they had to move their index finger upwards. To indicate that they had chosen the correct direction, they were instructed to press the key that corresponded to their movement direction (up, down, left, or right) and then they had to return to the home key. The feedback (effect picture or error feedback) was presented as soon as one of the outer response buttons was pressed. It remained visible on the screen until the home key was pressed and then another 500 ms. After the practice phase with 32 trials, the test phase with 771 trials (three experimental blocks consisting of 257 trials each) started. Each trial type (i.e., each of the 16 tool-effect cue combinations) and each possible transition between two trials occurred equally often within a block. The whole experiment took approximately 50 minutes.

The variable of movement transition now had three levels. These were movement repetition and movement shift within a response set, and, additionally, movement shift combined with a response set shift (see Figure 2.6). RT was measured as the time from stimulus presentation to the release of the home key.

2.3.2 Results

Median RTs and error rates are depicted in Figure 2.7 and were computed in dependence of compatibility, rule transition, and movement transition (movement repetition, movement shift within a response set, response set shift). For RT analysis, all error trials and all trials following an error were excluded (18.4 % averaged over all blocks). For error rates, all trials following an error were excluded (10.1 %).

RT Data. We conducted a $2 \times 2 \times 3$ ANOVA with compatibility (compatible vs. incompatible transformation rule), rule transition (rule repetition vs. switch) and movement transition (movement repetition, movement shift, response set shift) as within-participant variables.

There was a main effect of compatibility: Compatible tools were operated on average 353 ms faster than incompatible tools ($F(1, 19) = 50.5$, $MSE = 68573.5$; $p < 0.001$). Furthermore, the main effect of rule transition was significant: With a mean difference of 108 ms, participants were faster in rule repetition than in rule switch trials.

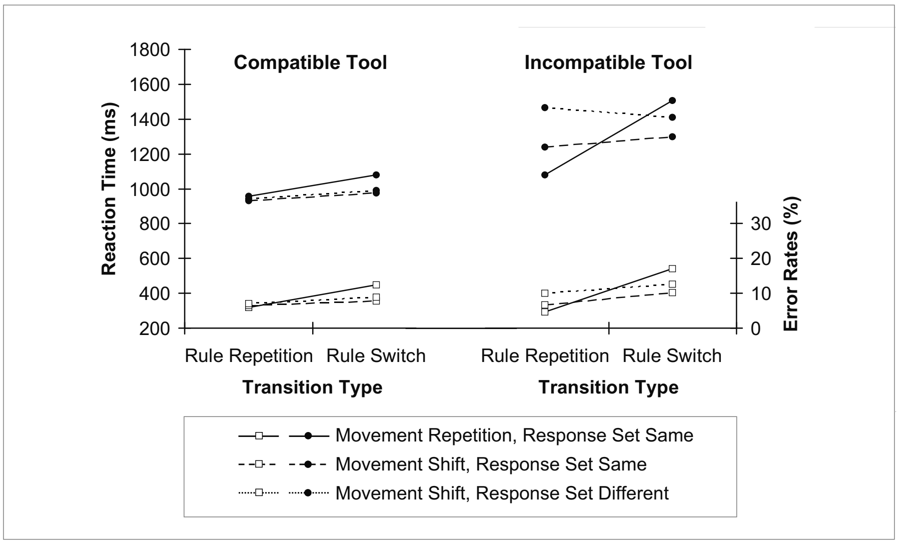

Figure 2.7: Mean RTs (filled circles) and error rates (open squares) for compatible (left) and incompatible (right) trials in Experiment 2 as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts, dotted lines response set switch trials).

As in Experiment 1, this rule transition effect was modulated by movement transition only if the tool in trial n incorporated an incompatible transformation rule ($F(2, 38) = 27.2$, $MSE = 8022.2$; $p < 0.001$ for the 3-way interaction between compatibility, rule transition and movement transition). In detail, the results were as follows: If the tool in trial n incorporated a compatible transformation rule, there was a rule repetition benefit for movement repetition trials, for movement shift trials, and – most notably – also for response set shift trials (all ps < 0.05). Consequently, the interaction between rule transition and movement transition was not significant for compatible tools. In contrast, if the tool in trial n incorporated an incompatible transformation rule, there was a strong rule repetition benefit for movement repetition trials ($p < 0.001$). The rule repetition benefit for movement shift trials was nonsignificant, and for response set shift trials there were even significant costs for rule repetitions in contrast to rule switches ($p < 0.01$). The interaction between rule transition and movement transition was thus highly significant ($F(2, 38) = 37.0$, $MSE = 17094.5$; $p < 0.001$). Entering spatial dimension (horizontal response set vs. vertical response set) as an additional variable did not change these results.

Error Rates. Participants made more errors for incompatible as compared to compatible tools ($F(1, 19) = 7.9$, $MSE = 33.5$; $p < 0.05$). The main effect of rule transition was significant as well ($F(1, 19) = 30.8$, $MSE = 43.3$; $p < 0.001$) with more errors in rule switch than in rule repetition trials. On a descriptive basis, this rule repetition effect was modulated by movement repetition, and this modulation was stronger for incompatible than for compatible tools, but the three-way interaction did not reach significance ($F(2, 38) = 1.1$, $MSE = 31.8$).

2.3.3 Discussion

The most important finding of Experiment 2 was that for compatible tools, rule repetitions were beneficial in movement repetition and in movement switch trials, but, most notably, also in response set switch trials. In contrast, this was not the case for incompatible tools for which a significant rule repetition benefit emerged only for movement repetition trials; in movement shift trials, rule repetition was less beneficial (trials without response set switch), or even lead to costs (trials with response set switch). Experiment 2 thus provided strong evidence for the notion that movement-effect transformations of tools with a compatible transformation rule are provided as default associations. The activation of the compatible transformation rule in the preceding trial seemed enough to facilitate movement selection in the current trial, independent of the concrete movement-effect transformation which was required.

Interestingly, for compatible tools, a response set switch had no influence on movement selection at all. This is obvious if one regards the three variables of movement transition (movement repetition, movement shift, response set shift) for compatible and for incompatible tools within rule repetition trials (the left data points in Figure 2.7). For compatible tools, participants were about equally fast for movement repetitions, movement shifts and response set shifts. On the contrary, for incompatible tools, participants were fastest if the movement was repeated, they were significantly slower if the response set remained the same, but the movement changed, and, most importantly, they were yet significantly slower if the movement and also the response set changed (ps < 0.01).

Finally, if only trials are considered in which the stimulus dimension and the response set did not switch from trial $n - 1$ to trial n, the main results from Experiment 1 were replicated. The way of responding differed between Experiment 1 and 2: In Experiment 1, participants had to conduct opening or closing movements with their fingers, in Experiment 2, they had to move their finger towards or away from the virtual ball. Still, this difference did not change the pattern of data. Obviously, moving the finger towards the object one wants to squeeze and away from the object one wants to release can be regarded as default movements in a similar manner as closing the fingers to squeeze or opening the fingers to release an object seem to be default movements.

Just like in Experiment 1, for incompatible tools, movement repetitions in rule and effect switch trials were the most difficult of all types of partial repetitions (see Figure 2.7). With the current paradigm, there was the chance to test the potential explanation raised in the discussion of Experiment 1 that not the movement repetition, but the associated effect switch was the reason for this result. In trials with a response set and transformation rule switch, effect repetitions / switches were not confounded with movement repetition / switches. Contrasting effect repetitions and switches in these trials, however, did not yield a significant result ($F(1, 20) < 1$, $MSE = 21026.6$). That is, performance was the same for effect switches and effect repetitions. It thus seems likely that the strong disadvantage for movement repetitions in rule and effect switch trials was indeed caused by the presentation of task elements on the screen which differed from the preceding trials. These should have biased participants towards a movement shift even though a movement repetition was required. Again, in Experiment 2, there was no such finding for compatible tools.

To summarize, the findings in Experiment 2 strongly support the notion that movement selection in order to achieve a required effect with compatible tools can rely on default associations between movements and effects, whereas movement selection for incompatible tools relies on controlled processing.

2.4 Discussion of Experiment 1 and 2

The first two experiments demonstrated the relevance of transformation rules in the use of simple mechanical tools. The benefit that was obtained for operating compatible as compared to incompatible tools and the benefit for transformation rule repetitions as compared to switches confirm and extend the findings of studies concentrating on opaque transformation rules (e.g., Imamizu et al., 2003) or transparent transformation rules in lever paradigms (e.g., Kunde et al., 2007; Massen & Prinz, 2007b).

Notably, differences between compatible and incompatible tools were evident in movement selection processes. The preceding movement-effect association and the requirement to operate one tool in the horizontal and another one in the vertical dimension influenced movement selection processes for incompatible, but not for compatible tools. We concluded that controlled processing was minimal for movement selection in order to achieve a desired effect with a compatible tool. On the contrary, there seemed to be controlled processing for movement selection in order to achieve a desired effect with an incompatible tool.

Our results thus support the hypothesis that the realization of movement-effect transformations which are inherent in compatible tools can rely on default associations between movements and effects. The default status of compatible movement-effect associations can be characterized by automatic movement activation upon effect anticipation and minimal requirements of controlled processing for subsequent movement selection. We suggested that the reason for this default status lies in the tool's structure. The operating movement and its associated effect – though spatially segregated – are obviously very much alike and entail high ideomotor compatibility. In terms of the common coding theory (Prinz, 1990), movements and distal effects of high ideomotor compatibility even refer to exactly the same codes in the cognitive system.

On the contrary, tools with an incompatible transformation rule contradict high ideomotor compatibility and therefore the selection of the operating movement upon effect anticipation is an effortful process requiring controlled processing. On the basis of these first two experiments, the specific processes leading to the correct operating movement for incompatible tools – explicit rule application or visuomotor imagery, for instance – cannot be determined.

One might wonder why there was an effect of rule transition at all for compatible tools. As a reminder: Participants were faster if they had to switch from a compatible to another compatible tool then when they had to switch from an incompatible to a compatible tool. If the realization of compatible movement-effect transformations could rely on default associations, one might expect that it does not make a difference whether the preceding trial was also a compatible one or an incompatible one. Still, it can be supposed that a great part of these rule transition effects was not due to movement selection processes, but due to the selection of the adequate transformation rule. It is likely that participants grouped the two compatible tools as belonging to one tool category, and the two incompatible tools as belonging to another tool category: If two consecutive tasks rely on the same response set, a repetition advantage is known to occur only when the corresponding stimuli belong to the same response-relevant category (Campbell & Proctor, 1993; Pashler & Baylis, 1991). Most notably, this holds even if this category is represented internally only (Kleinsorge, 1999). That is, in both, compatible and incompatible trials, tool identification and the assignment of the tool to the compatible or incompatible tool category probably preceded movement selection These processes were faster for the repetition of a tool category. It is likely that only afterwards, movement selection could enroll – with minimal requirements of controlled processing for compatible tools and in a controlled process which was influence by the preceding movement-effect transformation for incompatible tools.

After having obtained evidence that movement selection according to the compatible transformation rule entails only minimal requirements of controlled processing, the subsequent two experiments were conducted in order to elucidate the reason for the default status of compatible movement-effect associations. The hypothesis was, that the default status was primarily an effect of high ideomotor compatibility. However, apart from high ideomotor compatibility, there are further factors that might influence such a default status. One such factor is training with specific transformations; another one is the probability with which specific transformations occur. In the following, we asked whether manipulation of these two factors would reduce the differences between compatible and incompatible tools or even establish incompatible movement-effect associations as default associations. In other words, in the two subsequent experiments we tried to compensate for the effects of high ideomotor compatibility by changing rule probability or by training.

Chapter 3

The Effects of Rule Probability and Training

The instances in which people handle a tool with an incompatible transformation rule are rare in everyday life as compared to the innumerable action events of high ideomotor compatibility. This fact entails two consequences: Firstly, compatible movement-effect transformations are highly overlearned. Secondly, it might be an adaptive strategy to implement compatible movement-effect associations as default associations – and to put up with the unfavorable effect on situations with an incompatible transformation rule.

However, there are circumstances under which incompatible transformations do not seem to be particularly disadvantageous. For instance, when a driver grasps his steering wheel at the bottom part, the steering wheel implements an incompatible transformation between operating movements and resulting effects. Interestingly, this incompatible transformation does not seem to be disadvantageous as compared to a compatible transformation which is achieved by grasping the steering wheel at the top (e.g., Proctor et al., 2004). In this specific case, the desired distal action effect seems to activate the adequate operating movement easily, whether or not the movement-effect transformation is a compatible or an incompatible one. This results is in contrast to the results of Experiment 1 and 2 of the present work which indicate a strong advantage for compatible as compared to incompatible tools in terms of a compatibility effect and minimal controlled processing for movement selection only for the former, but not for the latter. Admittedly, and in contrast to our experiments, in the steering wheel paradigm by Proctor et al. (2004), there was no high ideomotor (in-)compatibility between operating movements and resulting effects: The distal effect was a cursor on the screen that moved on the horizontal line of the screen to the right for clockwise and to the left for counterclockwise rotations of the hands at the top or bottom part of the steering wheel. It is thus an empirical question whether under some circumstances, simple mechanical tools with an incompatible transformation rule can be operated in the same efficient manner as tools with a compatible transformation rule even if ideomotor compatibility for the latter is high. One possibility to investigate this question is to favor incompatible tools by frequent occurrence.

Additionally, there is evidence that the default status of movement-effect associations can be influenced by training. For instance, with relatively little costs, participants adapt to a simple reversal of their body movements when the effect movements are presented on a screen and are rotated by 180° (Cunningham, 1989). After training with such an opaque transformation rule, the return to spatially corresponding movement-effect transformations is typically marked by aftereffects (e.g., Kagerer et al., 1997). It therefore seems that an opaque transformation rule which disrupts the spatial correspondence between movements and their effects is in some cases adopted as the standard during training. However, it has also been reported that even with extended training, perfect adaptation to opaque transformations is not always possible but strongly depends on the kind of transformation (e.g., Heuer & Hegele, 2007). Again, it has not yet been systematically investigated whether it is possible to implement movement-effect associations of high ideomotor incompatibility as default associations during training with incompatible simple mechanical tools.

On the contrary, in conventional S-R compatibility studies the effects of training and rule frequency on compatibility effects have often been investigated (e.g., Dutta & Proctor, 1992; Hommel, 1994; Proctor & Lu, 1999). Therefore, in the following two experiments, methods were used which have proved useful to reduce, eliminate or even reverse compatibility effects in these studies. The first method was changing rule probability. The second was extensive training. We were especially interested in whether these manipulations would compensate for the effects of high ideomotor compatibility or even transfer the default status to incompatible movement-effect associations. The compatibility effect as well as the amount of controlled processing needed for movement selection according to the compatible as compared to the incompatible transformation rule were thus in the spotlight. Again, the influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was used as a measure for controlled processing. The rationale behind this approach has been described in the preceding chapter (see 2.1).

3.1 Experiment 3

In Experiment 3, rule probability was manipulated. In conventional S-R compatibility paradigms, the compatibility effect is often already eliminated when compatible and incompatible trials are equally likely but appear randomly intermixed (e.g., Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004). In this case, the direct and automatic route of response activation which has been assumed to activate the compatible response (Kornblum et al., 1990, see 1.4.1), seems to be suppressed because it is maladaptive in half of the trials (R. de Jong, 1995). Experiment 1 and 2 demonstrated that mixing compatible and incompatible trials in the tool-switching paradigm did not eliminate the compatibility effect. Quite to the contrary, there was evidence that compatible movement-effect associations had a default status. Resistant against mixing are also compatibility effects like the Simon or the Stroop effect which both origin in the automatic activation of responses caused by an actually response-irrelevant stimulus dimension. However, it has been repeatedly shown that even these compatibility effects are reversed when the majority of trials is non-corresponding (Greenwald & Rosenberg, 1978; Hommel, 1994; Logan & Zbrodoff, 1979; Marble & Proctor, 2000; Toth et al., 1995).

We applied this method of manipulating the frequency of compatible and incompatible trials for the tool-switching paradigm. Compatible and incompatible tools appeared randomly on the screen. However, in one condition, tools with an incompatible transformation rule were two times as frequent as tools with a compatible transformation rule (majority incompatible condition). In the other condition, tools with a compatible transformation rule were two times as frequent as tools with an incompatible transformation rule (majority compatible condition). In a control condition, the frequency of compatible and incompatible tools was balanced (balanced condition). The main question was whether the condition variable would have an influence on the default status of compatible as compared to incompatible movement-effect associations.

We predicted that if the default status of compatible movement-effect associations was susceptible to external requirements, it should be eliminated in the majority incompatible condition in which incompatible tools were favored by frequent occurrence. In this majority incompatible condition, incompatible movement-effect associations should obtain the default status. Consequently, a reversal of the compatibility effect should be expected in this condition. Along with this reversal, the amount of controlled processing (revealed by the influence of the movement-effect association in trial $n-1$ on movement selection in trial

n) should be enhanced for compatible tools and reduced for incompatible tools as compared to the balanced condition.

If, on the contrary, the default status of compatible movement-effect associations was primarily due to high ideomotor compatibility and could not be adapted to external requirements, the results of the majority incompatible condition should not differ much from the results of the balanced condition.

Finally, in the majority compatible as compared to the balanced condition, in any case, we expected a higher compatibility effect and enhanced controlled processing for incompatible tools due to their infrequent occurrence. Such an effect should be an indicator that subjects were generally responsive to changes in rule probability.

3.1.1 Method

Participants. Sixty-one right-handed participants (31 women and 30 men, mean age 24.8 years) took part. They were randomly assigned to one of the three conditions, 20 to the majority compatible condition, 21 to the majority incompatible condition, and 20 to the balanced condition.

Apparatus and Stimuli. The apparatus was the same as in Experiment 1. Stimuli were identical to those used in Experiment 1, but ice tongs and scissors were added to the group of compatible tools, and a crocodile clamp and a hairgrip were added to the group of incompatible tools.

Procedure and Design. The procedure was similar to Experiment 1, but it depended on the condition which tools were used. In the majority compatible condition, there were four tools with a compatible transformation rule (pliers, tweezers, scissors, ice tongs) and two with an incompatible transformation rule (clothespin, clip). In the majority incompatible condition, there were two tools with a compatible transformation rule (pliers, tweezers) and four with an incompatible transformation rule (clothespin, clip, crocodile clamp, hairgrip). Finally, in the balanced condition three tools with a compatible (pliers, tweezers, scissors) and three with an incompatible transformation rule (clothespin, clip, crocodile clamp) were used (see Figure 3.1). After trying out using the real tools, there was an initial practice phase consisting of 36 trials during which participants could get acquainted with the task and the response device. The subsequent main experiment had two blocks (a learning phase and a test phase) of 433 trials

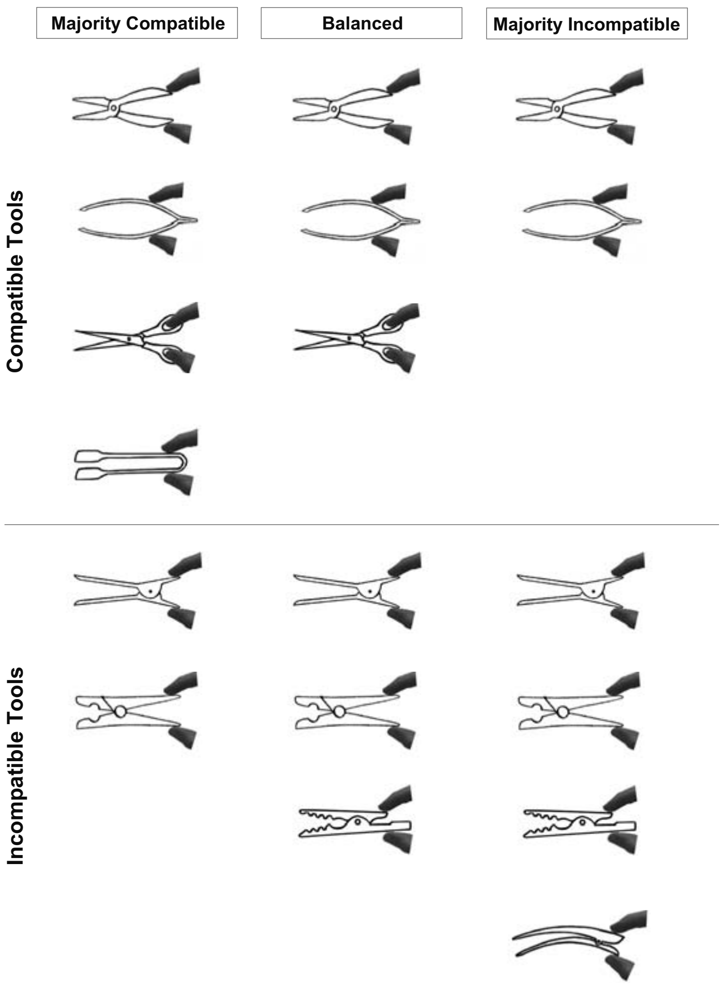

Figure 3.1: Stimuli and design used in Experiment 3. In the majority compatible condition, participants had to switch between four compatible and two incompatible tools; in the balanced condition, they had to switch between three compatible and three incompatible tools; in the majority incompatible condition, they had to switch between two compatible and four incompatible tools.

each, with a short break of approximately 20 seconds in between. The whole experiment took approximately 50 minutes.

The design was the same as in Experiment 1, only that condition (majority compatible, balanced, majority incompatible) was an additional between-participant variable. During the practice phase and, most importantly, also during the subsequent main experiment, each of the six tools appeared equally often. Accordingly, in the majority compatible condition the ratio of compatible to incompatible tools was 2 : 1 , in the majority incompatible condition the ratio of compatible to incompatible tools was 1 : 2, and in the balanced condition, the ratio was 1 : 1. The first block of the main experiment was considered as learning phase during which subjects should adapt to these ratios. The second block was considered as test phase and only this second block was used for the analysis of sequential effects.

3.1.2 Results

Only second-block trials were analyzed. All error trials and all trials following an error (15.3 %) were excluded from RT analysis. Trials following an error (8.1 %) were excluded from the analysis of error rates.

RT Data. We conducted a $2 \times 2 \times 2 \times 3$ ANOVA with compatibility, rule transition, and movement transition as within-participant variables and condition (majority compatible, majority incompatible, balanced) as between-participant variable (see Figure 3.2). There was no significant main effect of condition, that is, the majority compatible, the majority incompatible and the balanced condition were generally tasks of equal difficulty ($F(2, 58) < 1$, $MSE = 163071.3$).

The first question concerned the influence of the condition variable on the compatibility effect. Overall, the main effect of compatibility with lower RTs for tools incorporating a compatible transformation rule was highly significant ($F(1, 58) = 106.2$, $MSE = 30001.1$; $p < 0.001$). The condition variable however strongly influenced this compatibility effect ($F(2, 58) = 18.4$, $MSE = 30001.1$; $p < 0.001$ for the two-way interaction between compatibility and condition). The compatibility effect was largest in the majority compatible condition (272 ms; $p < 0.001$), it was significantly lower in the balanced condition (173 ms; $p < 0.001$), and in the majority incompatible condition it was numerically there, but statistically not significant any more (41 ms; $p = 0.28$).

The second question concerned the influence of the condition variable on the modulation of the rule repetition benefit by movement repetition. As a reminder:

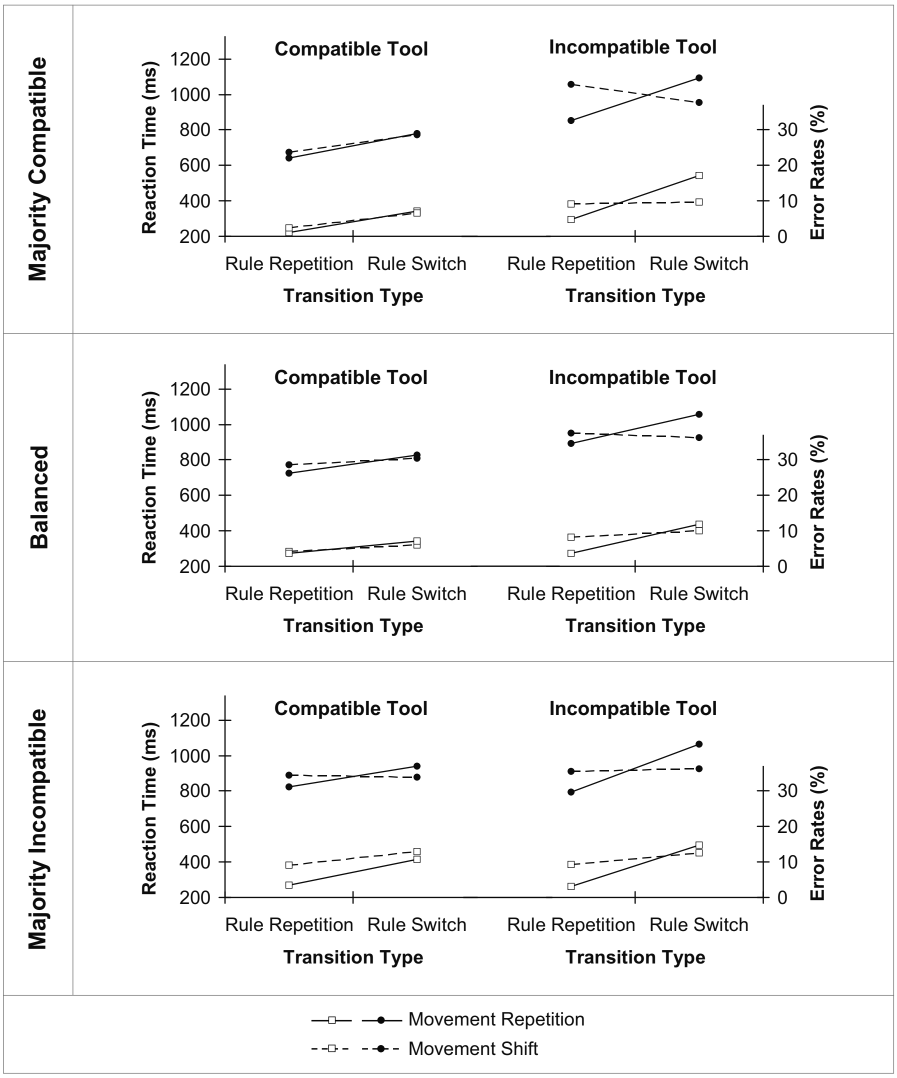

Figure 3.2: Mean RTs (filled circles) and error rates (open squares) for compatible (left) and incompatible (right) trials for the three groups (majority compatible, balanced, majority incompatible) in Experiment 3. Data are displayed as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts.)

The results of the previous experiments showed that only for incompatible, but not for compatible tools, the rule repetition benefit was significantly modulated by movement transition. Also in the current study, there was a rule repetition benefit ($F(1, 58) = 81.2$, $MSE = 11296.2$; $p < 0.001$), and the modulation of this benefit by movement transition was generally stronger for incompatible as compared to compatible tools ($F(1, 58) = 56.3$, $MSE = 4624.2$; $p < 0.001$ for the three-way interaction between compatibility, rule transition and movement transition). Most notably, however, the strength of this modulation depended on condition ($F(2, 58) = 5.6$, $MSE = 4624.2$; $p < 0.01$ for the four-way interaction between condition, compatibility, rule transition and movement transition). The strongest effect was observed in the majority compatible condition: In this condition, the modulation of the rule repetition benefit by movement transition was extraordinary strong for incompatible tools; it was absent for compatible tools. Consequently, the three-way interaction between compatibility, rule transition and movement transition was highly significant and furthermore significantly stronger than in the balanced condition ($p < 0.01$). Interestingly, a potential difference between the balanced and the majority incompatible condition in terms of this three-way interaction was far from being significant ($F(1, 39) < 1$; $MSE = 4089.9$).

In our view, the most spectacular finding was thus the following: In the majority incompatible condition, there was no significant advantage for operating compatible tools any more. Yet, in comparison to the balanced condition, the pattern of a stronger modulation of the rule repetition benefit by movement transition for incompatible relative to compatible tools did not significantly change. Based on these findings, we conducted a post-hoc analysis: We wanted to know whether the absence of a significant compatibility effect in the majority incompatible condition resulted from active and strategic suppression of compatible movement-effect associations due to their infrequent occurrence. An alternative possibility would be a general reduction in the ease with which compatible movement-effect transformations were realized due to a shift of the default status from compatible towards the more frequent incompatible movement-effect associations.

We therefore compared RTs in trials in which the same transformation rule was required two times in a row with trials in which the same transformation rule occurred three times in a row (we always concentrated on the last trial in the row). We included only trials with those tools which appeared in all three conditions. Normally one should expect ‘three in a row’ trials to be faster than

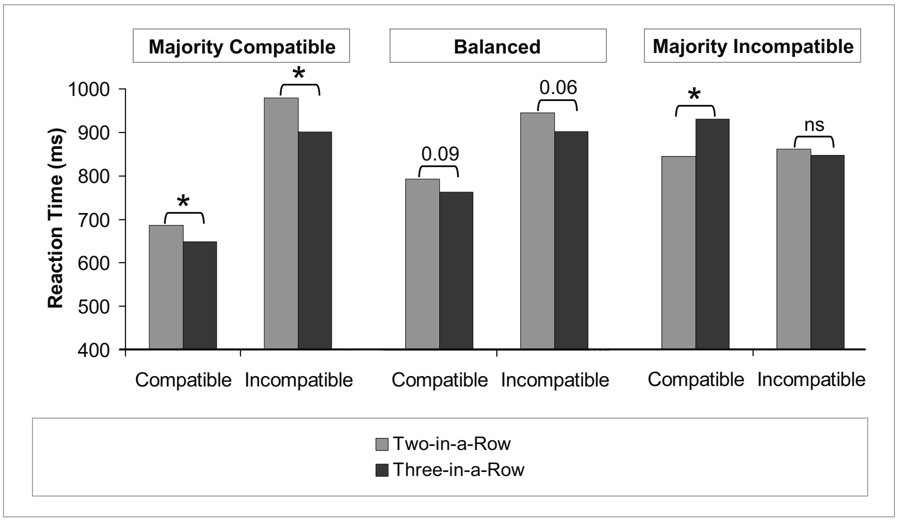

Figure 3.3: RTs for rule repetition trials in Experiment 3. The grey bar refers to first repetitions (same rule two times in a row), the black bar refers to second repetitions (same rule three times in a row).

'two in a row' trials because for the former participants can adapt to the rule. For instance, if a task sequence is not predictable in task switching paradigms, there is a gradual improvement in performance if the same task is repeated in a run of several trials (Monsell et al., 2003). Contrary, if compatible movement-effect associations were actively suppressed in the majority incompatible condition, compatible 'three in a row' trials should be slower than compatible 'two in a row' trials. In this case, participants should use frequency information to predict that 'three in a row' only seldom occurs and that it therefore might be useful to suppress compatible movement-effect associations after the first rule repetition.

Indeed, in the majority incompatible condition, compatible 'three in a row' trials were significantly *slower* than compatible 'two in a row' trials ($F(1, 20) = 6.0$, $MSE = 13001.7$; $p < 0.05$). On the contrary, in the majority compatible condition, incompatible 'three in a row' trials, which were infrequent as well, were significantly *faster* than 'two in a row' trials ($F(1, 19) = 4.8$, $MSE = 12699.9$; $p < 0.05$) as one should have expected from the results of task-switching paradigms. Only in this latter case, with rule repetition, participants seemed to adapt to the infrequent rule.

Admittedly, these results should not be given too much weight as in both conditions, there were on average only 8 correct compatible / incompatible 'three in a row' trials per participant. Still, the data are in line with the hypothesis of strategic suppression of compatible movement-effect associations based on frequency information in the majority incompatible condition. In all the remaining conditions, both, compatible and incompatible 'three in a row trials', occurred more frequently and – as it could have been expected – they were significantly, or at least marginally significantly faster than 'two in a row trials' (see Figure 3.3).

Error Rates. Error rates did not differ between conditions ($F(2, 58) < 1$). However, participants made more errors with incompatible than with compatible tools ($F(1, 58) = 30.1$, $MSE = 44.0$; $p < 0.001$), and this compatibility effect was modulated by condition ($F(2, 58) = 5.9$, $MSE = 44.0$; $p < 0.01$). It was highly significant in the majority compatible condition, but also in the balanced condition (ps < 0.001), however it was not significant in the majority incompatible condition.

Furthermore, participants made more errors in rule switch than in rule repetition trials ($F(1, 58) = 90.2$, $MSE = 39.2$; $p < 0.001$), and again, the modulation of this rule transition effect by movement transition was stronger for incompatible tools ($F(1, 58) = 12.5$, $MSE = 26.4$; $p = 0.001$). These effects, however, were not significantly modulated by condition.

In the post-hoc comparison of "two in a row" and "three in a row" trials, there were no significant effects (Fs < 1), apart from a tendency which mirrored RT data: For incompatible trials in the majority compatible condition, there were less errors in "three in a row" than in "two in a row" trials ($p = 0.09$).

3.1.3 Discussion

The central question of Experiment 3 was whether the manipulation of rule probability would reduce or even reverse the differences between compatible and incompatible movement-effect transformations when people use simple mechanical tools. Most notably, augmenting the probability of tools with an incompatible transformation rule (majority incompatible condition) indeed led to an elimination, though not reversal, of the compatibility effect. Participants were not significantly faster operating compatible as compared to incompatible tools any more. In this aspect, a difference between compatible and incompatible tools was thus eliminated by manipulating rule probability. Despite this result, compatible and incompatible tools still could not be set on equal footing. There was generally a stronger influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n for incompatible as compared to compatible tools in trial n. This difference between compatible and incompatible tools which was explained in terms of enhanced controlled processing for the latter did not significantly differ between the majority incompatible and the balanced condition.

On the contrary, the majority compatible and the balanced condition differed significantly in several aspects. In the majority compatible condition, the compatibility effect was significantly enhanced. Furthermore enhanced was the stronger influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n for incompatible as compared to compatible tools. It could be concluded, that in the majority compatible condition the amount of controlled processing required for movement selection in order to achieve a required effect with incompatible tools was extraordinary strong. In this condition, subjects were thus evidently responsive to changes in rule probability.

Finally, in the balanced condition (three compatible and three incompatible tools), all the results from Experiment 1 with two tools of each transformation rule were replicated.

Admittedly, the clear distinction between a minimal influence of the preceding movement-effect transformation for compatible tools and a pronounced influence of the preceding movement-effect transformation for incompatible tools could not be maintained regarding the results of the majority incompatible condition on a descriptive level (see Figure 3.2). Instead, there seemed to be an assimilation between compatible and incompatible tools in this condition. With much more power, such an assimilation might even have lead to a significant difference between the majority incompatible and the balanced condition with regard to sequential effects. The data of the post-hoc analysis, however, suggest that such an assimilation presumably did not rely on a (still incomplete) transfer of the default status from compatible to incompatible movement-effect associations. Instead, active and strategic suppression of compatible movement-effect associations based on frequency information seemed to play a crucial role. Although in the other conditions, movement selection was generally easier if a transformation rule was repeated three times in a row in contrast to two times, and although a similar finding has been reported for task-switching paradigms (Monsell et al., 2003), this did not apply to compatible tools in the majority incompatible condition. Instead, participants were even significantly slower for the second than for the first repetition of a compatible tool. It seems likely that participants used frequency information to predict that three-in-a-row trials were rather unlikely and therefore strategically suppressed compatible movement-effect associations after the first repetition.

In sum, the results again speak for a default status of movement-effect associations of high ideomotor compatibility on which people can rely for movement selection in the use of simple mechanical tools. Evidently, this default status cannot easily be reduced or even transferred to incompatible movement-effect associations by increasing the probability of incompatible movement-effect transformations.

3.2 Experiment 4

Experiment 4 was conducted in order to investigate whether the differences between compatible and incompatible transformation rules in the use of simple mechanical tools could be eliminated or even reversed by training. Obviously, some training sessions with incompatible tools cannot compensate for a whole life's training with movement-effect transformations of high ideomotor compatibility. Still we were interested in whether there would be any hints that incompatible movement-effect associations obtain a default status after training with incompatible tools. Of special relevance to this question were potential changes in the compatibility effect or the amount of controlled processing for movement selection that could be attributed to training.

For opaque transformation rules, training has already proved useful to establish transformed movement-effect associations as default associations (e.g., Kagerer et al., 1997). Training furthermore reduces compatibility effects in conventional S-R mapping paradigms. Incompatible S-R mappings experience greater improvement by training than compatible mappings and the spatial S-R compatibility effect is thus typically reduced, though not totally eliminated (e.g., Brebner, 1973; Dutta & Proctor, 1992; Fitts & Seeger, 1953; Proctor & Dutta, 1993; Wickens, 1984). The number of practice trials used in these studies goes up to 6300 (reported in Prinz, Aschersleben, Hommel, & Vogt, 1995), but after about 1000 practice trials, RTs hardly change any more (Dutta & Proctor, 1992).

Even a reversal after training has been reported to occur for the Simon effect. In a study by Proctor and Lu (1999), a Simon task was applied in which letter stimuli appeared randomly either on the same or on the opposite side of response. Participants had to respond to letter identity. They obtained the typical Simon effect with a benefit for trials in which stimulus and response location corresponded. However, the Simon effect was reversed when participants had practiced incompatible S-R mappings in a spatial compatibility task with circle stimuli for more than 1800 trials before they performed the Simon task. Presumably, incompatible S-R associations which had been learned during practice were automatically activated again in the Simon task. In a similar study, only 72 trials were used for training with incompatible S-R mappings (Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). Still, the Simon effect was eliminated in the subsequent test phase and 7 days after training, it was even reversed (Tagliabue et al., 2000; Tagliabue, Zorzi, & Umiltà, 2002).

In the present experiment, participants were particularly trained to achieve required effects with incompatible tools ('incompatible training condition'), or they received balanced training with both, incompatible and compatible tools ('balanced condition'). This balanced condition served to control for unspecific effects of tool-use training. Tools with the same transformation rule were presented blocked during training because with mixed presentation, participants would have practiced not only the rules, but also the transitions between compatible and incompatible tools in one condition more than in the other. Training took place in four sessions on four ot five consecutive days. In the fourth session, there was a test phase in which the original tool-switching paradigm was applied. Different tools as in the training phase were used to ensure that potential learning effects could not be attributed to perceptual factors. Compatible and incompatible tools appeared equally often in the test phase. We were especially interested whether training with incompatible tools would affect the compatibility effect and the amount of controlled processing needed to movement selection in order to achieve required effects with compatible or incompatible tools in the test phase. A measure of controlled processing was again provided by the analysis of sequential effects (see 2.1).

We predicted that if incompatible movement-effect transformations in tool use could be learned in a similar manner as incompatible S-R mappings (e.g., Proctor & Lu, 1999; Tagliabue et al., 2000), incompatible movement-effect associations should be activated automatically in the test phase in which both, the compatible and the incompatible transformation rule, were required. Training should then compensate for the advantage of high ideomotor compatibility. In this case a reduction or even elimination of the compatibility effect, as well as a reduction in the amount of controlled processing required for movement selection in order to operate incompatible tools should be expected for the incompatible as compared to the balanced training condition.

On the contrary, if training with incompatible movement-effect transformations could not compensate for the advantage of high ideomotor compatibility, no significant differences should be expected in the test phase after incompatible as compared to balanced training.

3.2.1 Method

Participants. Thirty-four right handed participants (23 women, 11 men, mean age 25.4 years) took part in the study. Seventeen participants were randomly assigned to the incompatible and seventeen to the balanced training condition.

Apparatus and Stimuli. The apparatus was the same as in Experiment 1. Stimuli were identical to those used in Experiment 3. In the training phase, scissors and ice tongs were used as compatible tools; the crocodile clamp and the hair grip were used as incompatible tools. In the test phase, tweezers and pliers (both compatible), as well as the clothespin and the clip (both incompatible) were used.

Procedure and Design. The experiment was run in four sessions on four or five consecutive days with one participant at a time. The sessions 1–3 and the first half of session 4 were considered as training phase. The second half of session 4 served as test phase.

At the beginning of the first session, participants were informed that they would have to handle tools, and they were asked to operate scissors, ice tongs, a crocodile clamp and a hair grip which were handed to them as real tools. Afterwards, pictures of these tools appeared on the computer screen and participants had to operate them via the response device used in Experiment 1. Again, a red or green ball signalled whether participants should close or open the distal grippers of the tool in order to squeeze or to release the ball. The proceeding of a trial was exactly the same as in Experiment 1. There were 16 initial trials during which participants should get acquainted with the task. For this short practice, tools were randomly mixed.

Subsequently, in the incompatible training condition, training sessions were organized as follows: Sessions 1–3 each consisted of four training blocks, Session 4 consisted of 2 training blocks, resulting in a total of 14 training blocks. Each block was made up of 10 miniblocks of 16 or 17 trials each.[1] In 9 of these miniblocks,

[1]The different number of trials in a miniblock was due to the restriction that each trial transition should appear equally often.

tools were incompatible, but there was one miniblock with 17 compatible tools at a random position. Summarized over all training sessions, there were thus 2044 trials with incompatible tools and 238 trials with compatible tools. That is, the ratio of incompatible to compatible was approximately 9 : 1.

Also in the balanced training condition, there were in total 14 training blocks. Again, each block consisted of 10 miniblocks of 16 or 17 trials each. Alternatingly, in 9 miniblocks tools were incompatible but there was one miniblock of 17 compatible tools at a random position, or 9 miniblocks were compatible, but there was one miniblock of 17 incompatible tools at a random position. Participants randomly started with a compatible or incompatible miniblock. Summarized over all training sessions, compatible and incompatible tools were thus represented with 1141 trials each. Consequently, the ratio of incompatible to compatible was 1 : 1. By means of this setup, the incompatible and the balanced training conditions were formally held as similar as possible.

Within a session, there was a short break of approximately 20 s after each block. In both conditions, participants had to switch between the crocodile clamp and the hair grip in miniblocks of incompatible tools, and between scissors and ice tongs in miniblocks of compatible tools. Switching from a miniblock of incompatible tools to a miniblock of compatible tools or vice versa was announced by the German word "Werkzeugwechsel" (tool switch) on the screen. Each possible transition between two compatible trials or two incompatible trials, respectively, occurred equally often within a block.

For the test phase in Session 4, the original tool-switching paradigm was applied. The procedure was exactly the same as described in Experiment 1. Each session (training or training + test) was completed in less than 60 minutes.

The design in the test phase was the same as in Experiment 1, but additionally, training condition (incompatible vs. balanced) was a between-participant-variable. Training effects in the training phase were analyzed as well. Within-participant variables were compatibility (compatible vs. incompatible tool) and session (sessions 1–4). Training condition (incompatible vs. balanced) was the between-participant variable.

3.2.2 Results

RT Data - Training Phase. We first analyzed data from the training phase. We therefore conducted a $2 \times 4 \times 2$ ANOVA with compatibility (compatible vs. incompatible transformation rule) and session (sessions 1–4) as within-participant variables and training condition (incompatible vs. balanced training) as between-

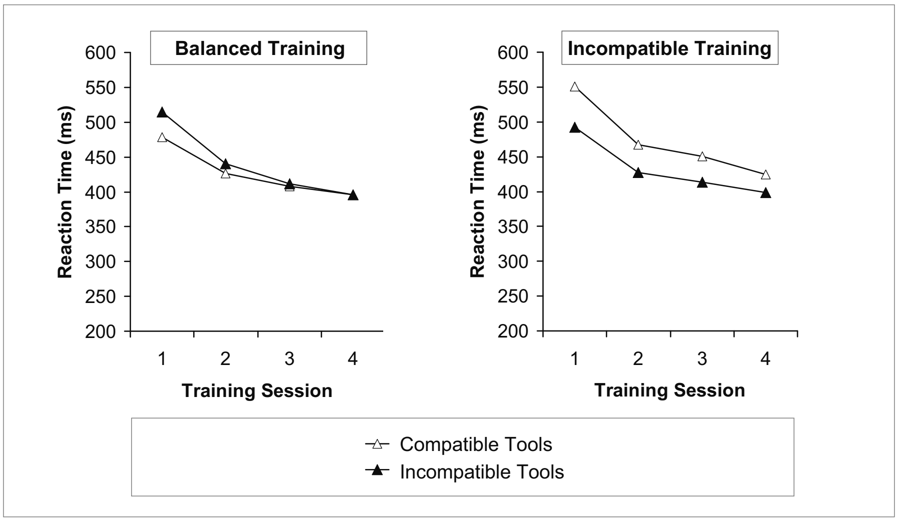

Figure 3.4: RTs data for compatible and incompatible trials over the four training session in Experiment 4 (balanced training condition on the left, incompatible training condition on the right side). With balanced training, the compatibility effect was eliminated by the forth session. With mostly incompatible training, it was reversed from the first session on.

participant variable (see Figure 3.4). The main effect of training condition was not significant ($F(1, 32) < 1$, MSE = 42125.9). Not surprisingly, there was a significant main effect of session ($F(3, 96) = 57.2$, $MSE = 2545.6$; $p < 0.001$). From the first to the forth training session, there was a significant decrease in RT from 509 to 404 ms. There was also a significant main effect of compatibility ($F(1, 32) = 6.2$, $MSE = 2049.3$; $p < 0.05$) which could further be described in terms of a highly significant interaction between compatibility and condition ($F(1, 32) = 24.1$, $MSE = 2049.3$; $p < 0.001$): In the balanced training condition, there was a small, but statistically significant advantage of 13 ms for operating compatible as compared to incompatible tools ($p < 0.05$). In the incompatible training condition, the compatibility effect was reversed and incompatible tools were operated 41 ms faster than compatible tools ($p < 0.001$). Furthermore, these positive and reverse compatibility effects were differentially influenced by practice ($F(3, 96) = 6.4$, $MSE = 567.6$; $p = 0.001$ for the three-way interaction between compatibility, session and training condition). In the balanced training condition, participants started with a compatibility effect of 36 ms in the first training session, and this was step by step eliminated until it reached zero in the forth training sessions. In the incompatible training condition, already in the first training session, the compatibility effect was reversed (59 ms) and it subsequently did not significantly change in the course of the four sessions ($F < 1$), even though overall RT became faster.

Error Rates – Training Phase. As in RT data, the main effect of training condition was not significant ($F < 1$), but there was a significant overall-improvement over the four sessions ($F(3, 96) = 4.0$, $MSE = 4.5$; $p = 0.01$). Furthermore, there was a main effect of compatibility ($F(3, 96) = 4.4$, $MSE = 3.3$; $p < 0.05$), and also a significant interaction between compatibility and condition ($F(1, 32) = 4.2$, $MSE = 3.3$; $p < 0.05$). In the balanced training condition, there was a compatibility effect and training did not eliminate this effect. In the incompatible training condition, the compatibility effect was eliminated in all training sessions.

RT Data – Test Phase. There was a compatibility effect ($F(1, 32) = 45.3$, $MSE = 34712.0$; $p < 0.001$), a rule repetition benefit ($F(1, 32) = 42.4$, $MSE = 22013.1$; $p < 0.001$), as well as a stronger modulation of this rule repetition benefit by movement transition for incompatible as compared to compatible tools ($F(1, 32) = 5.7$, $MSE = 6542.7$; $p < 0.05$) (see Figure 3.5). Neither the main effect of training condition, nor any interaction involving this variable was significant. We also analyzed only the first block of the test phase separately, but still the condition variable exerted no significant influence.

Error Rates – Test Phase. Error rates did not counteract RT data, but only the rule repetition benefit reached statistical significance ($F(1, 32) = 63.2$, $MSE = 93.6$; $p < 0.001$).

3.2.3 Discussion

Training itself was very effective. In the balanced training condition, the compatibility effect was eliminated. In the incompatible training condition, it was even reversed. These training effects, however, did not transfer to the test phase during which participants had to perform the tool-switching task with two new compatible and two new incompatible tools in mixed presentation. In this test phase, the compatibility effect recurred. Furthermore, there was a stronger influence of the preceding movement-effect transformation on movement selection in the current trial for incompatible as compared to compatible tools. As in the preceding experiments, we explained this effect by enhanced controlled processing for incompatible as compared to compatible tools. For these results, it did

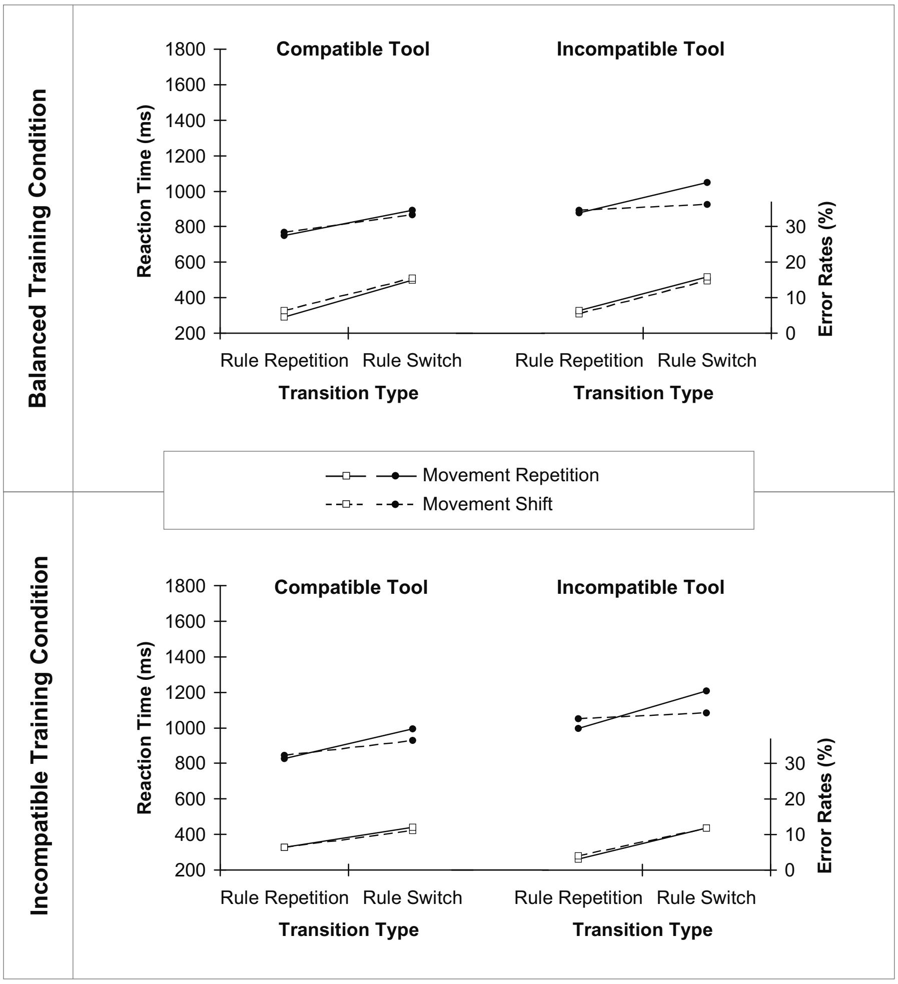

Figure 3.5: Mean RTs (filled circles) and error rates (open squares) after balanced training (top panel) and after incompatible training (bottom panel) in Experiment 4. Data are displayed as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts).

not make any difference whether participants had been trained in the incompatible or in the balanced condition. Even in the first block of the test phase, there was no significant influence of training condition.

At this point, it seems interesting to compare the data from the test phase with the data from Experiment 1 in which the same paradigm was used, but without preceding training. In the test phase of Experiment 4, participants were on average 251 ms faster than in Experiment 1 and the compatibility effect was reduced (152 ms versus 319 ms). Additionally, the influence of the preceding movement-effect transformation on movement selection for incompatible tools was not as marked in Experiment 4 than in Experiment 1. That is, there was a general training effect which was independent of training condition. As revealed by the reduced compatibility effect, this training effect was stronger for incompatible as compared to compatible tools – an observation which is well known from training with compatible and incompatible S-R mappings (e.g., Dutta & Proctor, 1992). Evidently, for incompatible, but not for compatible tools, there was ample scope für improvement by training. What seems important, however, is that the compatibility effect, though not as large as in Experiment 1, was still highly significant after training – despite its reversal or at least elimination during training. Furthermore, learning of incompatible movement-effect transformations was obviously independent of the default status of compatible movement-effect associations for which the very same results was obtained after balanced training, after incompatible training, as well as in Experiment 1. In other words, training with incompatible movement-effect transformations did not overwrite or replace the default status of movement-effect associations of high ideomotor compatibility.

Training in itself was even more successful than expected. In the incompatible training condition, the compatibility effect was already reversed during the first training session, and in the balanced condition, it was eliminated in the course of training, although the amount of training for compatible and incompatible tools was the same. These results suggest that people are very well able to adapt to an incompatible transformation rule in the use of simple mechanical tools if they do not have to switch between compatible and incompatible movement-effect transformations. Overall, with the blocked presentation, the relevance of the tool-associated transformation rule was surprisingly low anyway. RTs were quite low, and even in the first block of the balanced condition, the compatibility effect was rather small (36 ms) as compared to the one observed later in the test phase with mixed presentation (152 ms). The data thus suggest that movement selection processes differed between training and test. Within a block during training, participants could adopt one transformation rule as the standard and tool identification was thus not necessary any more. During the test phase with mixed presentation, each tool first had to be assigned to the compatible or incompatible tool category. Only then, the movement to achieve a required effect could be selected. In this case, the validity of compatible movement-effect transformations in some trials obviously resulted in a default status for compatible movement-effect associations.

As this work was primarily concerned with movement selection when people have to switch between tool-associated transformation rules, the question of what exactly might have facilitated movement selection in the training phase will not be discussed in greater depth at this point (for further considerations, however, see the General Discussion, section 6.5). Still, a possible caveat is linked to the fact that during the training phase, the transformation rule only switched between miniblocks. It might be suspected that participants during training commuted the tool-use task into a simple S-R mapping task in which they responded with an opening or closing finger movement to the color of the effect cue, but ignored the tool, as well as the effect picture (e.g., "in this block, in response to a red ball, I have to open my fingers; in response to a green ball, I have to close my fingers"). In this case, they would not have been trained to use tools with incompatible movement-effect transformations, but simply to practice a certain S-R mapping. This strategy cannot totally be excluded, however is very unlikely for the following reasons: Firstly, such a strategy could have been used in the incompatible as well as in the balanced training condition. However, whereas in the incompatible training condition, the compatibility effect already reversed during the first session, in the balanced condition, at least descriptively, it persisted up to the third session. Also in the error rates, it was present and even not eliminated by training. In a simple color-based S-R mapping task, there is no reason for such a compatibility effect in the balanced condition. Secondly, if indeed a color-based S-R mapping had been used during training, one could have expected a detrimental influence of this mapping in the test phase where the same colored effect cues were used, but the tools could not be ignored to select the correct movement. Yet, as already stated above, participants were significantly faster in the tool-switching paradigm in the test phase of Experiment 3 than in the identical tool-switching paradigm of Experiment 1 ($F(1, 48) = 10.9$, $MSE = 502353.6$; $p < 0.01$).

So, to summarize, training had familiarized participants with the tool-use task per se and especially with incompatible movement-effect transformations, but had not established incompatible movement-effect associations as default associations. This was true although these incompatible transformations between movements and effects had been practiced ten times more often than compatible ones in the incompatible training condition.

3.3 Discussion of Experiment 3 and 4

All in all, Experiment 3 and 4 provided evidence that neither training nor the manipulation of probability were sufficient to eliminate or even reverse the differences between compatible and incompatible transformation rules when participants had to switch between tools. Firstly, in Experiment 3, the compatibility effect was eliminated when the probability of an incompatible tool was two times higher than the probability of a compatible tool. Still, in terms of controlled processing for movement selection, there was no evidence that incompatible movement-effect associations gained the default status, and not even that compatible movement-effect associations lost their default status. Secondly, in Experiment 4, the compatibility effect was reversed after about 2000 trials of training with incompatible tools. Still the costs for operating incompatible tools in terms of higher RTs and error rates as well as enhanced controlled processing for operating these tools recurred when participants subsequently had to switch between compatible and incompatible tools.

Stable differences between compatible and incompatible tools were restricted to situations of switching. It seems that when in some trials the operating movement and the associated effect are of high ideomotor compatibility, the compatible operating movement is automatically activated upon effect anticipation as the default movement in all trials. It then has to be inhibited in trials in which an incompatible movement-effect transformation is required – unless it is not already strategically suppressed in advance as it seemed to be the case in Experiment 3. Admittedly, these assumptions about movement inhibition in incompatible trials are but speculative yet. They were taken up again in Experiment 7.

The ease with which incompatible movement-effect transformations are realized in the steering wheel task (e.g., Proctor et al., 2004), or for opaque movement reversal (Cunningham, 1989) are thus not predictive for situations of switching between compatible and incompatible simple mechanical tools. Furthermore, some of the current findings are in contradiction to the results of conventional

S-R compatibility paradigms, but this issue will be postponed to the General Discussion (see 6.5).

To summarize, the findings of Experiment 3 and 4 indicate that neither the manipulation of rule probability nor training can seriously rival the default status of compatible movemente-effect associations when people switch between simple mechanical tools. This extraordinary strength of compatible movement-effect associstions seems primarily due to high ideomotor compatibility and it cannot easily be overridden, and, least of all, it can be transferred to incompatible movement-effect associations.

An obvious question, however, is whether these results are specific for the use of simple mechanical tools. As we already stated before, high ideomotor compatibility between movements and their associated effects is very common in our everyday actions and happens, for instance, when we are acting with our hands only. The default status of compatible movement-effect associations in the tool-switching paradigm could thus be codetermined by the fact that compatible tools obviously extended the human fingers. However, also with conventional S-R compatibility paradigms it has been found that the impact of the specific S-R association in trial $n-1$ exerts a weaker influence on trial n if the rule for responding in trial n is the compatible one (Stoffels, 1996). More generally, it has been proposed that all the effects which are caused by external factors of the task environment decrease with increasing compatibility between actions and external events (Erlhagen & Schöner, 2002). Consequently, if high ideomotor compatibility was the only reason for the default status of compatible movement-effect associations in the tool-switching paradigm, evidence for this default status should also be obtained if the transformation was not coupled to a concrete tool body, but cued by some abstract rule cue. In contrast, if the default status of compatible movement-effect associations was codetermined by the perception of the tool which evidently extends the bodily effectors, such a default status should not be obvious for compatible movement-effect transformations which are cued by an abstract rule cue.

Similarly, until now we cannot say whether tool perception played a particular role for movement selection in order to achieve a required effect with incompatible tools. Accordingly, the aim of the two subsequent experiments was to compare tool switching with switching between compatible and incompatible transformation rules that were cued by abstract rule cues or written tool names.

Chapter 4

The Special Status of Afforded Rules in Tool Use

The Experiments 1–4 unanimously confirmed the default status of compatible movement-effect associations in the use of simple mechanical tools. Additionally, they showed that controlled processing is required for operating tools with an incompatible transformation between movements and effects – at least when people have to switch between compatible and incompatible tools. Part of the results obtained with the current paradigm can presumably be explained by high ideomotor (in-)compatibility between operating movements and their associated effects. Still, the transformation rules used in these experiments hold a second characteristic feature: They do not have to be defined explicitly, but they are evidently required by the tool's structure. That is, a simple mechanical tool is a transparent rule cue for a compatible or incompatible transformation rule.

In several studies, it has already been shown that tools directly evoke operating movements which are afforded by their structure (e.g., Tucker & Ellis, 1998). This activation is unspecific in that it concerns, for instance, the kind of grasp, but not the specific operating movement which will lead to a desired effect. For instance, the tools in our study each afforded the same two operating movements (opening or closing the handles). Automatic activation of these operating movements was thus not sufficient to select the specific movement to achieve a specific effect in a given trial.

The specific operating movement to achieve a desired effect is determined by the tool-associated transformation rule. Notably, however, also this transformation rule is evidently afforded by a mechanical tool's structure. It can be hypothesized that the acting person simply anticipates the desired effect along with imagining the respective tool movement which will lead to this effect and therefrom derives the adequate operating movement. If this was true, transformation rule application in tool use should differ from the application of explicit transformation rules which are cued by abstract rule cues. It should be an online process which is based on a lifelong experience with mechanical devices as well as on visual information that is directly available. Less controlled processing should in this case be necessary for transformation rule application in tool use than for the application of an explicit mapping rule which has to be retrieved from long-term memory. This hypothesis was tested in the Experiments 5 and 6.

In Experiment 5, we contrasted tool pictures and abstract rule cues in their capacity to elicit adequate operating movements to achieve required effects. In Experiment 6, tool pictures were contrasted with written tool names. In both cases we expected less controlled processing for movement selection in response to tool pictures. As explained in section 2.1 and as applied in the preceding experiments, the influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was used to indicate the amount of controlled processing necessary for movement selection.

4.1 Experiment 5

In Experiment 5, we compared the tool-switching condition with a rule-switching condition. The rule-switching condition could be characterized as follows: Mechanical tools were replaced by abstract rule cues which indicated whether to apply the compatible or the incompatible transformation rule. The assignment between rules and cues was arbitrary and thus had to be defined explicitly. Consequently, movement selection had to occur according to an explicit transformation rule. As there were two possible cues for each rule, we could dissociate a potential rule repetition benefit from a cue repetition benefit. The main question was whether sequential effects would interact with the condition factor and thus reveal reduced controlled processing for the tool-switching in comparison to the rule-switching condition.

4.1.1 Method

Participants. Forty right-handed participants (24 women and 16 men) with a mean age of 24.8 years participated. Twenty of them were randomly assigned to the tool-switching condition or to the rule-switching condition respectively.

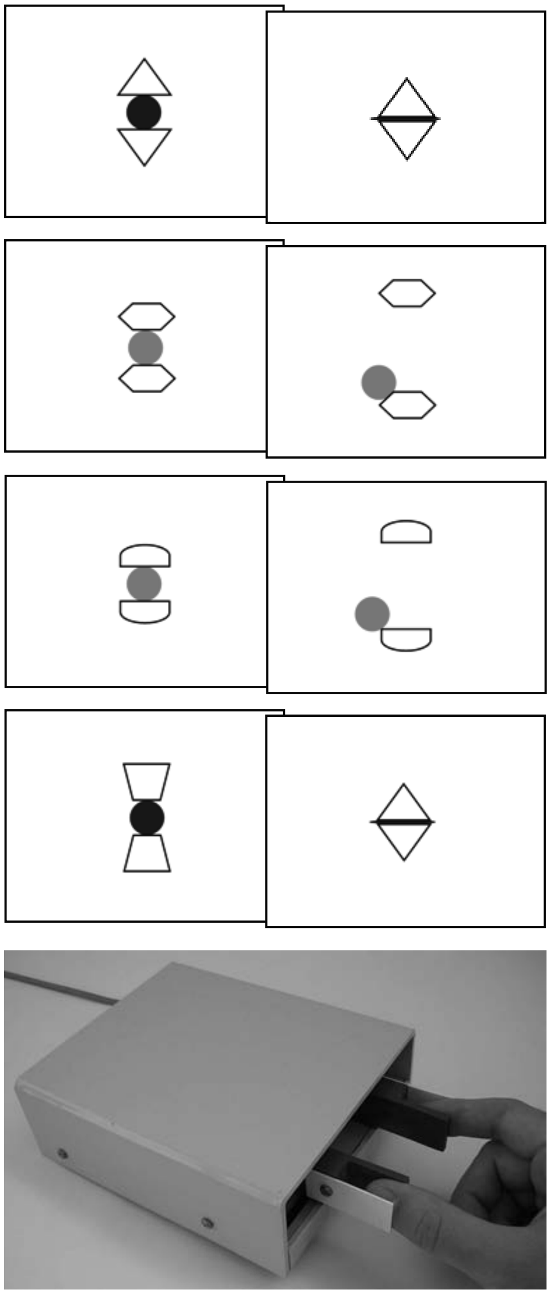

Figure 4.1: Stimulus material and response device in the rule switching condition of Experiment 5. The procedure was the same as in Experiment 1, only that tools were replaced by geometric symbols. For triangles and hexagons, the transformation rule was compatible, for trapezoids and rounded rectangles, it was incompatible (or vice versa).

Apparatus and Stimuli. The apparatus was the same as in Experiment 1. For the tool-switching condition, stimuli were identical to those used in Experiment 1. In the rule-switching condition instead of the tool stimuli, there were four geometric stimuli (a pair of triangles, a pair of hexagons, a pair of rounded rectangles, and a pair of trapezoids) with their contours drawn in black on a white background. In each trial, one pair appeared on the screen, signalling the valid transformation rule. Each pair was aligned vertically as if its two elements were mirrored at a horizontal line. Elements subtended a visual angle of approximately 3.5° in height and 2.5° in length; between the two elements, there was a gap subtending a visual angle of 2.1° filled by the green or red ball. If the correct movement was executed in the response device, an effect picture was presented: Depending on the current trial, the gap between the two symbols was extended and thus the ball was released, or it was reduced and thus the ball was squeezed (see Figure 4.1).

Procedure and Design. The procedure of tool switching was the same as in Experiment 1. The procedure of rule switching was the same as in Experiment 1 as well, only that the instructions were adapted to the condition: Participants were instructed to squeeze or to release the ball that was caught in the pair of geometric symbols. They were informed that this could be achieved by opening or closing their fingers in the response device. For half of the participants, triangles and hexagons signaled a compatible transformation rule (e.g., closing the geometric symbols and thus squeezing the ball = closing the fingers in the response device); rounded rectangles and trapezoids signaled an incompatible transformation rule (e.g., closing the geometric symbols and thus squeezing the ball = opening the fingers in the response device). For the other half this mapping was reversed. Furthermore, the design was the same as in Experiment 1, only that condition (tool switching vs. rule switching) was an additional between-participant variable.

4.1.2 Results

Tool and rule repetition trials were not considered in the analyses. All error trials and all trials following an error (15.8 %) were excluded from RT analysis. For the analysis of error rates, all trials following an error (8.5 %) were eliminated.

RT Data. We conducted a $2 \times 2 \times 2 \times 2$ ANOVA with compatibility, rule transition, and movement transition as within-participant variables and condition (tool switching vs. rule switching) as between-participant variable (see Figure 4.2).

The main effect of condition was not significant ($F(1,38) < 1$, $MSE = 565988.7$). However, there were main effects of compatibility and of rule transition: Compatible rule application was 278 ms faster than incompatible rule application ($F(1,38) = 101.9$, $MSE = 60708.6$; $p < 0.001$); rule repetition trials were 77 ms faster than rule switch trials ($F(1,38) = 39.1$, $MSE = 12140.0$; $p < 0.001$).

As in Experiment 1, the effect of rule transition was modulated by movement transition, and this modulation was stronger if the tool / rule cue in trial n signalled an incompatible as compared to a compatible transformation rule $F(1,38) = 30.6$, $MSE = 14170.9$; $p < 0.001$ for the three-way interaction between compatibility, rule transition and movement transition).

Most notably, however, the modulation of the rule transition effect by movement transition also depended on the condition factor. In the rule-switching condition, the interaction between rule transition and movement transition was generally much stronger than in the tool-switching condition ($F(1,38) = 15.8$, $MSE = 24506.1$; $p < 0.001$ for the three-way interaction between condition, rule transition and movement transition).

In detail, the results were as follows: If in trial n a *tool* signaled the *compatible* transformation rule, there was a rule repetition benefit for both, movement repetition as well as movement shift trials (ps < 0.05), with the interaction between rule transition and movement transition failing to reach significance ($F(1,19) = 3.2$, $MSE = 6537.3$). If in trial n, an abstract *rule cue* signalled the *compatible* transformation rule, the rule repetition benefit was significant only in movement repetition trials ($p < 0.001$); this resulted in a significant interaction between rule transition and movement transition ($F(1,19) = 25.4$, $MSE = 7262.4$; $p < 0.001$). Similarly, if in trial n, a *tool* signaled the *incompatible* transformation rule, there was a significant rule repetition benefit only in movement repetition trials ($p < 0.001$), and the interaction between rule transition and movement transition was significant ($F(1,19) = 12.4$, $MSE = 17495.7$; $p < 0.01$). Finally, the strongest modulation of the rule repetition benefit by movement repetition was manifest if an abstract *rule cue* signaled the *incompatible* transformation rule. In this case, there was a large rule repetition benefit for movement repetition trials (p $<$ 0.001), there were considerable rule repetition costs in movement shift trials ($p < 0.001$) and the interaction between

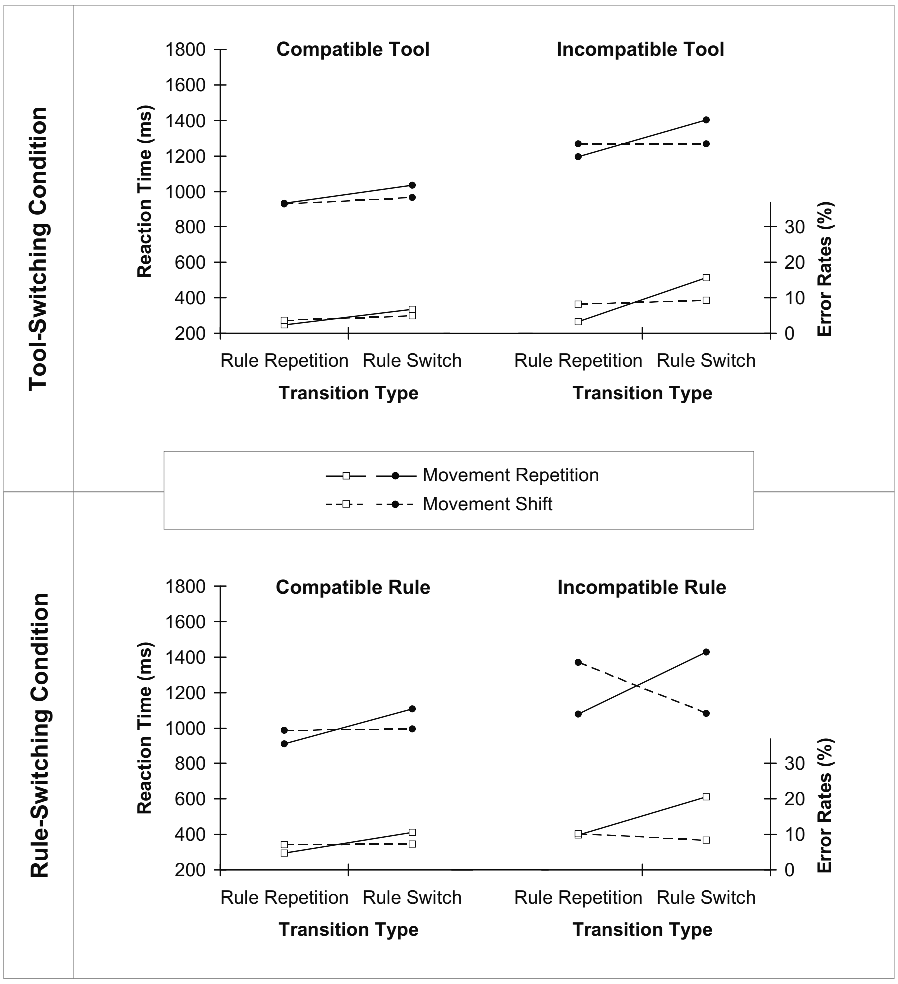

Figure 4.2: Mean RTs (filled circles) and error rates (open squares) for tool switching (top panel) and rule switching (bottom panel) in Experiment 5. Data are displayed as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts).

rule transition and movement transition was highly significant ($F(1,19) = 44.1$, $MSE = 46058.5$; $p < 0.001$).

Finally, there was a significant four-way interaction ($F(1,38) = 8.0$, $MSE = 14170.9$; $p < 0.01$). For both, the compatible and the incompatible transformation rule, the condition factor had a significant influence on the modulation of the rule repetition benefit by movement repetition. However, this effect of condition was more pronounced for the incompatible ($F(1,38) = 14.5$, $MSE = 31777.1$; $p = 0.001$) than for the compatible rule ($F(1,38) = 5.9$, $MSE = 6899.9$; $p < 0.05$).

Error Rates. Participants made significantly more errors in the rule-switching than in the tool-switching condition ($F(1,38) = 4.2$, $MSE = 181.9$; $p < 0.05$). There were furthermore more errors for incompatible than for compatible transformation rule application ($F(1,38) = 23.9$, $MSE = 75.4$; $p < 0.001$) and also in rule switch trials as compared to rule repetition trials ($F(1,38) = 63.2$, $MSE = 23.0$; $p < 0.001$). The three-way interaction between compatibility, rule transition, and movement transition was significant, too ($F(1,38) = 5.2$, $MSE = 53.5$; $p < 0.05$): As in RT data, the dependence of the rule repetition benefit on movement repetition was stronger for incompatible ($F(1,38) = 21.9$, $MSE = 64.0$; $p < 0.001$) than for compatible rule application ($F(1,38) = 10.1$, $MSE = 18.9$; $p < 0.01$). There was however no effect of condition on the interaction between rule transition and movement transition ($F < 1$, $MSE = 53.5$).

4.1.3 Discussion

The most relevant finding in Experiment 5 was a much weaker influence of the movement-effect transformation from trial $n-1$ on movement selection in trial n for the tool-switching as compared to the rule-switching condition. This finding implicates that controlled processing for movement selection was reduced for tool switching as compared to rule switching.

In all remaining aspects, the data of both conditions were very much alike. In both conditions, there was a compatibility effect and a rule repetition benefit. Furthermore, as revealed by the influence of the movement-effect transformation in trial $n-1$, controlled processing was reduced for movement selection according to a compatible as compared to an incompatible transformation rule in both conditions.

Interestingly, also the influence of condition on controlled processing seemed to be larger for the incompatible than for the compatible transformation rule.

Table 4.1: Affordances and high ideomotor compatibility of compatible and incompatible tools and abstract rule cues

	Compatible	**Incompatible**
Mechanical Tool	High Ideomotor Compatibility Afforded	— Afforded
Abstract Rule Cue	High Ideomotor Compatibility —	— —

Though we had not predicted such a differential influence, it still seems to agree with the preceding statements. In compatible rule-switching trials, a controlled step of rule application should have been necessary because there was no tool that apparently extended the fingers. Still, movement-effect transformations were of high ideomotor compatibility. In terms of the common coding approach, they referred to identical codes in the cognitive system. One could assume that the movement that was required by the compatible transformation rule was thus already automatically activated by effect anticipation before it was selected in a controlled process.

For the incompatible transformation rule in the rule-switching condition, on the other hand, neither the rule cue on its own, nor automatic activation provided a hint which response to choose. Presumbably, controlled processing for movement selection thus had to be extraordinarily strong. That is, two factors seemed to reduce the need for controlled processing: The first factor was high ideomotor compatibility of compatible movement-effect transformations. The second factor was the obvious requirement to apply a specific transformation rule as it was afforded by the mechanical tools. Both factors applied to operating a tool with a compatible transformation rule. Only one of them was relevant for operating a tool with an incompatible transformation rule, or for movement selection in response to an abstract rule cue which signalled the compatible transformation rule, respectively. Neither of them applied to movement selection in response to an abstract rule cue which signalled the incompatible transformation rule. These conclusions are summarized in Table 4.1.

What is important, only in the error rates, but not in RT data, there was a main effect of condition. That is, participants were more likely to confuse abstract geometric stimuli than tool stimuli; however, in trials without such a mistake, switching between tool-associated transformation rules or between explicitly defined transformation rules were generally tasks of equal difficulty.

To summarize, Experiment 5 revealed effects of reduced controlled processing when transformation rules for movement selection were afforded by tools as compared to cued by abstract rule cues. It was argued that tool stimuli directly evoked the required operating movement (compatible transformation rule), or at least directly prompted the user to imagine the tool movement in order to select the required operating movement (incompatible transformation rule). These are processes that should be promoted by or even depend on visually perceiving the tool that has to be operated. Consequently, the effects we obtained with tool pictures should not be evoked by written tool names. We tested this assumption in Experiment 6.

4.2 Experiment 6

In Experiment 6, the tool-switching condition in which tool pictures were presented was contrasted with a condition in which written tool names appeared on the screen. It has already been reported that only the perception of real tools or tool pictures, but not written tool names or written tool-use actions directly activate tool-associated operating movements without additional processing necessary (Adamo & Ferber, 2008; Riddoch, Humphreys, Heslop, & Castermans, 2002). In the present Experiment, we wanted to test whether pictures of simple mechanical tools, but not tool names, additionally have the capacity to directly prompt the specific movement to attain a specific effect.

Participants had to operate tools that was displayed on the screen as words or as pictures. If tool pictures evidently afforded a certain transformation rule, the analysis of sequential effects in the picture condition should reveal reduced controlled processing for movement selection in comparison to the word condition.

4.2.1 Method

Participants. Thirty-two right-handed participants (mean age of 25.1 years; 15 women, 17 men) participated. Sixteen participants were randomly assigned to the picture condition and sixteen to the word condition.

Apparatus and Stimuli. The apparatus was the same as described in Experiment 1. Furthermore, stimuli in the picture condition were identical to those

Figure 4.3: Stimulus material and response device in the word condition of Experiment 6. The procedure was the same as in Experiment 1, only that tools were replaced by written tool names.

used in Experiment 1. In the word condition, verbal stimuli were used instead of tool pictures: In each trial, one of the four German words, “Kneifzange” (pliers), “Pinzette” (tweezers), “Wäscheklammer” (clothespin), or “Klemme” (clip), appeared on the screen. Words were written in black font on a white background, font size subtended a visual angle of 1°. At a distance of 2.6° left to the tool word, a red or green ball was placed in the gap between two black-bordered horizontal bars. This pair of bars subtended a visual angle of 2.5° in height and length, with 2.1° for the gap between them. Immediately following the correct operating movement executed in the response device, the effect picture appeared on the screen. Either the two bars moved apart and the ball was released, or the bars moved together and the ball was squeezed (see Figure 4.3).

Procedure and Design. The procedure in the picture condition mirrored Experiment 1. In the word condition, the procedure was similar. Participants first practiced with the real tools and were then instructed that in each trial, one of the four tool names would be presented on the screen. They should then squeeze or release the ball between the two bars and should imagine that these bars constituted the distal grippers of the tool that was specified aside. They were instructed to respond by opening or closing their fingers in the response device as if they were directly handling this tool at its grab handles. That is, for tweezers and pliers, the finger movement had to follow the direction of the required effect (e.g., releasing the ball in the distal grippers = opening the fingers). For the clothespin and the clip, the finger movement had to be antagonistic to the required effect movement (e.g., releasing the ball in the distal grippers = closing the fingers).

The design was the same as in Experiment 1, but additionally, condition (pictures vs. words) was a between-participant variable.

4.2.2 Results

Tool and word repetition trials were not considered in the analysis. All error trials and the trials following an error (16.8 %) were excluded from RT analysis, all trials following an error (8.9 %) were excluded from the analysis of error data.

RT Data. A $2 \times 2 \times 2 \times 2$ ANOVA was conducted with compatibility, rule transition and movement transition as within-participant variables and condition (pictures vs. words) as between-participant variable (see Figure 4.4).

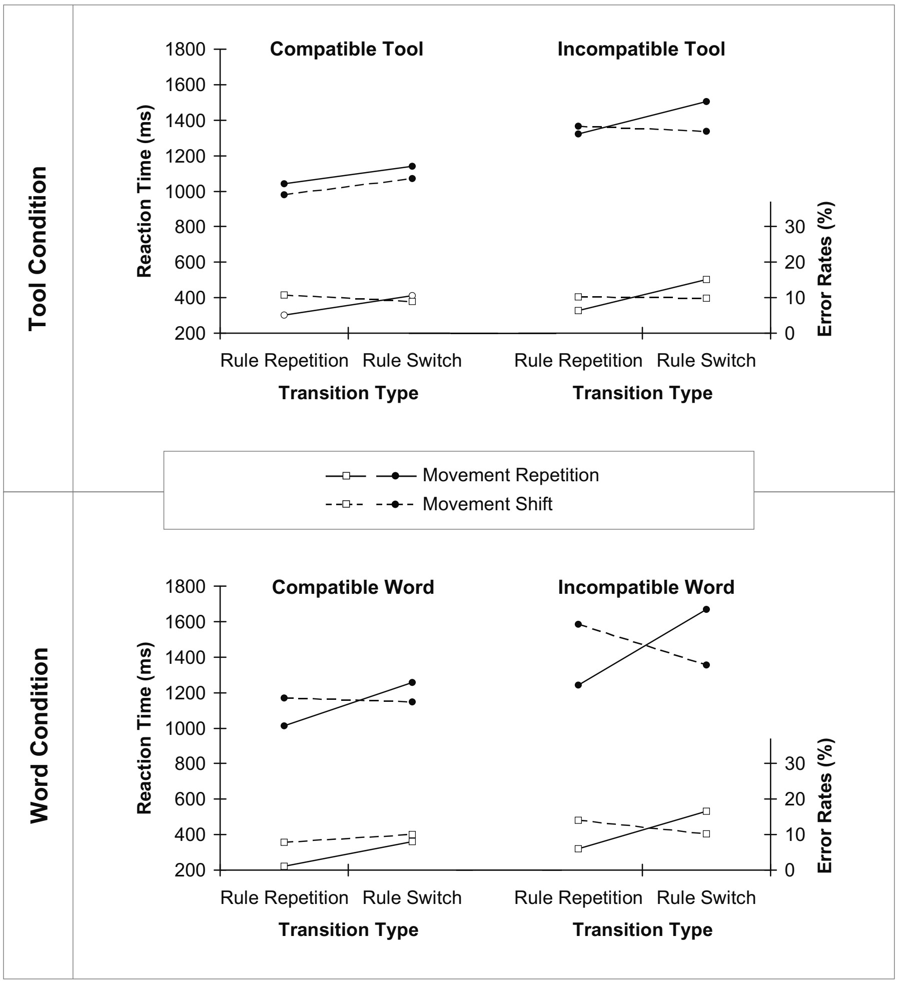

Figure 4.4: Mean RTs (filled circles) and error rates (open squares) for the tool condition (top panel) and the word condition (bottom panel) in Experiment 6. Data are displayed as a function of rule transition (rule repetition vs. switch) and movement transition (continuous lines indicate movement repetitions, dashed lines movement shifts).

The main effect of condition was not significant ($F(1,30) < 1$, $MSE = 961013.6$). There was a significant main effect of compatibility ($F(1,30) = 36.0$, $MSE = 182592.0$; $p < 0.001$): Participants were 303 ms faster if the tool picture / word signalled a compatible as compared to an incompatible transformation rule. Furthermore, the main effect of rule transition reached significance ($F(1,30) = 12.8$, $MSE = 45111.5$; $p = 0.001$): Participants were 93 ms faster for rule repetitions than for rule switches.

Again, this rule repetition benefit was modulated by movement repetition. The modulation was particularly strong if the tool picture / word in trial n signalled an incompatible transformation rule, but weaker if the transformation rule was compatible ($F(1,30) = 36.5$, $MSE = 9844.4$; $p < 0.001$ for the three-way interaction between compatibility, rule transition and movement transition).

Most notably, also the condition variable had a significant influence on the modulation of the rule repetition benefit by movement repetition: In the word condition, this modulation was considerably stronger than in the picture condition ($F(1,30) = 10.6$, $MSE = 45865.7$; $p < 0.01$ for the three-way interaction between condition, rule transition and movement transition).

These were the results in detail: If a tool *picture* in trial n incorporated the *compatible* transformation rule, the rule repetition benefit was significant for both, movement repetition as well as movement shift trials ($p < 0.05$); thus the interaction between rule transition and movement transition was not significant ($F(1,15) < 1$, $MSE = 9633.8$). If a tool *word* in trial n signaled the *compatible* transformation rule, there was only a significant rule repetition benefit for movement repetition trials ($p < 0.05$), leading to a significant interaction between rule transition and movement transition ($F(1,15) = 9.0$, $MSE = 30865.0$; $p < 0.01$). Similarly, if a tool *picture* in trial n incorporated the *incompatible* transformation rule, the rule repetition benefit was significant only in movement repetition trials ($p < 0.05$), and therefore the interaction between rule transition and movement transition was significant ($F(1,15) = 12.4$, $MSE = 14809.0$; $p < 0.01$). The modulation of the rule repetition benefit by movement repetition was strongest, if a tool *word* in trial n signaled the incompatible transformation rule: In this case, the rule repetition benefit was strong in movement repetition trials ($p < 0.001$) and there were rule repetition costs in movement shift trials ($p < 0.05$), resulting in a highly significant interaction between rule transition and movement transition ($F(1,15) = 30.8$, $MSE = 56112.4$; $p < 0.001$).

In addition, the four-way interaction just failed to reach significance ($F(1,30)$ $= 3.6$, $MSE = 9844.4$; $p = 0.07$). There was a tendency for a stronger influence of the condition variable on the modulation of the rule repetition effect by movement repetition for the incompatible in comparison to the compatible transformation rule.

Error Rates. There was no significant main effect of condition ($F(1,30) < 1$, $MSE = 217.1$). The main effect of compatibility was significant with less errors for the compatible than for the incompatible transformation rule ($F(1,30) = 25.2$, $MSE = 26.5$; $p < 0.001$). Also the main effect of rule transition was significant with less errors for rule repetition than for rule switch trials ($F(1,30) = 9.3$, $MSE = 83.9$; $p < 0.01$). Additionally the three-way interaction between compatibility, rule transition and movement transition was significant, mirroring the effects in RT data ($F(1,30) = 4.2$, $MSE = 33.0$; $p < 0.05$). The modulation of the rule repetition effect by movement repetition was, however, not significantly influenced by the condition variable ($F(1,30) < 1$, $MSE = 33.0$).

4.2.3 Discussion

The critical outcome of Experiment 6 was a weaker influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n for the picture condition as compared to the word condition. We interpreted this finding in terms of reduced controlled processing for movement selection in the picture as compared to the word condition.

The compatibility effect and the rule repetition benefit were observed as in the preceding experiments. Furthermore, the influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n again revealed generally reduced controlled processing for movement selection according to a compatible as compared to an incompatible transformation rule in trial n. Overall, the picture condition and the word condition were tasks of equal difficulty. Neither in RT data, nor in the error rates, there was a main effect of condition.

In all crucial aspects, the results obtained with written tool names in Experiment 6 thus strongly resembled those obtained with abstract rule cues in Experiment 5. Therefore, it is likely that in the word condition participants used the strategy to retrieve an explicit compatible or incompatible transformation rule for movement selection. In this case, the tool words should have served as explicit rule cues. These results go well with the notion that tool pictures, but not explicit rule cues or tool words, afford a certain transformation rule and therefore directly prompt the adequate operating movement to achieve a required effect among movement alternatives.

4.3 Discussion of Experiment 5 and 6

The results of Experiment 5 and 6 were very much alike. Controlled processing, as indicated by the influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n, was weaker for tool pictures as compared to explicit rule cues or written tool names. These results strongly support the notion that for tool pictures, movement selection in order to achieve the required effect was an on-line process which relied on visual information and experience with mechanical devices: The transformation between a movement and an effect was obviously afforded by the tool picture. Therefore, explicit rule application in order to select the correct operating movement did not seem to be necessary.

Notably, the selection of the adequate operating movement required least controlled processing for *compatible* movement-effect transformations which were *afforded* by tool pictures. High ideomotor compatibility alone, as it was present in the conditions with abstract rule cues or written tool names as well, was thus not sufficient to get the effects of minimal controlled processing for movement selection. Indeed, in terms of controlled processing, there seemed to be no difference between compatible transformation rules which were cued by abstract rule cues, or incompatible transformation rules which were cued by tool pictures. This is evidence that the compatible transformation rule had to be specified by the physical affordances of the stimulus in order to directly trigger the appropriate movement. In other words, compatible tools obviously extended the fingers and one can assume that movement selection took place directly upon effect anticipation as if the desired effect was achieved by the hand only, without the involvement of a tool.

The data indicate that movement selection in order to achieve a required effect with incompatible tools required controlled processing. Still this amount of controlled processing was reduced as compared to the amount required for movement selection in response to abstract rule cues or written tool names when these cued the incompatible transformation rule. These results support the hypothesis that also for incompatible tools, tool pictures promoted processes of movement selection which relied on directly perceivable tool affordances and presumably also on everyday experience with mechanical devices: The correct operating movement could be derived from the tool picture by anticipating the desired effect along with imagining the associated tool movement. One could assume that such a kind of visuomotor imagery backed up an inverse model which simulated the movement-effect transformations of an incompatible tool and thus predicted the operating movement which was adequate to achieve a desired effect.

What about the possibility that tool pictures triggered similar processes of rule application as abstract rule cues or written tool names, but were just easier to discriminate, thus reducing the need for controlled processing? In this case, one should have expected a main effect of condition with significantly faster RTs in the picture condition than in the other conditions. Yet we got such a main effect neither in Experiment 5, nor in Experiment 6. The crucial point thus is that there seemed to be a qualitative, and not a quantitative difference in processing between the condition with tool pictures, on the one hand, and the conditions without tool pictures, on the other hand.

Experiment 6 additionally served to exclude another caveat, namely the one that not tool stimuli per se, but practical operating experience might have led to the observed effects. In Experiment 5, one crucial difference between the tool-switching and the rule-switching condition was that for the former, participants had to practice with real tools before the main experiment started, whereas for the latter, no such practice was possible. Furthermore, participants should have had the possibility to practice with the given tools in many occasions of their everyday life, whereas the geometric stimuli as rule cues were entirely new to them. In Experiment 6, however, the same tools were used in the picture and in the word condition and prior to both conditions participants practiced operating the real tools. Operating experience was thus the same in both conditions, only presentation mode differed. Still the effects of reduced controlled processing emerged only in the picture but not in the word condition.

To summarize, the special status of transformation rules which are afforded by the structure of simple mechanical tools was confirmed. The results suggest that the selection of an adequate operating movement in response to tool pictures requires less controlled processing than the selection of an operating movement in response to abstract rule cues or written tool names. Still, the concrete processes proceeding between tool identification and movement selection remain speculative. Therefore, in the following experiment, brain activation in the tool-switching paradigm was accessed by fMRI.

Chapter 5

Neuronal Correlates of Transformation Rules in Tool Use

5.1 Experiment 7

In Experiment 7, event-related fMRI was used in order to further investigate how transformation rules are applied in the use of simple mechanical tools. The tool-switching paradigm of Experiment 1 was used again with some adaptations to the fMRI setting.

Our preceding behavioral experiments revealed that movement selection to achieve a desired effect required less controlled processing in response to tool pictures than in response to abstract rule cues or written tool names. It was speculated that participants primarily relied on perceptual information about the tool's structure, and not on explicit knowledge to select the adequate operating movement to achieve a desired effect.

For compatible tools, the compatible transformation rule was evidently afforded by the tool's structure and furthermore, movements and their associated effect entailed high ideomotor compatibility. It was suggested that movement selection could take place as if participants were acting with their fingers only: The operating movement to achieve a desired effect seemed to be activated automatically upon effect anticipation and then seemed to be selected as the default movement.

For incompatible tools, controlled processing was required for movement selection, though not as much as for movement selection according to an explicit transformation rule which was cued by an abstract rule cue. It was presumed that movement selection relied on the anticipation of the desired effect along with the imagination of the associated tool movement. It was furthermore suggested that such a process of visuomotor imagery might back up an internal model of the movement-effect transformations of incompatible tools. Furthermore, it was hypothesized that for operating incompatible tools, compatible movement-effect associations had to be inhibited.

Still, evidence for these assumptions was only indirect. They would be backed up by showing that movement selection in tool use differs from the application of explicit mapping rules on the neurofunctional level and mirrors processes of visuomotor imagery and of updating an internal model.

To this aim, two contrasts were of particular interest in this fMRI study. The first was the contrast of incompatible versus compatible tools. The second was the contrast of transformation rule switches versus repetitions. Both contrasts have often been investigated in studies on explicit rule application and the results of these studies are fairly consistent. For the present experiment, it was hypothesized that the results obtained with the tool-switching paradigm should differ in some critical aspects from the results obtained with explicit rule application. In the following, these hypothesis will be illustrated, first centering on the contrast of incompatible versus compatible tools.

Incompatible versus compatible transformations. To begin with, the results well-known from the application of explicit mapping rules will be outlined. In conventional S-R compatibility studies in which mapping rules are explicitly defined, response selection according to an incompatible as compared to a compatible S-R mapping holds two critical characteristics: On the one hand, task difficulty is not given by the stimulus itself or by the response itself, but by the instructed mapping rule that associates a specific (visual or auditory) stimulus with a specific (motor) response. On the other hand, response selection via the automatic route, which favors compatible mappings, has to be inhibited (e.g., Kornblum et al., 1990). Accordingly, as it will be outline below, the neuronal correlates associated with the contrast of incompatible versus compatible S-R mappings can be functionally dissociated into areas of *sensorimotor integration* and areas of *cognitive control*.

Sensorimotor integration in S-R compatibility tasks is typically associated with a fronto-parietal network (Dassonville et al., 2001; Matsumoto, Misaki, & Miyauchi, 2004; Schumacher & D'Esposito, 2002). The exact locations of activation depend on the specific task and the stimulus material (Schumacher, Elston, & D'Esposito, 2003). However, there are some areas of sensorimotor integration which are consistently activated across different stimulus modalities and paradigms. These are the bilateral intraparietal sulcus (IPS) extending to superior and inferior parietal areas, as well as prefrontal and premotor regions (Casey, Thomas, Davidson, Kunz, & Franzen, 2002; Dassonville et al., 2001; Iacoboni, Woods, & Mazziotta, 1996; Jiang & Kanwisher, 2003; Lee et al., 2006; Lungu, Liu, Waechter, Willingham, & Ashe, 2007; Matsumoto et al., 2004; Schumacher & D'Esposito, 2002; Schumacher, Hendricks, & D'Esposito, 2005; Schumacher, Cole, & D'Esposito, 2007; Wager et al., 2005).

Furthermore, *Cognitive control* and response inhibition in S-R compatibility tasks have been associated with the frontal and prefrontal cortex (Wager et al., 2005). More specifically, the anterior cingulate cortex (ACC) is a prominent area of adjusting cognitive control (e.g., Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Lungu et al., 2007). In S-R compatibility tasks, the ACC presumably helps to shield the incompatible response which is required by the task rule against the automatic tendency to give a compatible response (Dassonville et al., 2001; Lee et al., 2006; Schumacher & D'Esposito, 2002; Schumacher et al., 2007; Wager et al., 2005).

We expected to find some of these activations also for the incompatible condition of the tool-switching paradigm even if – as we hypothesized – processes of visuomotor imagery were involved in movement selection.

It was hypothesized that frontal areas of cognitive control like the ACC would be activated if compatible movement-effect associations had to be inhibited for the use of incompatible tools. Furthermore, by definition, visuomotor imagery includes sensory as well as motor processes which have to be integrated. Visuomotor imagery in order to access the operating movement in tool use should thus activate areas of sensorimotor integration like the IPS, the prefrontal and the premotor cortex – areas which are activated as well in conventional S-R compatibility paradigms. Especially the IPS seems to be the core region for the imagination of movements (M. S. Cohen et al., 1996; Creem-Regehr, Neil, & Yeh, 2007; Tagaris et al., 1998; Vingerhoets et al., 2002). In the tool-switching paradigm, activation in these areas was expected to be stronger for incompatible than for compatible tools because for the former, there seemed to be no way to rely on movements which were automatically activated upon effect anticipation. In this regard, no differences in the activation pattern were thus expected between the tool-switching paradigm and conventional S-R compatibility paradigms which require the application of explicit mapping rules.

However, it is important to note that apart from the IPS two additional regions are typically activated for tasks requiring the imagination of movement in response to visual stimuli, for instance in mental rotation tasks. These regions are located within the occipital cortex and the cerebellum (Creem-Regehr et al., 2007; Vingerhoets et al., 2002). In the occipital cortex, the extrastriate areas BA 18 and 19 are known to be a processing center of object motion (M. S. Cohen et al., 1996; Barnes et al., 2000; Tagaris et al., 1998; Vingerhoets et al., 2002). In the cerebellum, bilateral activation has been related to covert action (Luft, Skalej, Stefanou, Klose, & Voigt, 1998; Tagaris et al., 1998; Vingerhoets et al., 2002). Beyond that, in the internal model approach, activation in the lateral cerebellum has been associated with an internal model simulating the transformation rule of a tool (Imamizu et al., 2003). Notably, activation in the occipital cortex and the cerebellum is typically not enhanced in the incompatible condition of conventional S-R compatibility paradigms. Stronger activation in these areas for incompatible as compared to compatible tools would thus be a strong indicator for processes of visuomotor imagery which relate to an internal model of the incompatible tool-associated transformation rule.

Rule switches versus rule repetitions. The second contrast dealt with the neural mechanisms responsible for updating the transformation rule when people switch between tools. Transformation rule switch trials were contrasted with transformation rule repetition trials. Again we will first present cortical areas which are typically activated for switching between explicit mapping rules.

If participants have to switch between explicit and task-defined defined S-R mapping rules, for instance in task-switching paradigms, switching-related activity is localized in frontal and parietal regions. More specifically, three areas have been reported to be involved in the cognitive processes associated with a task switch as compared to a task repetition (e.g., Barber & Carter, 2005; Brass & Cramon, 2002, 2004; Gruber, Karch, Schlueter, Falkai, & Goschke, 2006). The left inferior frontal junction (IFJ), an area near the junction of the inferior frontal sulcus, has been reported to play a crucial role in updating the set of task-appropriate S-R mappings. The inferior frontal gyrus is linked to the selective retrieval of the relevant S-R mappings when interference arises from the currently non-relevant task. Finally, the interparietal sulcus seems to be involved in the process of visuomotor integration during which the task-relevant S-R mapping rule is applied to the stimulus (Brass & Cramon, 2002, 2004).

In contrast to conventional task-switching paradigms which concentrate on the processes of switching between explicitly defined mapping rules, studies investigating how people switch between tool transformations are rare. Furthermore, only paradigms requiring predictive, that is, cue-based switches (as opposed to on-line adaptation) are relevant to the current issue because in our tool-switching paradigm, tool pictures cued the relevant transformation rule. In a study by Imamizu and Kawato (2008), predictive switches between transformation rules have been associated with activity in the superior parietal lobule (SPL). The authors assume that the SPL exerts a functional influence on the cerebellum, the location where the appropriate internal model of the transformation is activated. Switching-related activity which is presumably associated with the direct activation of an internal model has been reported as well. Bursztyn, Ganesh, Imamizu, Kawato, and Flanagan (2006) associated activation which was located directly in the lateral cerebellum and in motor areas with the process of predictively activating an internal model of skilled object manipulation (e.g., of grasping an object).

If switching between simple mechanical tools with different transformation rules was thus a process similar to updating an internal model, we could expect parietal and/or cerebellar and motor activation instead of the fronto-parietal network which is typically reported for conventional task-switching paradigms.

To summarize, our hypotheses were the following: For the first contrast of incompatible versus compatible tools, we expected activation in the IPS, the extrastriate cortex and the lateral cerebellum which have typically been associated with visuomotor imagery. In addition, we expected to find activation in frontal areas which are involved in cognitive control, for instance in the ACC. For the second contrast of transformation rule switches versus repetitions, we expected activation in parietal and/or cerebellar and motor areas which are presumably involved in updating the internal model of a tool-associated transformation rule.

5.1.1 Materials and Methods

Participants. Fifteen healthy right-handed participants (7 women and 8 men, mean age 25.6 years) took part in the experiment. They gave their informed consent.

Apparatus and Stimuli. Tool stimuli were identical to those used in Experiment 1. There were, however, differences in the presentation of effect pictures. In the practice phase, directly following a correct response, an effect picture was displayed on the screen as in Experiment 1. In the case of an error, the word "Fehler" (the German word for "error") appeared. In the main experiment, the German words “richtig” (“correct”), “falsch” (“wrong”), and “zu spät” (“too late”) written in black on a white background served as effect pictures to reduce perceptual complexity for correct trials.

The response device was similar to the one used in Experiment 1, but it was made of MR-compatible material. In the practice phase, participants were seated in front of the computer screen and the response device was placed on the table in front of them. When participants were lying in the scanner for fMRI recording, the response device was fixed on a low table in height of the participant’s waist. From their point of view the two bars always pointed to the right side. Stimulus presentation, image pulse acquisition and recording of the responses were carried out with the software package Presentation (www.neurobs.com).

Procedure. The experiment started with a practice session outside the scanner. This session was identical with the practice session in Experiment 1. The same was true for the main experiment except for the following modifications: Each trial had a fixed duration of 6000 ms to allow for the inertia of the hemodynamic response. To cover different time points of the hemodynamic response, the presentation of the blank screen at the beginning of each trial was jittered between 0 and 1500 ms. Afterwards the stimulus picture appeared for 600 ms and starting from its presentation participants had 3000 ms to respond. Participants were however encouraged to respond as quickly as possible. After this interval, the feedback appeared on the screen for 1000 ms. The trial ended with a blank screen and its duration depended on the preceding jitter. The interstimulus interval thus varied randomly between a minimum of 500 ms and a maximum of 3500 ms.

The main experiment consisted of 321 trials. Each trial type (i.e., each of the eight tool-effect cue combinations) and each possible transition between two trials occurred equally often within a block. 20 nothing trials during which the screen remained blank for 6000 ms were randomly interspersed. The main experiment lasted about 35 minutes.

Behavioral Data Acquisition. Behavioral data (RT and accuracy) were collected while participants performed the task in the scanner. As in the preceding experiments, the time from stimulus presentation to the initiation of an opening or a closing motion of the fingers in the response device was measured as RT.

fMRI Data Acquisition. MRI was conducted with a 3T Trio scanner (Siemens, Erlangen, Germany). Functional scans were collected using a single shot, T2*-weighted, gradient recalled echo planar imaging (EPI) sequence (repetition time 2000 ms, echo time 30 ms, 90° flip angle, acquisition bandwidth 100 kHz). Twenty-four axial slices covering the whole brain were acquired (19.2 cm field of view, 64×64 matrix, 4 mm thickness, 1 mm gap) parallel to the AC-PC axis. In a separate session structural scans were acquired. These were the 24 anatomical MDEFT slices and 24 EPI-T_1 slices with the same geometrical parameters (slices, resolution) and the same bandwidth as used for the functional data. Stimuli were displayed using VisuaStim (Magnetic Resonance Technologies, Northbridge, USA), consisting of two small TFT-monitors placed directly in front of the eyes. With a resolution of 800×600 pixels and a refresh rate of 60 Hz, they simulated a distance of about 100 cm to a normal computer screen.

Behavioral Data Analysis. All trials following a nothing trial and all tool repetition trials were excluded from data analysis. Furthermore, for RT analysis, all errors and all trials following an error were excluded (10.3 %); for the analysis of error rates, all trials following an error were excluded (5.4 %). As in Experiment 1, median RTs and error rates were analyzed in a $2 \times 2 \times 2$ ANOVA with compatibility (compatible vs. incompatible transformation rule), rule transition (rule repetition vs. rule switch), and movement transition (movement repetition vs. movement shift) as within-participant variables. We thus wanted to find out whether the findings from the preceding experiments could be replicated with the slightly changed paradigm.

fMRI Data Analysis. Processing and statistical analysis of functional data were performed using Statistical Parametric Mapping (SPM5, Wellcome Department of Imaging Neuroscience, London, UK), implemented in MATLAB 7 (Mathworks, Inc., Sherborn, MA, USA). The first 5 images were discarded to ensure that the signal had reached equilibrium. To correct for the effect of head motion across time, the scans for each participant were realigned to the first scan. In addition, during realignment, images were corrected for distortions of the EPI-field (unwarping). The slice timing function was used to correct for differences in image acquisition time between slices. Anatomical images were co-registered to the average realigned EPI image. Subsequently, the unified segmentation approach was performed (Ashburner & Friston, 2005). All images were spatially normalized to the standard Montreal Neurological Institute (MNI) template and smoothed using isotropic Gaussian kernels of 7 mm to compensate for normal anatomical variations between participants and to conform the data to a Gaussian model. The data were filtered to eliminate slow signal drifts (highpass filter of 100 s).

Statistical analyses were first performed on individual participant's data using the general linear model as implemented in SPM5 (Friston et al., 1995). A model convolved with the canonical hemodynamic response function was applied. Events were modeled time-locked to the onset of the stimulus picture and additionally parameterized by RT. The motor response and the feedback were modeled separately, as well as tool repetition trials, trials including an error, trials following an error and trials following a nothing trial.

On the first level, for each participant, two linear contrasts were defined: i) incompatible versus compatible tool; ii) transformation rule switch from trial $n-1$ to trial n versus transformation rule repetition. These individual contrasts were then taken to the second level to perform group random effects analyses with one sample t-tests. Activated areas with a minimum cluster size of 20 voxels were considered significant if they exceeded a statistical threshold of $p < 0.05$, FWE-corrected for multiple comparisons on the cluster level. All results are reported in MNI coordinate space.

In addition to whole-brain contrast analyses, we were interested in whether switching related activity would be modulated by the variables compatibility and movement transition. We therefore conducted a signal strength analysis using the program rfxplot (Gläscher, in press). Critical regions and their associated coordinates were derived from the random effects analysis of the contrast between transformation rule switches versus repetitions. Around each activated region, a sphere with a radius of 8 mm was defined. Within this sphere, for each individual participant the voxel with the maximum effect was selected for analysis. The mean values for each region were subsequently entered into a $2 \times 2 \times 2$ ANOVA with the variables compatibility, rule transition and movement transition.

5.1.2 Results

Behavioral Data

RT Data ANOVA. As in the preceding experiments, there was a main effect of compatibility ($F(1, 14) = 54.0$, $MSE = 30098.6$; $p < 0.001$) and a main effect of rule transition $F(1, 14) = 18.3$, $MSE = 10661.4$; $p < 0.01$). Movement selection was 232 ms faster for compatible than for incompatible tools, and 80 ms faster in transformation rule repetition than in rule switch trials. Furthermore, as in Experiment 1, the modulation of the rule transition effect by movement

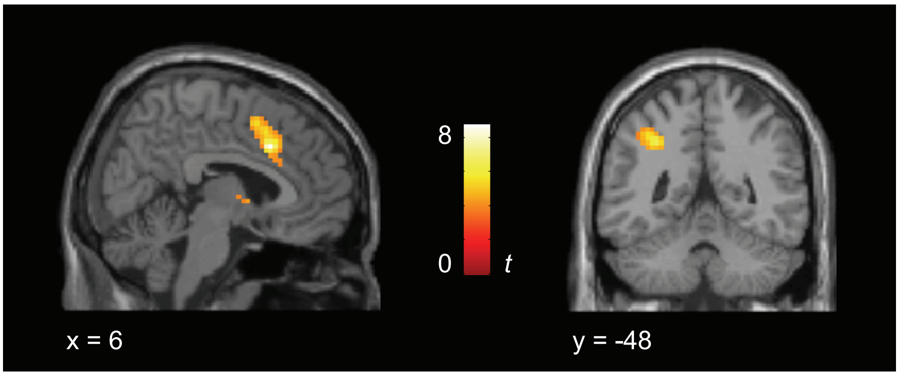

Figure 5.1: Contrast of incompatible versus compatible tools. Typical areas associated with cognitive control (ACC) and sensorimotor integration (IPS). Activation map averaged over 15 participants (t-threshold at $t = 3.79$, uncorrected) mapped onto an individual brain from the inhouse database. Red labels indicate positive t-values. Sagittal plane on the left showing activity in the right ACC (6, 18, 36), coronal plane on the right showing activity in the left IPS (−30, −48, 39).

transition was significantly stronger for incompatible than for compatible tools $F(1,14) = 9.5$, $MSE = 5556.9$; $p < 0.01$ for the three-way interaction between compatibility, rule transition and movement transition).

Error Rates. Error rates were higher for incompatible than for compatible tools $F(1,14) = 40.7$, $MSE = 16.3$; $p < 0.001$). Furthermore they were higher in rule switch than in rule repetition trials $F(1,14) = 7.4$, $MSE = 30.4$; $p < 0.05$). No further effects were significant.

The behavioral effects obtained in the preceding experiments were thus replicated with the slightly changed paradigm.

fMRI Data

Whole-Brain Analysis

Incompatible versus Compatible Tools. The first question we addressed was the neuronal basis of the compatibility effect in tool use. As predicted from both, conventional S-R compatibility tasks and tasks which require the imagination of movement, we observed activation in the fronto-parietal cortex for the contrast of incompatible versus compatible tools. There were two foci of activation in the parietal cortex: One in the left anterior IPS, the other one in the

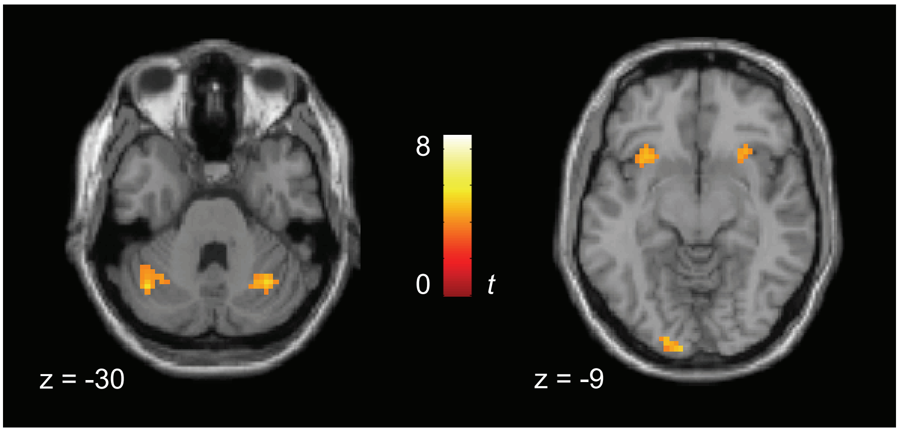

Figure 5.2: Contrast of incompatible versus compatible tools. Typical areas associated with visuomotor imagery. Activation map averaged over 15 participants (t-threshold at $t = 3.79$, uncorrected) mapped onto an individual brain from the inhouse database. Red labels indicate positive t-values. Axial plane on the left showing bilateral activity in the cerebellum (33, −60, −30; −39, −63, −30), axial plane on the right showing activity in the left BA 18 (−9, −99, −9).

left precuneus. Furthermore, we observed activation in the left dorsal premotor cortex.

Areas which have typically been associated with response inhibition and cognitive control were activated, too. We found bilateral activation in the ACC with its maximum on the right, as well as in the IFJ and in the inferior frontal cortex (see Figure 5.1).

Most notably, there was also enhanced activity in regions which can be associated with the imagination of movement in response to visual stimuli. The left occipital cortex was activated in BA 18, an area belonging to the extrastriate cortex. Furthermore, the cerebellum was activated bilaterally. Activation on the ipsilateral side of responding was significant, whereas activation on the left side just failed to reach significance ($p = 0.058$) (see Figure 5.2).

There was an additonal subcortical activation in the basal ganglia. Bilaterally, its center was located in the medial part of the pallidum. Table 5.1 summarizes significant peak hemodynamic responses for this contrast. The reverse contrast of compatible minus incompatible tools showed no significant activations.

Rule Switch versus Rule Repetition Trials. This contrast was computed to access the brain activation associated with switching between tool-associated

Table 5.1: Contrast of incompatible vs. compatible tools. Antatomical location and MNI coordinates with $t < 3.79$ ($p < 0.05$, FWE-corrected on cluster level)

Region	Side	Volume	MNI Coordinates			
		mm^3	x	y	z	t_{max}
Anterior cingulate cortex	R	627	6	18	36	8.73
Inferior frontal cortex	R	129	30	24	0	6.33
Inferior frontal cortex	L	498	−30	27	0	5.72
Inferior frontal junction	R	174	45	−3	27	5.17
Inferior frontal junction	L	84	−45	6	30	5.65
Dorsal premotor cortex	L	216	−27	−9	54	5.25
Intraparietal Sulcus	L	147	−30	−48	39	6.37
Precuneus	L	120	−15	−63	36	6.54
Extrastriate cortex	L	114	−9	−99	−9	5.07
Cerebellum	R	99	33	−60	−30	5.38
Basal ganglia, pallidum	R	213	12	3	−3	6.59
Basal ganglia, pallidum	L	246	−18	−9	0	6.03

Table 5.2: Contrast of transformation rule shift vs. repetition trials. Anatomical location and MNI coordinates with $t < 3.79$ ($p < 0.05$, FWE-corrected on cluster level)

Region	Side	Volume	MNI Coordinates			
		mm^3	x	y	z	t_{max}
Anterior vermal area	R	276	6	−48	−24	6.68
Dentate nucleus	R	81	18	−57	−39	4.33

transformation rules. The only two significantly activated areas were localized in the cerebellum, a large one (276 mm^3) in the anterior vermal area (Larsell lobules IV – V), a smaller one (81 mm^3) in the right dentate nucleus (Schmahmann et al., 1999). The reverse contrast of rule repetitions minus rule switches revealed no significantly activated areas. Table 5.2 summarizes significant peak hemodynamic responses for this contrast.

Signal Strength Analysis We were interested whether switching-related activity in the anterior vermal area and the dentate nucleus was modulated by the variables compatibility and movement transition. We therefore ran a $2 \times 2 \times 2$

ANOVA with the variables compatibility, rule transition and movement transition for each region. We will first report on vermal activity: There was no effect of compatibility. However, there was a significant interaction between rule transition and movement transition ($F(1, 14) = 7.7$, $MSE = 0.3$; $p < 0.05$). Switching-related activity was especially enhanced in movement repetition trials. This was due to the fact that in rule repetition trials in which also the movement had to be repeated, vermal activity was rather low (see Figure 5.3).

In the dentate nucleus, enhanced activity in rule switch as compared to rule repetition trials was significantly modulated neither by compatibility nor by movement transition. Descriptively though, the pattern of activation followed the one in the anterior vermal area.

5.1.3 Discussion

The present data suggest that transformation rule application in the tool-switching paradigm differs from the application of explicit mapping rules in important aspects. Activation associated with the contrast of incompatible versus compatible tools could be subsumed under two categories. On the one hand, enhanced activation in the ACC, the IFJ, the inferior frontal cortex and the medial part of the pallidum bore evidence of processes of response inhibition and cognitive control. On the other hand, enhanced activation in the IPS, the precuneus, the dorsal premotor cortex, the prestriate cortex and the lateral cerebellum could be associated with visuomotor imagery. Furthermore, activation in the anterior vermal area and in the dentate nucleus was associated with the contrast of transformation rule switches versus repetitions. It was presumably involved in updating the tool-associated transformation rule. In the following, the functional role of the activated areas will be discussed in more detail.

Regions Involved in Cognitive Control for Operating Incompatible Tools. The process of operating incompatible as compared to compatible tools was accompanied by enhanced activation in the ACC, the IFJ, the inferior frontal cortex and the medial part of the pallidum. In preceding studies, these areas have been associated with cognitive control and response inhibition. Strong activation in the ACC was hypothesized. The center of this activation was located in the dorsal, "cognitive" ACC (Bush, Luu, & Posner, 2000). This area is typically activated in the incompatible condition of conventional S-R compatibility paradigms (e.g., Schumacher et al., 2007), but also in tasks which require response inhibition (e.g., Braver, Barch, Gray, Molfese, & Snyder, 2001; Nakata et al., 2008). It has

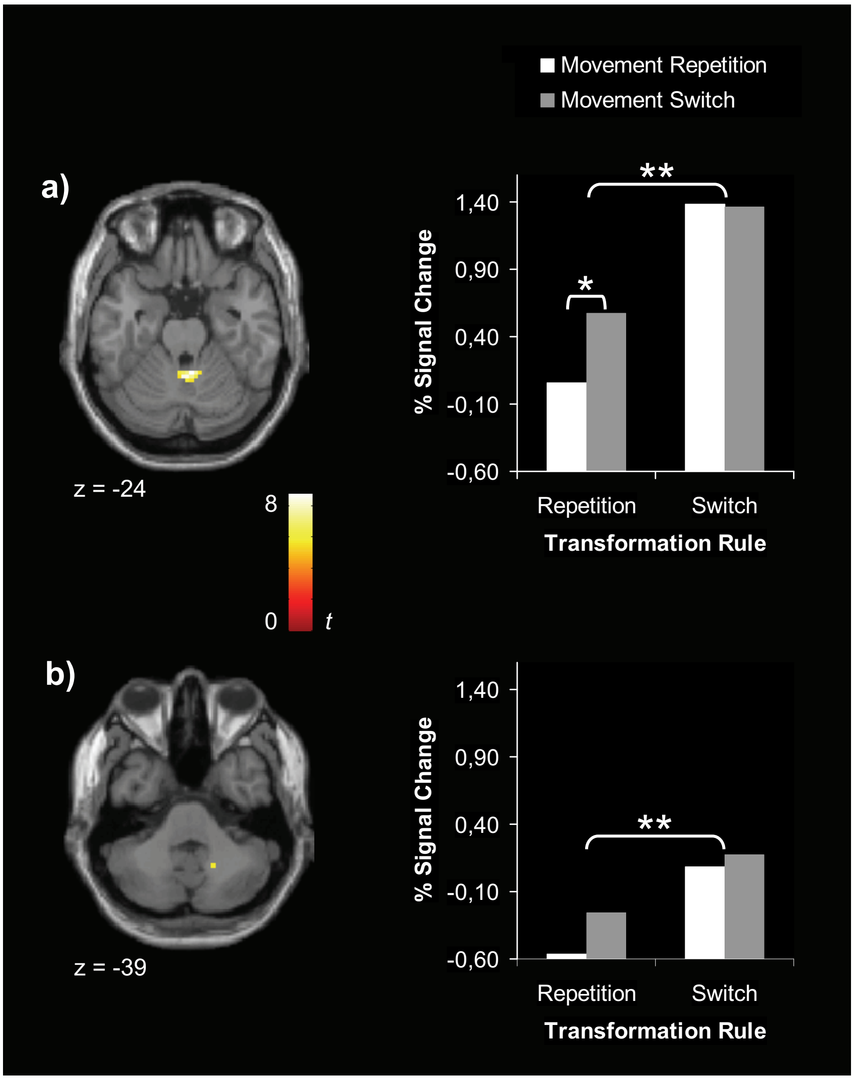

Figure 5.3: Contrast of transformation rule switches versus repetitions. Activation map averaged over 15 participants (t-threshold at $t = 3.79$, uncorrected) mapped onto an individual brain from the inhouse database. Red labels indicate positive t-values. **a)** Axial plane on the top showing activity in the right anterior vermis (6, −48, −24). The diagram reports mean beta values as a function of rule transition and movement transition in this region. Data are aggregated over compatible and incompatible trials as there was no effect of compatibility. The asterisk indicates the significant interaction movement transition × rule transition. **b)** Axial plane at the bottom showing activity in the right dentate nucleus (18, −57, −39). Again, the diagram reports mean beta values in this region. The interaction movement transition × rule transition was not significant.

been assigned a crucial role in detecting competition or conflict between responses (Botvinick et al., 1999; Braver et al., 2001; Carter, Botvinick, & Cohen, 1999; Kerns et al., 2004). The IFJ has been associated with processes of controlled response selection as well. It is activated when a task switch requires updating the set of task-appropriate S-R mappings (Brass & Cramon, 2002) or when a response to infrequent stimuli has to be selected (Derrfuss, Brass, Neumann, & Cramon, 2005; Chikazoe et al., 2009). In the tool-switching paradigm, activation in both regions presumably reflected the need for controlled processing when movement-effect associations of high ideomotor compatibilty were automatically activated, but an incompatible movement-effect transformation was required to operate the tool.

Activation in the inferior frontal cortex has frequently been reported for nogo tasks (Chikazoe et al., 2009; Coxon, Stinear, & Byblow, 2007; McNab et al., 2008; Schulz et al., in press), movement inhibition (Coxon et al., 2007) and Eriksen Flanker tasks (Bunge et al., 2002). Interestingly, the inferior frontal cortex has also been reported to be activated in a condition in which graspable objects displayed on the computer screen afforded a precision grip, but the explicit task rule required a power grip, or vice versa (Grèzes et al., 2003). It therefore seems to play a crucial role in the inhibition of overlearned responses which are directly evoked by a stimulus. A similar role has been assigned to the medial aspect of the pallidum: This part of the basal ganglia holds a crucial role in movement inhibition (B. M. de Jong & Paans, 2007; Grillner, Hellgren, Ménard, Saitoh, & Wikström, 2005). It is activated, for instance, when a motor action has to be interrupted (Toxopeus et al., 2007). We assume that in the current study, the inferior frontal cortex and the medial aspect of the pallidum were involved in the inhibition of the compatible movement which was automatically activated upon effect anticipation.

To sum it up, if a tool required an operating movement that was spatially incompatible to the desired effect, cognitive control processes were engaged for movement selection as reflected by activation in the ACC and the IFJ. The inhibition of the misleading movement-effect association of high ideomotor compatibility was presumably mediated by the inferior frontal cortex and the medial aspect of the pallidum. Similar processes of cognitive control and response inhibition have been reported for a broad spectrum of tasks in which the required responses conflict automatic or overlearned responses.

Regions Involved in Visuomotor Imagery for Operating Incompatible Tools. Enhanced activation in parietal areas, the extrastriate cortex, the lateral cerebellum and the dorsal premotor cortex suggest the involvement of visuomotor imagery in the process of movement selection for operating incompatible tools. Three of these regions, the parietal cortex, the extrastriate cortex and the lateral cerebellum are typical areas associated with the imagination of movement in response to visual stimuli (Vingerhoets et al., 2002; Creem-Regehr et al., 2007).

In the parietal cortex, there were two foci of activation, one in the anterior IPS and one in the left precuneus. The IPS is an interface between perceptive and motor systems and has been related to processes of sensorimotor integration (Grefkes & Fink, 2005). The precuneus has been assigned a role in visuospatial imagery and in the storage of object shape (Cavanna & Trimble, 2006; Gardini, Cornoldi, Beni, & Venneri, 2008). Both regions thus seem to contribute to the integration of visual information derived from the tool picture on the one hand, and processes of movement imagination on the other hand.

Activation in the extrastriate cortex was located in the left BA 18. This region is involved in the perception as well as in the imagination of object motion (e.g., M. S. Cohen et al., 1996), but also in the extraction of task-relevant information from visual stimuli (Canessa et al., 2008; Meehan & Staines, 2007). In any case, activation in this area seems relevant to the claim that the appropriate operating movement in response to the stimulus was not selected on the basis of an explicit rule, but directly inferred from the tool picture.

Bilateral activation in the lateral cerebellum has been associated with the imagination of action. It has been reported for mental rotation tasks (Tagaris et al., 1998; Vingerhoets et al., 2002), motor imagery tasks (e.g., Alkadhi et al., 2005; Ryding, Decety, Sjöholm, Stenberg, & Ingvar, 1993), and it also seems to represent an internal model simulating the movement-effect transformations of a tool (e.g., Imamizu et al., 2003). We propose that the cerebellar activation in our study might be related to an internal model of the incompatible tool-associated transformation rule whose inverse model, which predicts the adequate movement to achieve a required effect, is backed up by a process of visuomotor imagery.

In addition to these three prominent areas involved in the imagination of movement, activation in the left dorsal premotor cortex was in congruence with the hypothesis of visuomotor imagery. The dorsal premotor cortex receives visual input via different parts of the parietal lobes and plays a role in the execution, but also in the internal simulation of object-directed action (Canessa et al., 2008). Notably, it is activated in mental rotation or imagery tasks which involve a reference to one's own motor activity, for instance during the comparison of rotated tool pictures (Schubotz & Cramon, 2003; Vingerhoets et al., 2002). In the present experiment, the reference to one's own motor action is self-evident: The assumed process of visuomotor imagery refers to a visual tool stimulus figuratively extending the fingers. Imagining a tool movement should thus include imagining the associated operating movement. We proposed that access to this operating movement was actually a consequence of visuomotor imagery.

Summing up, there were strong indications that the selection of the correct operating movement for an incompatible tool relied on visuomotor imagery of the associated tool movement, thus relating to an internal model. Parietal and premotor activity could also have been expected if the correct operating movement was selected on the basis of an explicit incompatible mapping rule (e.g., Schumacher et al., 2007). However, given the activation in extrastriate and cerebellar regions, reliance on explicit rule application alone seems unlikely.

Activation was predominantly left-sided for cortical areas with contralateral coding and right-sided for the cerebellum with ipsilateral coding. Participants had to execute the operating movements with the fingers of their right hand. It is, however, important to note that activation could not be explained by the actual operating movement, that is, the finger movement in the response device, or by the mere perception of a tool: In this case, similar results for both, compatible and incompatible tools, should have been obtained. As it was already stated above, the imagination of the tool movement presumably provided access to the associated operating movement in the use of incompatible tools.

Left-lateralization in cortical activation is typical for real tool use and also for the imagination of tool-use actions (Lewis, Phinney, Brefczynski-Lewis, & DeYoe, 2006). Furthermore, several of the activated areas were in agreement with those reported in other studies on tool use which do not dissociate between compatible and incompatible transformations. For instance, the left IPS has been reported to be the most important part of the tool-use network (Moll et al., 2000). Its activation has been characterized to represent "knowledge of how the tool works" (Higuchi et al., 2007, p. 355). Furthermore, in this study by Higuchi et al. (2007), cerebellar activity has been reported for the imagination and execution of everyday tool-use actions involving tools like screwdrivers or pliers. Most notably, the MNI coordinates of cerebellar activity in the imagination condition of the study by Higuchi and collegues (32, −62, −28) almost exactly corresponded to those found in the present study (33, −61, −21). This correspondence strongly supports the hypothesis that imagery is used to select the correct operating movement for incompatible tools.

Interestingly, in the literature, the pattern of activation for the manipulation of an object with the fingers only or with compatible pliers have been reported to be very much alike. The only difference in cortical activation has been located in the IPS (Inoue et al., 2001). Given this result and given the activation differences between incompatible and compatible tools in the present study, it seems likely that the process of operating compatible tools was related to acting with the hands only.

Finally, tool-related activation has been dissociated into a ventral stream leading to the inferiotemporal cortex and representing semantic knowledge and a dorsal stream leading to the posterior parietal cortex and representing action-related knowledge (Frey, 2007; Lewis et al., 2006). The lack of temporal activation for the contrast of incompatible versus compatible tools in the present experiment is in accordance with the hypothesis that the tool-associated transformation rules were realized in the dorsal processing stream.

Regions Involved in Updating Tool-Associated Transformation Rules. For a switch between tools incorporating different transformation rules, the only two areas activated were located in the cerebellum. They was situated in areas of basal motor processing, namely in the anterior vermal area of the lobules IV and V and in the dentate nucleus. This was surprising because in former studies, cerebellar activation associated with updating an internal models of movement dynamics has been reported (Bursztyn et al., 2006), but was located laterally in the cerebellar lobes and therefore in regions associated with cognitive processing and movement simulation.

The anterior cerebellum is somatotopically organized reflecting a homunculus and specific areas can thus be associated with bodily limbs. The anterior vermal area which was activated in the present study for transformation rule switches as compared to repetitions represents the fingers of the ipsilateral hand (Rijntjes, Buechel, Kiebel, & Weiller, 1999). It is involved in the simple execution of voluntary finger movements (Deiber et al., 1998), but also in movement control: Its activation generally increases with the complexity of finger movements (Chan, Huang, & Di, in press). For instance, activation in the anterior vermal region that was almost identical to activation in the present study has been reported for complex versus simple finger tapping movements (Catalan, Honda, Weeks, Cohen, & Hallett, 1998; Sadato, Campbell, Ibáñez, Deiber, & Hallett, 1996), for complex as compared to simple bimanual movement coordination (Kraft et al., 2007) and for the pantomime of tool-use actions versus simple finger tapping (Choi et al., 2001). Most notably, the finger tapping paradigms (Catalan et al., 1998; Sadato et al., 1996) involved finger-thumb opposition. For instance, in the complex condition, participants had to tap the four remaining fingers against the thumb in a specific sequence; in the simple condition, they repeatedly had to tap with the index against the thumb. Finger-thumb opposition reminds of the opening and closing movements which were executed by thumb and index finger in the response device used in our experiment.

However, it is important to note that the activation in the anterior vermal area in our experiment does not seem due to finger movement complexity: Movement repetitions and switches were equally likely in transformation rule switch as compared to repetition trials. Data were parameterized by RT so it could neither be an effect of RT which was higher in transformation rule switch trials. The most plausible explanation seems that not the finger movement in itself, but the entire motor action including the fingers and the tool determined the complexity of the movement. The cerebellum plays a crucial role for the coordination and integration of separate limb movements (Casabona, Valle, Bosco, & Perciavalle, 2004; Thach, Goodkin, & Keating, 1992), and vermal regions are activated with higher coordination demands (Tracy et al., 2001). It is thus likely that vermal activation in the present paradigm was caused by the fact that with a transformation rule switch, finger movements had to be coordinated and integrated with the movements of the new kind of tool.

The second smaller activated region is in agreement with this suggestion. The dentate nucleus is involved in movement planning (Fisher, Boyd, & Winstein, 2006). Again enhanced activation has been reported for more complex finger and hand movements (Debaere, Wenderoth, Sunaert, Hecke, & Swinnen, 2003; Dimitrova et al., 2006; Vaillancourt, Thulborn, & Corcos, 2003).

The signal strength analysis showed that activity in both cerebellar regions did not differ for compatible or incompatible tools. However, activity in the anterior vermis was especially low if the transformation rule as well as the finger movement had to be repeated. This finding seems plausible because in these trials, one and the same movement-effect transformation simply had to be repeated. It is likely that in this case, motor complexity and the necessity of motor integration processes were lowest.

There are thus no hints in the present data that switching between transformation rules in tool use resembles the processes of updating explicit mapping rules. Instead, updating the tool-associated transformation rule seems to be a process of motor integration between finger movements and a compatible or incompatible tool. The differences between these results and the results by Bursztyn et al. (2006) and Imamizu and Kawato (2008) can presumably be explained by the fact that only in the present study tools had to be operated which figuratively extended the operating fingers. In contrast to the former two studies different kinds of transformations thus relied on a concrete physical basis. From the present results we cannot conclude whether cerebellar activity in the anterior vermal area and the dentate nucleus were involved in updating an internal model. However, it is likely that the integration between the fingers and the tool was at least an essential prerequisite.

To summarize, the data of both contrasts reported here indicate that transformation rules which are incorporated in simple mechanical tools differ from explicit mapping rules in important aspects. The data suggest that the following processes are involved in the application of an incompatible as compared to a compatible transformation rule in tool use: Movement selection involves controlled processing and movement-effect associations of high ideomotor compatibility have to be inhibited as revealed by activation in the ACC, the IFJ, the inferior frontal cortex and the medial aspect of the pallidum. The selection of the adequate operating movement to achieve a desired effect then involves visuomotor imagery of the associated tool movement. This process is reflected by activation in the parietal and premotor cortex and, above all, activation in the extrastriate cortex and the lateral cerebellum. For a switch between tools which incorporate different (compatible or incompatible) transformation rules, movement complexity is increased and motor integration has to occur between finger movements and the new type of tool. In these processes, the anterior vermal area and the dentate nucleus are involved.

Chapter 6

General Discussion

In the following discussion, I will first review the experimental findings which I presented in this thesis. I will then discuss in which ways these findings are helpful to characterize the representation and application of transformation rules for movement selection in tool use. Subsequently, I will relate the results to existing theories on rule-based movement selection. Finally, I will discuss practical implications of the present work as well as its limitations and questions for future research.

6.1 Summary of Experimental Findings

The experiments presented in this dissertation were conducted in order to elucidate how people represent and apply compatible and incompatible transformation rules for movement selection when they use simple mechanical everyday tools. A tool-switching paradigm was applied and participants had to switch between simple mechanical everyday tools displayed on the screen. In each trial, the task was to squeeze or to release an object in the distal grippers of the tool by performing the adequate operating movement. Each of the tools incorporated either a compatible or an incompatible transformation between operating movements and distal effects at the tip of the tool. Participants had to operate each tool via a response device as if they were directly handling it.

Based on this paradigm, it could be investigated whether tool-associated transformation rules obtain an independent and functionally relevant representation in the cognitive system. To this end, RTs and error rates in trials in which the tool changed but the transformation rule remained the same from trial $n-1$ to trial n were compared with the performance in trials in which the tool and also the transformation rule changed. Furthermore, the differences between operating tools with an incompatible as compared to a compatible transformation rule could be assessed in terms of RTs and error rates, but also in their requirement of controlled processing for movement selection. Following the event file logic (Hommel, 1998b), greater influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was taken as evidence for enhanced controlled processing (Waszak et al., 2005).

In Experiment 1, the basic form of the tool-switching paradigm was applied. Reaction times and error rates were lower if participants had to switch between different tools that incorporated the same transformation rule (e.g., between tweezers and pliers) as compared to costs for switching between tools incorporating different transformation rules (e.g., between a clothespin and pliers). These results were taken as evidence that compatible and incompatible transformation rules of simple mechanical tools hold an independent and functionally relevant representation in the cognitive system. Moreover, Experiment 1 revealed differences between compatible and incompatible transformation rules in tool use: There was a compatibility effect. The selection of the operating movement was faster and more accurate for compatible than for incompatible tools. Furthermore, an influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was evident for incompatible tools. For compatible tools movement selection was not significantly influenced by the movement-effect transformations in the preceding trial. These findings support the hypothesis that controlled processing was required for movement selection in order to achieve a desired effect with incompatible tools, but that the requirements of controlled processing were minimal for operating compatible tools.

Experiment 2 was conducted to test whether the realization movement-effect transformations which are implemented by compatible tools can rely on default associations between movements and effects. There was a benefit for repeating the compatible transformation rule whether or not tools appeared in the same or in different spatial (horizontal or vertical) dimensions and whether or not the response set was thus the same or a different one in trial $n-1$ and trial n. The activation of the compatible transformation rule in the preceding trial seemed enough to facilitate movement selection in a current trial, and this benefit was independent of the specific movement-effect transformation which was required. There was no such independence for incompatible tools. It was therefore concluded that for compatible tools movement selection in order to achieve a desired effect could rely on default associations between movements and effects.

In Experiment 3 and 4 it was investigated whether these differences between compatible and incompatible tools could be compensated for by changing rule probability or by training. In Experiment 3, the compatibility effect was indeed eliminated when incompatible tools had to be operated in the majority of trials. Still, changing rule probability in favor of incompatible tools could not substantially change the amount of controlled processing required for movement selection. There were furthermore signs of active and strategic suppression of compatible movement-effect associations. On the contrary, the differences between compatible and incompatible tools in terms of controlled processing were still significantly strengthened if compatible tools had to be operated in the majority of trials.

In Experiment 4, training with incompatible tools in four consecutive sessions was successful and the compatibility effect was eliminated in pure blocks. However, training with incompatible tools as compared to training with both, compatible and incompatible tools, did not differentially influence the results in the subsequently performed tool-switching paradigm. There was still a substantial compatibility effect and still, controlled processing was enhanced for movement selection in order to operate incompatible as compared to compatible tools. The default status of compatible movement-effect associations thus could not easily be overridden neither by changing rule probability nor by training. It was suggested that high ideomotor compatibility between operating movements and their associated effects at the distal tip of the tool was the reason for the default status of compatible movement-effect associations.

Experiment 5 and 6 revealed the impact of an additional characteristic of transformation rules which are incorporated in simple mechanical tools: These are evidently afforded by the tool's structure. In Experiment 5 the main differences between compatible and incompatible tools were replicated with abstract rule cues which cued a compatible or an incompatible transformation rule. Still, less controlled processing seemed to be required for movement selection in response to tool pictures as compared to movement selection in response to abstract rule cues. The same was true in Experiment 6 in which written tool names instead of abstract rule cues were contrasted which tool pictures. We concluded that movement selection in the tool-switching condition was an on-line process based on visual information and on a lifelong experience with mechanical devices, and not primarily a process based on the retrieval of explicit knowledge. It was suggested that compatible tools obviously extended the fingers and movement selection could take place directly upon effect anticipation as if the desired effect was achieved by the hand only, without the involvement of a tool. For incompatible tools, it was proposed that the correct operating movement could be derived from the tool picture by anticipating the desired effect along with imagining the associated tool movement.

Finally, in Experiment 7, the application of transformation rules in the tool-switching paradigm was investigated by event-related fMRI. The contrast of incompatible versus compatible tools revealed activation in the IPS, the precuneus, the dorsal premotor cortex, the lateral cerebellum and the extrastriate cortex. These areas can be associated with visuomotor imagery. Furthermore, activation in the ACC, the IFJ, the inferior frontal cortex and the medial aspect of the pallidum provided evidence that movement inhibition and cognitive control were required for movement selection in order to achieve a desired effect with incompatible as compared to compatible tools. These findings strengthen the notion of a default status of compatible movement-effect associations and of a process of visuomotor imagery for the realization of incompatible movement-effect transformations. The contrast of transformation rule switch as compared to repetition trials yielded activation in the anterior vermal area and the dentate nucleus. Activation in both regions can be associated with a process of motor integration between the tool and the operating fingers. With reference to research on the application of explicit mapping rules it was concluded that updating a transformation rule in the tool-switching paradigm differed from updating an explicit mapping rule in important aspects.

Taken together, the experiments of this dissertation provided evidence for an independent and functionally relevant representation of tool-associated transformation rules in the cognitive system, for the advantage of high ideomotor compatibility between movements and their associated effects at the tool's distal tip, as well as for the capacity of a simple mechanical tool to afford a specific transformation rule. These seem to be important characteristics of transformation rules inherent in simple mechanical tools and in the present experiments, they had an impact on movement selection.

6.2 Tools: Somewhere Between Hands and Explicit Rules

In the literature on tool use, it is sometimes proposed that tool-use actions strongly resemble natural reaching or grasping movements which are executed by the hands only (e.g., Iriki, Tanaka, & Iwamura, 1996; Schaefer, Rothemund, Heinze, & Rotte, 2004; Umiltà et al., 2008). For instance, in the study by Umiltà et al. (2008) which has been presented in the introduction (see 1.2.1.1), it did not matter which type of tool macaques had to use in order to grasp objects. Activation in the primary motor cortex was always related to the distal effect. The authors concluded that both, tools with a compatible or incompatible transformation rule, are controlled in an effect-oriented manner and in the same manner as the natural hand. Still, evidence for the strong resemblance between tool-use actions and actions which are executed by the hands only is incomplete. For instance, in the study by Umiltà et al. (2008), the comparison of activation for different types of tools was centered on single cell recodings in the primary motor cortex. Potential activation differences in further areas were not reported. Without this kind of information, it cannot be ruled out that there were crucial differences between hand and tool-use actions, and also between tool-use actions involving different types of transformation rules.

Our own work was not aimed at a direct comparison between actions performed with the hands only, or with tools. Still the results obtained with the tool-switching paradigm clearly indicate that at least movement selection in order to use a tool with an incompatible transformation rule cannot be put on the same level with movement selection in order to perform an action with the hands only. An important argument is that natural grasping or reaching movements are provided instantaneously (e.g., Favilla, 1996). On the contrary, for tools with an incompatible transformation rule, the relatively high RTs, the strong influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n, as well as neuronal activation in areas of movement inhibition and cognitive control as obtained in Experiment 1, 2 and 7 bore evidence of effortful and controlled processing.

Movement selection in order to operate a tool with a compatible transformation rule did not depend on a high amount of controlled processing and thus seemed more similar to movement selection to perform actions without a tool. Still, RTs in the range of about 1000 ms were obtained for operating compatible tools (e.g., in Experiment 1). These relatively high RTs speak for the assumption that there was a step preceding movement selection: The compatible or incompatible tool category had to be accessed by tool identification. On the contrary, it is self-evident that such a process is not needed when actions are performed with the hands only. Consequently, compatible as well as incompatible tool-use actions are more complex than actions performed without a tool – at least when people have to switch between different tools.

The ease with which people execute natural reaching or grasping movements is opposed to controlled movement selection according to explicitly defined mapping rules. Explicit mapping rules are often applied to coordinate movement selection in conventional experimental paradigms. They have to be learned and are then retrieved in a controlled process in the situation of application (e.g., Mayr & Kliegl, 2003). The present work provided evidence that movement selection in tool use cannot be equated with such a kind of explicit rule application either. Transformation rules in tool use are afforded rules which are determined by the tool structure. The present data let us conclude that after a tool was assigned to the compatible or incompatible tool category, the adequate movement to achieve a desired effect was either provided as the default movement directly upon effect anticipation or could be accessed by anticipating the desired effect along with imagining the associated tool movement. There seemed to be no need for explicit rule definition and application. It seems that less controlled processing is therefore required for movement selection in order to achieve a required effect in tool use in contrast to movement selection according to an explicit transformation rule. These assumptions were confirmed particularly by the Experiments 5, 6 and 7.

Additionally, the process of switching between tool-associated transformation rules seems to differ from switching between explicitly defined mapping rules. As revealed by switching-related activity in the anterior vermal region and the dentate nucleus in Experiment 7, switching between tools that incorporated different transformation rules was associated with motor integration between the operating fingers and the new type of tool. This finding seems related to the proposition that during tool use, the body schema, which codes the position of bodily limbs in space (Head & Holmes, 1911), is temporarily modified to include a handheld tool (Iriki et al., 1996; Schaefer et al., 2004). It has been assumed that tools are thus controlled in a similar manner as bodily limbs. Although this view is not undisputed (e.g., Holmes, Spence, Hansen, Mackay, & Calvert, in press), the present study shows that neurofunctional activation associated with switching between simple mechanical tools was at least located in similar areas as activation caused by complex finger movements. It is therefore likely that motor complexity of tool-use actions is not only determined by the complexity of the operating movement, but also by the the relation between operating movement and tool movement.

To sum up, it seems that movement activation by effect anticipation becomes more complex if the immediate correspondence between movement and effect is

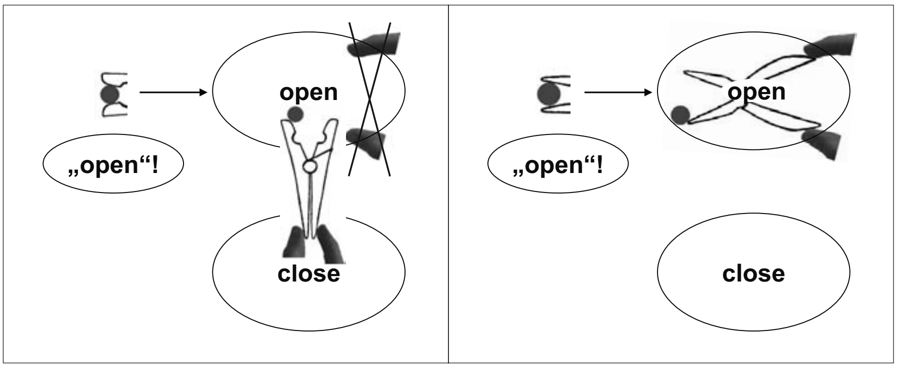

Figure 6.1: Processes which might underlie movement selection in order to achieve desired effects with compatible or incompatible tools: The effect is anticipated in response to the effect cue. For incompatibel tools (left panel), the correct operating movement is automatically activated upon effect anticipation, but has to be inhibited. The correct operating movement is then accessed by imagining the associated tool movement which will lead to the desired effect. For compatible tools (right panel), the compatible operating movement is activated upon effect anticipation and can be selected directly.

disrupted by a tool. The present data suggest that tool-use actions can neither be equated with natural reaching or grasping movements, nor do they require the same amount of controlled processing as movement selection according to an explicit and arbitrarily defined rule. The assignment of a tool to the compatible or incompatible tool category takes some time and an integration between tool and operating hand has to occur. It seems that subsequently, for compatible tools, the adequate operating movement to achieve a required effect is directly provided upon effect anticipation as the default movement and thus in a similar manner as a natural hand movement. For incompatible tools it is accessed by effect anticipation along with imagining the respective tool movement while the compatible movement-effect association, which would be valid for actions performed without a tool, has to be inhibited. These conclusions are summarized in Figure 6.1.

Finally, there remains the question whether it is adequate to speak of a transformation *rule* despite the fact that after tool identification people can rely on movement-effect associations which hold a default status or which can at least be derived from the tool structure. The term rule, however, seems appropriate as it refers to a set of movement-effect transformations which can be realized given a certain tool structure and which entails specific characteristics, for instance compatibility or incompatibility between operating movements and associated effects. Although not explicitly defined, the transformation rule causes transfer effects when people switch between different tools. These transfer effects are abstract in that they do not depend on the repetition of a specific tool, but only on the repetition of compatible or incompatible movement-effect transformations. A transformation rule can thus be regarded as an independent and functionally relevant parameter of a tool use action.

6.3 The Advantage of High Ideomotor Compatibility in Tool Use

In all types of switching paradigms used in the present work (tool, rule or word condition), compatible movement-effect transformations had an outstanding role: RTs and error rates were substantially lower than for incompatible movement-effect transformations. Neither in Experiment 5 (tool switching versus rule switching) nor in Experiment 6 (tool pictures versus written tool names) the size of this compatibility effect interacted with the condition factor. That is, it was not unique to transformation rules which are incorporated in mechanical tools, but probably evoked by the setup of opening and closing movements in the response device and their associated effect movements of opening and closing.

As it has been pointed out in the introduction (see 1.5), strong ideomotor compatibility was presumably the reason for this compatibility effect: For the compatible transformation rule, movements and their associated effects were almost identical. Admittedly, the term "almost identical" might seem too strong because the operating movement of the fingers was spatially segregated from the distal effect movement. It is, however, justified if one assumes a common representational domain in which motor actions and their associated proximal and distal effects are coded in the same format and bidirectionally linked to each other. Such a domain has been proposed by the common coding theory (Prinz, 1990; see 1.2.1.2). In terms of this theory, for the compatible transformation rule, movements and their associated effects rely on the very same codes. The activation of an effect by effect anticipation is thus identical with the activation of the compatible operating movement. These considerations can explain the ease with which compatible movements were realized upon effect anticipation in our switching paradigms on the one hand, and the necessity to inhibit compatible movement-effect associations in the use of incompatible tools on the other hand.

Compatible movement-effect transformations which were afforded by tool pictures showed an additional characteristic: In particular the data obtained in Experiment 2 indicate that after the tool category had been identified, the selection of the compatible operating movement was not only facilitated by automatic activation: This operating movement even seemed to be directly provided with a minimal amount of controlled processing required. There was evidence that such a default status of compatible movement-effect associations could not easily be changed even when incompatible movement-effect associations were favored by the experimental design due to higher probability (Experiment 3) or training (Experiment 4). The reason for this default status of compatible movement-effect associations probably can be ascribed to high ideomotor compatibility between movements and effects, but also to the use of tool pictures. Tool pictures entail high ecological validity. Participants were supposed to imagine that they were operating the tool on the screen and they readily agreed on the impression of directly handling the tool. Tools with a compatible transformation rule were thus direct extensors of the fingers not only in a symbolical, but also in a pictorial sense. After the tool category had been identified, movement selection could thus take place as if the effect was achieved by the hand only.

On the contrary, in the rule-switching and also in the word condition, in which there were no tools which obviously extended the operating fingers, controlled processing was necessary to realize compatible movement-effect transformations. Presumably, an explicit rule was applied for movement selection.

Hunt and Klein (2002) state that in most conventional S-R paradigms, "additional processing is required to translate the task-relevant attribute of the stimulus into the arbitrary response required in the instructions by the experimenter" (p. 536). Still there are other types of compatible actions which are directly or even automatically evoked by an external event without explicit rule application. These are, for instance, prosaccades. Hunt and Klein (2002) assume that a prosaccade, that is, an eye movement towards a stimulus, is an evolutionary provided reflex which can be retrieved instantaneously. Likewise, Reuter, Philipp, Koch, and Kathmann (2005) argue that for prosaccades, responses are not actively selected, but simply triggered by the stimulus, whereas for antisaccades, that is, eye movements away from a stimulus, a motor program has to be chosen actively. Admittedly, saccades seem to have a more automatic character than reaching or grasping movements performed by the hands (Hutton, 2008). Furthermore, the paradigms of switching between pro- and antisaccades used by Hunt and Klein (2002) or by Reuter et al. (2005) and the tool-switching paradigm used in the present work are not directly comparable due to differences in their design and the experimental setup. Still some of their results are similar.

For instance, in the study by Reuter et al. (2005), responses from trial $n-1$ influenced movement selection in trial n only for antisaccades but not for prosaccades. This result reminds of the transition effects obtained in the present work with the tool-switching paradigm. It seems that there is a class of motor actions which hold a default status and thus can be retrieved with minimal requirements of controlled processing – though they may differ in the degree to which they are performed truly automatically.

To conclude, minimal requirements of controlled processing for movement selection in order to achieve required effects with compatible tools were presumably due to two factors: On the one hand, there was high ideomotor compatibility between operating movements and the effect movements which were required at the distal tip of the tool. On the other hand, this high ideomotor compatibility was obviously afforded by the tool structure: The tool obviously extended the fingers which were holding this tool.

6.4 Afforded Rules in Tool Use

Not only the compatible, but also the incompatible transformation rule was obviously afforded by the tool structure in our experiments. The resulting effects of reduced controlled processing in comparison to explicit rule application remind of studies reporting automatic movement activation by visually perceiving a tool (e.g., Tucker & Ellis, 1998). However, there was a crucial difference between both types of studies: In activation-by-perception studies like the one by Tucker and Ellis (1998), movement activation was in accordance with the physical surface features of the tool, but not effect-oriented. On the contrary, in the tool-switching paradigm, participants had to select a specific operating movement in order to obtain a specific effect.

It may well be that tool perception in our experiments caused automatic motor activation in accordance with physical surface features of the tool as well. However, this activation should have been very much alike for all tool types because all the tools were operated in a similar manner. Automatic motor activation by tool perception was thus not sufficient to select the specific operating movement in order to obtain a specific effect. To this end, the tool-associated transformation rule had to be realized.

Yet there are at least two important parallels between the classical view of tool affordances and the notion of afforded transformation rules. First, also in the tool-switching paradigm, movement selection in order to achieve a required effect seemed to rely on visually perceiving the tool (see Experiments 5-7). For instance, only with *pictures* of compatible tools, there were minimal requirements of controlled processing for movement selection. Second, transformation rules in tool use as well as classical tool affordances seem to be associated with action-related knowledge, but not with tool semantics. The target area of the ventral stream which processes object semantics is the temporal cortex, whereas the parietal cortex is the target area of the dorsal stream concerned with knowledge about object manipulation (Goodale & Milner, 1992; Milner & Goodale, 1995). In our work, the differences between compatible and incompatible tools were associated with activation in frontal, parietal, occipital, and subcortical areas. Notably, temporal areas were not involved. Similarly, automatic motor activation by object perception as described in the study by Tucker and Ellis (1998) is accompanied by activation in parietal, but not in temporal areas (e.g., Grèzes et al., 2003).

In sum, the concept of afforded transformation rules in tool use cannot be equated with the classical notion of tool affordances which refers to automatic motor activation by tool perception but still there are parallels between both concepts.

It might be suspected that also abstract rule cues can obtain the capacity to afford a compatible or incompatible transformation rule if people learn that these cues are reliably associated with compatible or incompatible movement-effect transformations. In this case, after some practice with abstract rule cues, controlled retrieval of explicit knowledge should be replaced by an on-line process of deriving the information needed for movement selection directly from the rule cue. As a consequence, the differences in controlled processing required for movement selection in response to tool pictures or abstract rule cues, respectively, should decrease. In Experiment 5 there was the chance to test this assumption. In a post-hoc analysis, controlled processing, which was measured as the influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n, was compared between the first and the second block of trials during the main experiment. The result contradicted the assumption that affordances can easily be learned for abstract rule cues. The effect of reduced controlled processing for the tool-switching as compared to the rule-switching condition did not change between the first and the second block of trials ($F(1, 38) < 1$, $MSE = 19273.9$ for the four-way interaction between rule transition, movement transition, paradigm and block). There was thus no tendency for assimilation between tool switching and rule switching as regards the amount of controlled processing they require – at least in the course of the 386 experimental trials. This was true although movement selection was generally easier in the second as compared to the first block: There was a decrease in RT in both conditions ($F(1, 38) = 66.5$, $MSE = 58347.1$; $p < 0.001$). These results, however, leave open whether simply much more experience with these abstract rule cues would be required, or whether only transparent, and not abstract rule cues can afford a transformation rule.

6.5 Theoretical Perspectives

Dual-Route Models and High Ideomotor Compatibility. Although there was evidence that the application of compatible and incompatible transformation rules in tool use differs from explicit rule application, theories of explicit rule application cannot totally be ignored in this discussion. The data of the present work turn upside down some of the empirical findings and theoretical assumptions which have been reported for conventional S-R mapping paradigms. This finding is all the more relevant as it is generally assumed that the results from conventional S-R paradigms also apply to many instances of response selection in everyday life.

For conventional S-R mapping paradigms, it has been postulated that the automatic activation of a compatible response assumed by dual-route models (e.g., Kornblum et al., 1990) is suppressed if compatible and incompatible trials are mixed (e.g. R. de Jong, 1995). Consequently, response selection in mixed blocks seems to occur exclusively via the route of explicit rule application. This theoretical assumption has been motivated by the finding that with mixed presentation as compared to pure blocks, responding is generally slowed, but especially so for compatible trials. The compatibility effect is thus reduced or even eliminated (e.g., Duncan, 1977; Ehrenstein & Proctor, 1998; Shaffer, 1965; Stoffels, 1996). A related observation comes from task-switching paradigms: If there are two tasks and one is more difficult than the other one, it is often easier to switch to this more difficult task. For instance, switch costs are larger for switching to the compatible as compared to the incompatible task (Crone, Bunge, Molen, & Ridderinkhof, 2006). It has been suggested that participants prepare in advance for the more difficult task and inhibit the easier task.

On the contrary, in the tool-switching paradigm, there was neither a reduction nor even an elimination of the compatibility effect with mixed presentation. Quite the contrary, in Experiment 1, the compatibility effect even had the extraordinary size of 319 ms with mixed presentation of compatible and incompatible tools. However, in the pure blocks of the first training session in Experiment 4, responding was generally faster than with mixed presentation, but the compatibility effect was only 36 ms. That is, conversely to what has been reported for conventional S-R mapping paradigms, in our experiments, the compatibility effect was much higher in mixed than in pure blocks. Additionally, switching costs were not larger for switching to the compatible as compared to the incompatible transformation rule. These results were not specific to tool stimuli, but were similarly obtained in the rule-switching and the word condition.

In the literature, there are indeed some examples in which an enhancement instead of a reduction of the compatibility effect occurs for mixed blocks. However, these are cases in which conceptual and perceptual similarity between stimuli and their associated responses was rather low, for instance when participants had to respond to location words by button presses (Vu & Proctor, 2004). Consequently, these effects cannot be compared with the compatibility effect in the tool-switching paradigm: Here, we even have high ideomotor compatibility.

It thus seems that in contrast to conventional S-R mapping paradigms, participants did not suppress the compatible movement in advance when there was an equal likelihood for compatible and incompatible tools – although they might have been able to do so as depicted by the data of the majority incompatible condition in Experiment 3. Quite the contrary, the compatible operating movement seemed to be strongly activated in all trials and then had to be inhibited if an incompatible transformation rule was required. The results of Experiment 7 were in congruence with this assumption. Movement selection in order to operate incompatible tools was associated with activation in several areas of conflict detection and movement inhibition, as there are the ACC, the IFJ, the inferior frontal cortex, and the medial part of the pallidum.

It was neither the aim of this study to formulate a new theory which centers on detailed differences between conventional S-R compatibility effects on the one hand and compatibility effects in the use of simple mechanical tools on the other hand, nor are the present data suffient to do so. Still some considerations will be expressed in the following which may account for the present findings.

We already stated that there was high ideomotor compatibility between movements and their associated effects for the compatible transformation rule. In terms of the common coding theory (Prinz, 1990; see 1.2.1.2), movements and effects relied on identical codes and as a consequence, compatible movements were activated automatically upon effect anticipation. Most notably, in all our experiments, the action always started with externally cued effect anticipation and consequently, it can be assumed that in any case, the compatible movement was automatically activated first. The suppression of this movement should thus have been an effortful process and probably would not have compensated for its benefit in half of the trials in which the incompatible transformation rule was required. Only in the majority incompatible condition in Experiment 3, the effort of suppressing the compatible movement-effect association seemed worth its benefit.

It can only be speculated that participants changed their strategy of movement selection with blocked presentation for which the compatibility effect was much smaller and, despite an equal number of compatible and incompatible trials, could even be eliminated. Again, such an elimination stands in contrast with the results of conventional S-R compatibility paradigms in which practice only serves to reduce but not to eliminate the compatibility effect. A possible explanation might be that in pure blocks, participants were able to recode the operating movements according to the currently relevant transformation rule and compatibility between movements and effects thus did not matter any more. Indeed there is evidence that the importance of operating movements is much reduced when people use the same tool over longer periods of time (Müsseler & Sutter, in press). In this case, people might even be unaware of their operating movements and, independent of the required transformation, the distal effect gains in importance for directly activating the motor action. As a consequence, the disadvantage for incompatible movement-effect transformations should disappear in longer periods of using the same tool (or tools with the same transformation rule, respectively) – which is exactly what we observed in the training blocks.

Finally, it has to be noted that an elimination of the compatibility effect in mixed blocks has been observed for S-R mappings which have been characterized as being of high ideomotor (in-)compatibility (Vu & Proctor, 2004). It would be interesting to find the reason for this discrepancy between the findings by Vu and Proctor (2004) and our work by varying the experimental setup between theirs and ours in terms of response mode, stimulus type, and S-R or R-E context.

To summarize, several results obtained with our switching paradigm contradict the results obtained with conventional S-R compatibility paradigms. The reason for these discrepancies can presumably be ascribed to high ideomotor compatibility between movements and their associated effects in the present paradigm. One should thus be cautious to generalize the theoretical assumptions derived from conventional S-R compatibility paradigms to another context of rule application.

Internal Models of Transformation Rules. A second theoretical line points to the internal model approach which has been proposed to explain how people apply transformation rules in tool use. This approach is primarily based on data obtained for on-line adaptation to opaque movement transformations. Nevertheless, it has been postulated that it applies to the use of simple mechanical tools and to tool-use in everyday life as well (Imamizu, Higuchi, et al., 2007). In the present work, especially the results from Experiment 7 fit well with some of the central assumptions of the internal model approach. Similarities and differences will be discussed in the following, centering on differences between compatible and incompatible movement-effect transformations first and then on the process of switching between transformation rules.

It has been postulated that internal models of movement-effect transformations are located in the cerebellum (Imamizu et al., 2003). Activation is often found bilaterally in the cerebellar lobes (e.g., Imamizu et al., 2003, 2004). In general, this area has been associated with the mental simulation of movement, and indeed, an internal model seems to simulate the movement-effect transformations of a tool. In our Experiment 7, activation in these cerebellar areas was stronger for tools with an incompatible as compared to a compatible transformation rule with the peak of activation on the ipsilateral side of hand movement. This kind of activation might thus be related to an internal model simulating the movement-effect transformations an incompatible tool. Additional activation in the IPS, the dorsal premotor cortex, and particularly in the extrastriate cortex suggested that the simulation of incompatible movement-effect transformations was not abstract but based on visuomotor imagery of the tool movement. Furthermore, the results from the behavioral experiments 5 and 6 were in line with the assumption that movement selection in response to tool pictures was primarily based on visual information. To our knowledge, such a result has not been found in previous studies investigating movement-effect transformations in the framework of the internal model approach. This is not surprising because opaque transformations have mostly been used in these studies. Evidently, visuomotor imagery to back up an internal model of a tool is only possible when there is a concrete tool body whose movement can be imagined.

The reverse contrast of compatible versus incompatible tools did not show any activation although in former research, different kinds of transformations were associated with different internal models whose activation could spatially be segregated. Still, the conclusion that there was no internal model simulating movement-effect transformations of compatible tools is premature. As illustrated before, movement selection in order to achieve a desired effect with a compatible tool was presumably very similar to using the fingers only to achieve the effect. That is, an internal model simulating the movement-effect transformations of the fingers and an internal model simulating the movement-effect transformations of a compatible tool were presumably very much alike. In the tool-switching paradigm, finger movements, however, were required to handle both, compatible and incompatible tools. It therefore might be that activity associated with finger movements on the one hand and with the use of compatible tools on the other hand could not be disentangled with the present paradigm.

In former studies, the processes of switching between different transformation rules or between different internal models respectively, have been investigated in two kinds of paradigms. In one kind of paradigm, a switch is not signalled explicitly and thus, on-line adaptation to the new transformation rule has to occur (Imamizu et al., 2004). In the other kind of paradigm, there is an explicit context cue which signals the valid transformation (Bursztyn et al., 2006; Imamizu & Kawato, 2008). In this case, the adequate internal model can be selected in a predictive manner before acting. Only this latter kind of paradigm seems of relevance to our work because in the tool-switching paradigm, the transformation rule could be accessed by tool identification prior to acting. In Experiment 7, switching-related activity was found in cerebellar regions in the anterior vermal region and the dentate nucleus which have ordinarily been associated with increased movement complexity of finger movements (Catalan et al., 1998; Debaere et al., 2003). As it has already been illustrated in section 5.1 and 6.2, it seems that this activity was due to integration between the operating finger movements and the new type of tool. These regions have not yet been reported for predictive switches between opaque transformation rules. This discrepancy can probably be attributed to the fact that opaque transformations do not figuratively extend the bodily effectors. For instance, in the study by Bursztyn et al. (2006) who investigated the processes of switching between opaque transformation rules, switching-related cerebellar activity was located more laterally in areas which have not been associated with basal motor, but more abstract processing.

Finally, despite its relevance for motor or motor-related processing, cerebellar activation in the lateral lobes and even in the dentate nucleus has also been associated with purely cognitive functioning, for instance with conflict resolution and cognitive control (e.g., Berger et al., 2005; Kim, Ugurbil, & Strick, 1994; Schweizer et al., 2007), or with the process of updating S-R mappings according to an explicit rule (Bischoff-Grethe et al., 2002). Still there are three reasons which render unlikely that cerebellar activity in Experiment 7 was purely cognitive and not at least motor-related. First, lateral cerebellar activity, with the peak of activation on the right side was found for operating incompatible in contrast to compatible tools. Given the ipsilateral coding of movement in the cerebellum, this kind of activity was most likely associated with imagining the tool movement to access the associated operating movement of the right hand. Second, activation in the extrastriate cortex obtained in our study strongly favors the hypothesis of visuomotor simulation and not the one of explicit rule application (e.g., Vingerhoets et al., 2002). Third and finally, switching-related vermal activity was located exactly in the area associated with finger movements of the right hand while participants indeed had to use these fingers in order to operate the tool. It thus seems most plausible that this activation was purely motor-related.

To summarize, it seems that the internal model approach can be adapted to explain transformation rule application in the use of simple mechanical tools if one abstracts from the original notion that internal models specify basal movement parameters only. Still it has to be taken into account that the presence of a concrete tool body introduces some differences to opaque transformations which have often been used to investigate internal models. Crucial differences are the following: On the one hand, if a simple mechanical tool is visually perceived, the simulation of its movement-effect transformations seems to rely on visuomotor imagery. On the other hand, motor integration seems to occur between a simple mechanical tool and the operating fingers. Furthermore, whereas it has been assumed that internal models of opaque transformation rules are not consciously realized, it is still an open question to which degree the application of the tool-associated transformation rule in the tool-switching paradigm was a conscious process.

6.6 Practical Implications

A glance into a well-equipped tool box or an inspection of a surgeon's instruments will provide several examples of simple mechanical tools which entail compatible as well as incompatible transformation rules. The concrete situation of tool application should determine whether the effects of the present work are of practical relevance. In the following it will be assumed that the aim is to optimize operational procedures and to minimize errors. In this case, an obvious recommendation derived from the present work is to avoid tools with an incompatible transformation rule if possible. Results indicate that for these the selection of the operating movement to achieve a desired effect is not as efficient as for tools with a compatible transformation rule and stronger controlled processes are required. This should apply especially to situations in which people have to switch between different tools under pressure of time. Sometimes though, there may be no way to avoid a tool with an incompatible transformation rule because the incompatible movement-effect transformation results from a fulcrum or a spring which is necessary for adequate functioning. In this case, it might even be helpful to add a mechanism which re-inverses the distal effect in a way that it becomes compatible to the operating movement again. However, it remains to clarify whether such a more complicated tool structure would cancel out the benefit of compatibility between movements and their associated effects.

A second practically relevant finding of the present work are the costs associated with switching between tools incorporating different transformation rules as compared to a rule repetition benefit. For tools with an incompatible transformation rule, switching seems especially detrimental if similar operating movements have to be applied to compatible and incompatible tools. The preceding movement-effect transformation exerts a strong influence on the selection of the current operating movement. However, it has to be kept in mind that even for tools with compatible movement-effect transformations some time is requires to update the transformation rule. This time required, however, seems to be independent of the preceding and the current operating movement.

Furthermore, mechanical transparency can be recommended. There is a tendency to replace simple mechanical tools with more and more complicated technical devices for which the operating movements are not self-evident. The present work suggests that even if the same operating movements are required for simple mechanical tools and for tools with a non-transparent structure, the former will require less controlled processing than the latter. A possible way to reduce controlled processing for tools with a nontransparent structure might be to strengthen the affordances of these tools by additional features like arrows or by a design which emulates transparency.

Finally, effects in the range of tenth or hundredth of milliseconds as obtained in the present work seem negligible in most situations of tool use in everyday life.

Still, it has to be considered that the additional amount of controlled processing which is required for operating tools with an incompatible transformation rule or tools with a non-transparent structure might become critical if attentional resources are lacking for a concurrent task. Also it has to be kept in mind that at least in the present work, training and strategy did not easily change the amount of controlled processing required for movement selection.

In sum, it seems advantageous if tool structures are adapted to human expectancies and habits. That is, they should ideally retain the overlearned correspondence between body movements and their associated effects, they should obviously afford their associated movement-effect transformations, and the kind of transformation between operating movements and resulting effects should be kept as constant as possible when people switch between different tools. Most efficient in terms of movement selection seems a tool which simply extends the operating hand, but effectively strengthens one of its functions (e.g., by power transmission). Although some of these recommendations might seem trivial, they are often violated as Donald Norman states in his book "Things that make us smart: Defending human attributes in the age of the machine": "We are overwhelmed with an onslaught of technological devices that have been designed from the machine-centered point of view, technological devices that confuse us, that alter normal social relations. Our self-created technological world controls and dominates us. The signs are clear, from confusion and difficulty in using household and office appliances to a heavy incidence of human error in industry." (Norman, 1994, p. 11).

6.7 Restrictions of the Current Work

Presumably the most relevant question concerning the results of controlled experimental paradigms is whether these results can be generalized to situations outside the laboratory. Ecological validity is relatively high in the present work as compared to conventional S-R mapping studies. Still, there are some points which might restrict generalizability to tool use in everyday life.

First, in the tool-switching paradigm used in the present work, tools were displayed on a computer screen and the same response device was used for different kinds of tools. This way, tactile information idiosyncratic to each tool got lost. As a consequence, only the tool appearance could be used to select the correct operating movement in the experiments presented here, whereas the combination of visual and tactile information can be used for movement selection in actual tool use.

Second, in everyday life, context information might play a crucial role to facilitate adequate movement selection in tool use, but it was not present in our experiments. For instance, a surgeon might be able to operate his instruments flawlessly in the operating room and in a fixed sequence, but might make more mistakes if he is tested in a different context or is disturbed in his usual sequence. This lack of context information is perhaps also the reason why error rates were relatively high in the experiments of this study.

Third, tools normally do not instantaneously change in the hands of the person who has to operate them. There is often a longer interval between the use of different tools and also a single tool is often used for a longer operating sequence. However, there are situations in everyday life which come close to instantaneous changes, for instance when tools are consecutively passed to a dentist or to a surgeon by the assistant. Also in this case, rapid switches between tools are required.

Forth, always the same two operating movements to achieve the same two effect movements had to be executed for different types of tools in the tool-switching paradigm. Still, there is a multitude of further operating movements and effects which can be realized with diverse tools. At least, however, opening and closing movements of the fingers associated with opening and closing movements of distal grippers are typical movements in the use of simple mechanical tools.

Finally, in everyday life, people are well able to operate tools they know without visually perceiving them. One might therefore argue that in the present work tool perception on the screen activated processes visuomotor imagery, but that these processes had not much to do with the processes involved in movement selection in order to operate real tools. The present data, however, do not exclude that the processes of anticipating a desired effect along with imagining the associated tool movement might also be triggered by perceiving a real tool via others than the visual senses.

Although there are thus some obvious objections against unrestrained generalizability, the main findings and conclusions of the present work most likely can be applied to actual tool use as well: On the one hand, also in actual tool use, detrimental effects of compatibility have been observed (e.g., in laparoscopic surgery). On the other hand, the affordance of a tool to apply a specific transformation rule is presumably even stronger in actual tool use than in the tool switching paradigm. That is, the advantage of high ideomotor compatibility and the capacity of tools to afford their transformation rules can be regarded as important characteristics of transformation rules which are incorporated in simple mechanical tools.

To conclude, the present results obtained in a highly controlled experimental setting call for the continuation of research in an applied setting and, most importantly, the results of the present study seem to justify this effort.

6.8 Conclusions

The present work was motivated by the question of how transformation rules are represented and applied for movement selection in the use of simple mechanical tools which are well-known from everyday life. New in this work is the use of a tool-switching paradigm: Simple mechanical everyday tools like clothespins and pliers had to be operated in a controlled experimental setting. This paradigm allowed us to investigate the independent representation of tool-associated transformation rules in the cognitive system. It revealed a rule repetition benefit and a strong advantage for compatible as compared to incompatible movement-effect transformations in tool use. It furthermore showed that less controlled processing was required for the selection of an operating movement in response to tool pictures as compared to abstract rule cues. It remains to clarify to what extent these effects influence the efficiency of our actions in everyday routines of tool use. Altogether, the present work reveals important characteristics of tool-associated transformation rules and hopefully will be helpful to stimulate future research in the context of applied tool use.

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Bibliographische Darstellung

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Compatible and Incompatible Transformation Rules in Tool Use

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Fakultät für Biowissenschaften, Pharmazie und Psychologie der Universität Leipzig

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Referat

Spatial transformations between operating movements at the tool's handle and their distal effects at the tool's tip are a characteristic feature of tool-use actions. The aim of this thesis was to elucidate how people represent and apply compatible (operating movement = effect movement) and incompatible (operating movement ≠ effect movement) transformation rules when they use simple mechanical everyday tools.

In the seven experiments presented in this thesis, a tool-switching paradigm was applied. In each trial the picture of a simple mechanical tool appeared on the screen. Participants had to operate this tool via an operating device in order to achieve required effects at the tool's distal tip. Tools incorporated either a compatible or an incompatible transformation rule. Furthermore, there were trials in which the tool changed but the transformation rule remained the same from trial $n-1$ to trial n and trials in which the tool and also the transformation rule changed. Reaction times and error rates as well as functional imaging data were collected as dependend variables.

Taken together, the data provide evidence for an independent and functionally relevant representation of tool-associated transformation rules in the cognitive system, for the advantage of high ideomotor compatibility between movements and their associated effects, as well as for the capacity of a simple mechanical tool to afford a specific transformation rule. These effects can be regarded as important characteristics of transformation rules in the use of simple mechanical tools and in the present experiments, they substantially influenced processes of movement selection.

Zusammenfassung

Einleitung

Ein charakteristisches Merkmal einer Werkzeughandlung ist die räumliche Transformation zwischen der Handbewegung, die das Werkzeug bedient, und dem daraus resultierenden Effekt, nämlich der Werkzeugbewegung. Die Art dieser Transformation hängt von der Werkzeugstruktur ab. Die vorliegende Dissertation beschäftigt sich mit der Frage, wie Menschen kompatible (Handbewegung ist räumlich kompatibel zum resultierenden Effekt) und inkompatible (Handbewegung ist räumlich inkompatible zum resultierenden Effekt) Transformationsregeln repräsentieren und anwenden, wenn sie einfache mechanische Alltagswerkzeuge bedienen, um mit diesen bestimmte Effekte zu erreichen. Es gibt bereits Evidenz, dass solche Bewegungs-Effekt Transformationen im Werkzeuggebrauch einen wesentlichen Einfluss auf Prozesse der Handlungsplanung haben können (Kunde et al., 2007; Massen & Prinz, 2007b). Auf konzeptueller Ebene ist es sogar möglich, die Auswahl der richtigen Handbewegung um einen bestimmten Effekt zu erreichen mit der Anwendung einer expliziten Zuordnungsregel zu erklären.

Jedoch sprechen zwei Gründe dafür, dass eine Gleichstellung von Transformationsregeln einfacher mechanischer Werkzeuge und expliziten Zuordnungsregeln nicht zutreffend ist. Erstens besitzt ein Werkzeug einen Aufforderungscharakter ('affordance'), eine ganz bestimmte Transformationsregel anzuwenden. Folglich kann die Hypothese aufgestellt werden, dass die Handbewegung, die zu einem erwünschten Effekt führt, direkt aus dem Werkzeug erschlossen wird ('visuomotor imagery'). In diesem Fall sollte die Auswahl dieser Handbewegung in geringerem Maße kontrollierte Verarbeitungsmechanismen erfordern als für den Abruf einer expliziten Zuordnungsregel notwendig wären. Zweitens besteht für Werkzeuge mit einer kompatiblen Transformationsregel hohe ideomotorische Kompatibilität (Greenwald, 1972) zwischen Handbewegungen und daraus resultierenden Effektbewegungen: Diese sind quasi identisch. Daher kann vermutet werden, dass die Handbewegung um einen erwünschten Effekt zu erreichen sogar direkt als eine Art Default-Bewegung bereitgestellt wird.

Diese theoretischen Überlegungen motivierten die Experimente dieser Dissertation. Ein Werkzeugwechsel-Paradigma wurde angewandt. In jedem Durchgang erschien ein einfaches mechanisches Alltagswerkzeug auf dem Bildschirm und eine farbige Kugel musste im Werkzeug zusammengedrückt oder aus dem Werkzeug fallengelassen werden. Die Farbe der Kugel spezifizierte, welcher dieser Effekte

(Zusammendrücken oder Fallenlassen) erreicht werden sollte. Jedes der Werkzeuge realisierte entweder eine kompatible Transformationsregel (z.B., Zange und Pinzette, auch 'kompatible Werkzeuge' genannt) oder eine inkompatible Transformationsregel (z.B., Wäscheklammer und Klemme, auch 'inkompatible Werkzeuge' genannt). Probanden bedienten eine Antwortapparatur mit den Fingern, als ob sie das Werkzeug direkt bedienen würden. Für kompatible Werkzeuge war die Fingerbewegung folglich identisch mit dem resultierenden Effekt (etwa führte bei der Zange eine Schließbewegung der Finger zu einer Schließbewegung der Greifer). Für inkompatible Werkzeuge war die Fingerbewegung entgegengesetzt zum resultierenden Effekt (etwa führte bei der Wäscheklammer eine Schließbewegung der Finger zum Öffnen der Greifer).

Basierend auf diesem Paradigma wurde untersucht, ob Transformationsregeln im Werkzeuggebrauch eine eigenständige und funktional relevante Repräsentation im kognitiven System besitzen. Zu diesem Zweck wurden Reaktionszeiten und Fehlerraten in Durchgängen, in denen das Werkzeug von Durchgang $n-1$ zu Durchgang n wechselte, die Transformationsregel aber dieselbe blieb, verglichen mit der Leistung in Durchgängen, in denen das Werkzeug und auch die Transformationsregel wechselten. Außerdem wurden die Unterschiede zwischen kompatiblen und inkompatiblen Werkzeugen untersucht. Verglichen wurden hierfür Reaktionszeiten und Fehlerraten, als auch das Maß kontrollierter Verarbeitung für die Auswahl der richtigen Handbewegung. Ein stärkerer Einfluss der spezifischen Bewegungs-Effekt Transformation in Durchgang $n-1$ auf die Auswahl der Handbewegung in Durchgang n wurde als Evidenz für ein größeres Maß an kontrollierter Verarbeitung angesehen (Waszak et al., 2005).

Zusammenfassung der wissenschaftlichen Ergebnisse

In Experiment 1 wurde das oben beschriebene Werkzeugwechsel-Paradigma angewandt. Reaktionszeiten und Fehlerraten der Probanden waren niedriger, wenn die Werkzeuge in Durchgang $n-1$ und Durchgang n die gleiche Transformationsregel hatten (z.B., Wechsel zwischen Pinzette und Zange) als wenn die Transformationsregel wechselte (z.B., Wechsel zwischen Wäscheklammer und Zange). Diese Ergebnisse zeigen, dass kompatible und inkompatible Transformationsregeln einfacher mechanischer Werkzeuge eine eigenständige und funktional relevante Repräsentation im kognitiven System besitzen. Außerdem zeigten sich Unterschiede zwischen kompatiblen und inkompatiblen Transformationsregeln: Es gab einen Kompatibilitätseffekt. Probanden waren schneller und korrekter in Durchgängen mit kompatiblen im Vergleich zu inkompatiblen Werkzeugen.

Darüber hinaus beeinflusste für inkompatible Werkzeuge die Bewegungs-Effekt Transformation in Durchgang $n-1$ die Auswahl der Handbewegung in Durchgang n. Für kompatible Werkzeuge gab es einen solchen Einfluss nicht. Diese Ergebnisse deuten darauf hin, dass kontrollierte Verarbeitung für die Auswahl der richtigen Handbewegung notwendig war, um mit einem inkompatiblen Werkzeug einen erwünschten Effekt zu erreichen, während für kompatible Werkzeuge die Notwendigkeit kontrollierter Verarbeitungsprozesse minimal war.

In Experiment 2 wurde der Default-Status von Bewegungs-Effekt Transformationen, die mit kompatiblen Werkzeugen realisiert werden, getestet. Die Wiederholung einer kompatiblen Transformationsregel wirkte sich vorteilhaft auf Reaktionszeiten und Fehlerraten der Probanden aus. Dieser Effekt war unabhängig davon, ob die Werkzeuge in Durchgang $n-1$ und Durchgang n in der gleichen oder in unterschiedlicher (horizontaler oder vertikaler) räumlichen Dimension präsentiert wurden und das response set folglich in beiden Durchgänge das gleiche, oder ein unterschiedliches war. Für inkompatible Werkzeuge gab es nur einen Wiederholungsvorteil für Werkzeuge innerhalb einer räumlichen Dimension. Die Ergebnisse von Experiment 2 unterstützten somit die Hypothese, dass Bewegungs-Effekt Transformationen, die mit kompatiblen Werkzeugen realisiert werden konnten, einen Default-Status besaßen and daher direkt bereitgestellt wurden, wenn die kompatible Transformationsregel aktiviert war.

In Experiment 3 und 4 wurde untersucht, ob die gefundenen Unterschiede zwischen Handlungen mit kompatiblen und inkompatiblen Werkzeugen durch Manipulation der Wahrscheinlichkeit einer bestimmten Transformationsregel oder durch Training reduziert oder sogar umgekehrt werden können. In Experiment 3 wurde der Kompatibilitätseffekt eliminiert, wenn die Werkzeuge in der Mehrheit der Durchgänge inkompatibel waren. Dennoch änderte sich das Maß kontrollierter Verarbeitung, das für die Bewegungsauswahl notwendig war, nicht bedeutend. Außerdem gab es Hinweise auf aktive und strategische Suppression kompatibler Bewegungs-Effekt Assoziationen. Umgekehrt wurden die Unterschiede zwischen kompatiblen und inkompatiblen Werkzeugen bezüglich ihrer Erfordernis kontrollierter Verarbeitung zur Bewegungsauswahl noch signifikant verstärkt, wenn die Werkzeuge in der Mehrheit der Durchgänge kompatibel waren.

In Experiment 4 war das Training mit inkompatiblen Werkzeugen in vier aufeinanderfolgenden Sitzungen erfolgreich und der Kompatibilitätseffekt kehrte sich im Vergleich reiner kompatibler und reiner inkompatibler Blöcke um. Im sich anschließenden Werkzeugwechsel-Paradigma wirkten sich diese Trainingseffekte jedoch nicht aus. Es gab wieder einen Kompatibilitätseffekt, und wiederum war die Erfordernis kontrollierter Verarbeitung zur Bewegungsauswahl höher für inkompatible als für kompatible Werkzeuge. Der Default-Status kompatibler Bewegungs-Effekt Transformationen konnte also weder durch Wahrscheinlichkeitsmanipulation noch durch Training leicht aufgehoben werden. Es wurde vorgeschlagen, dass der Grund für einen solchen Default-Status die hohe ideomotorische Kompatibilität zwischen Handbewegungen und daraus resultierenden Effektbewegungen war.

In Experiment 5 und 6 wurde untersucht, ob der Aufforderungscharakter einfacher mechanischer Werkzeuge, eine bestimmte Transformationsregel anzuwenden, für die Bewegungsauswahl genutzt wird. In Experiment 5 wurden die Unterschiede zwischen kompatiblen und inkompatiblen Werkzeugen mit abstrakten Regel-Cues, die die Gültigkeit kompatibler oder inkompatibler Transformationsregeln anzeigten, repliziert. Jedoch war für die Bewegungsauswahl in Reaktion auf einen abstrakten Regel-Cue ein höheres Maß kontrollierter Verarbeitung notwendig als für die Bewegungsauswahl in Reaktion auf ein Werkzeugbild. Das gleiche galt in Experiment 6, in welchem geschriebene Werkzeugnamen mit Werkzeugbildern kontrastiert wurden. Diese Ergebnisse legen nahe, dass die Bewegungsauswahl im Werkzeugwechsel-Paradigma ein Online-Prozess war, welcher auf visueller Information und praktischer Erfahrung mit mechanischen Geräten basierte, und nicht primär ein gedächtnisbasierter Prozess, der auf explizites Wissen zurückgriff. Es wurde vorgeschlagen, dass für kompatible Werkzeuge die korrekte Fingerbewegung direkt mit der Antizipation des erwünschten Effektes bereitgestellt wurde. Für inkompatible Werkzeuge wurde angenommen, dass der erwünschte Effekt zusammen mit der zugehörigen Werkzeugbewegung antizipiert und so die korrekte Fingerbewegung erschlossen wurde ('visuomotor imagery').

In Experiment 7 wurde die Anwendung von Transformationsregeln im Werkzeugwechselparadigma mit ereigniskorrelierter funktioneller Magnetresonanztomographie untersucht. Der Kontrast inkompatibler versus kompatibler Werkzeuge zeigte Aktivierungen im interparietalen Sulcus, im Precuneus, im dorsalen prämotorischen Cortex, im lateralen Cerebellum und im extrastriatären Cortex. Diese Aktivierungen können im Sinne von 'visuomotor imagery' zur Bewegungsauswahl für die Handhabung inkompatibler Werkzeuge interpretiert werden. Weiterhin waren in diesem Kontrast der anteriore cinguläre Cortex (ACC), die 'inferior frontal junction' (IFJ), der inferiore frontale Cortex und das mediale Pallidum aktiviert. Diese Aktivierungen lassen erkennen, dass Bewegungsinhibition und kognitive Kontrolle für die Handhabung inkompatibler verglichen mit kompatiblen Werkzeuge notwendig war. Die Ergebnisse wiesen somit wiederum auf einen

Default-Status kompatibler Bewegungs-Effekt Transformationen hin, sowie auf Prozesse von 'visuomotor imagery' für die Umsetzung inkompatibler Bewegungs-Effekt Transformationen. Der Kontrast von Transformationsregel-Wechsel versus Wiederholung zeigte Aktivierungen im Gebiet der anterioren Vermis sowie im Nucleus Dentatus. Beide Regionen deuten auf einen Prozess der Integration zwischen Werkzeug- und Handbewegung hin. Diese Ergebnisse zeigen, dass sich die Anwendung von Transformationsregeln im Werkzeugwechsel-Paradigma in wichtigen Aspekten von der Anwendung expliziter Zuordnungsregeln unterschied.

Insgesamt erbringen die Experimente dieser Dissertation Evidenz für eine unabhängige und funktional relevante Repräsentation werkzeugbasierter Transformationsregeln im kognitiven System, für einen Vorteil hoher ideomotorischer Kompatibilität zwischen Handbewegungen und Effektbewegungen, sowie für den Aufforderungscharakter einfacher mechanischer Werkzeuge, zur Bewegungsauswahl eine bestimmte Transformationsregel anzuwenden.

Summary

Introduction

Spatial transformations between operating movements at the tool's handle and their effect movements at the tool's distal tip are a characteristic feature of tool-use actions. The kind of transformation depends on a tool's structure. The aim of this thesis was to elucidate how people represent and apply compatible transformation rules (operating movement = effect movement) and incompatible transformation rules (operating movement $\neq$ effect movement) when they use simple mechanical everyday tools. Previous research has revealed evidence that the transformation between desired effects and required operating movements can substantially influence the processes of movement selection when people use simple mechanical tools (Massen & Prinz, 2007b; Kunde et al. 2007). On a conceptual basis, it is even possible to explain movement selection in tool use in terms of the application of an explicit mapping rule which has to be retrieved from long-term memory.

However, there are two reasons why it might be inadequate to put transformation rules of simple mechanical tools on equal footing with explicit mapping rules. First, tool-associated transformation rules are afforded by the tool's structure. Consequently, it can be hypothesized that the adequate operating movement to achieve a desired effect is accessed by anticipating this desired effect along with imagining the associated tool movement – a process referred to as visuomotor imagery. If this was true, less controlled processing should be required for transformation rule application in tool use than for the retrieval of an explicit mapping rule from long-term memory. Second, for tools that incorporate a compatible transformation rule and simply extend the effectors, the operating movement entails high ideomotor compatibility (Greenwald, 1972) with the distal effect movement: Both are quasi identical. The operating movement thus might even be activated automatically upon effect anticipation and then might be selected as the default movement.

These theoretical considerations motivated the experiments presented in this thesis. A tool-switching paradigm was applied and participants had to switch between simple mechanical everyday tools displayed on the screen. Each of these tools incorporated either a compatible (pliers and tweezers, also referred to as 'compatible tools') or an incompatible (clothespin and clip, also referred to as 'incompatible tools') transformation between operating movements and distal effects at the tip of the tool. Participants had to operate each tool by their fingers via a response device as if they were directly handling it. In each trial, the task was to squeeze or to release an object in the distal pincers of the tool by performing the adequate operating movement. That is, for tools with a compatible transformation rule, finger movements were identical with the resulting effect movements (e.g., closing the fingers to operate pliers resulted in a closing movement of the pliers' distal pincers). For tools with an incompatible transformation rule, finger movements were opposite to the resulting effect (e.g., closing the fingers to operate a clothespin resulted in an opening movement of the clothespin's distal pincers).

Based on this paradigm, it was investigated whether tool-associated transformation rules obtain an independent and functionally relevant representation in the cognitive system. To this end, reaction times and error rates in trials in which the tool changed but the transformation rule remained the same from trial $n-1$ to trial n were compared with the performance in trials in which the tool and also the transformation rule changed. Furthermore, the differences between operating tools with an incompatible as compared to a compatible transformation rule could be assessed in terms of reaction times and error rates, but also in their requirement of controlled processing for movement selection. Greater influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was taken as evidence for enhanced controlled processing (Waszak et al. 2005).

Summary of Experimental Findings

In Experiment 1, the basic form of the tool-switching paradigm was applied. Reaction times and error rates were lower if participants had to switch between different tools that required the same transformation rules (e.g., between tweezers and pliers) as compared to costs for switching between tools with different transformation rules (e.g., between a clothespin and pliers). These results were taken as evidence that compatible and incompatible transformation rules of simple mechanical tools hold an independent and functionally relevant representation in the cognitive system. Moreover, Experiment 1 revealed differences between compatible and incompatible transformation rules in tool use: There was a compatibility effect. The selection of the operating movement was faster and more accurate for compatible than for incompatible tools. Furthermore, an influence of the movement-effect transformation in trial $n-1$ on movement selection in trial n was evident for incompatible tools. For compatible tools movement selection was not significantly influenced by the movement-effect transformation in the preceding trial. These findings support the hypothesis that controlled processing was required for movement selection in order to operate incompatible tools, but that the requirements of controlled processing were minimal for operating compatible tools.

Experiment 2 was conducted to test whether movement-effect transformations which are realized by compatible tools hold a default status. There was an advantage for repeating the compatible transformation rule whether or not tools appeared in the same or in different spatial (horizontal or vertical) dimensions and whether or not the response set was thus the same or a different one in trial $n-1$ and trial n. The activation of the compatible transformation rule in the preceding trial seemed enough to facilitate movement selection in a current trial, and this benefit was independent of the specific movement-effect transformation which was required. There was no such independence for incompatible tools. It was therefore concluded that for compatible tools movement-effect transformations were directly provided as default associations.

In Experiment 3 and 4 it was investigated whether these substantial differences between movement selection for compatible and incompatible tools could be compensated for by changing rule probability or by training. In Experiment 3, the compatibility effect was indeed eliminated when incompatible tools had to be operated in the majority of trials. Still, changing rule probability in favor of incompatible tools did not substantially change the amount of controlled processing required for movement selection. There were furthermore signs of active and strategic suppression of compatible movement-effect associations. On the contrary, the differences between compatible and incompatible tools in terms of controlled processing were still significantly strengthened if compatible tools had to be operated in the majority of trials.

In Experiment 4, training with incompatible tools in four consecutive sessions was successful and the compatibility effect was eliminated in pure blocks. However, training with incompatible tools as compared to training with both, compatible and incompatible tools, did not differentially influence the results in the subsequently performed tool-switching paradigm. There was still a substantial compatibility effect and still, controlled processing was enhanced for movement selection in order to operate incompatible as compared to compatible tools. The default status of compatible movement-effect associations thus could not easily be overridden neither by changing rule probability nor by training. It was suggested that high ideomotor compatibility between operating movements and their associated effects at the distal tip of the tool was the reason for the default status of compatible movement-effect associations.

Experiment 5 and 6 revealed the impact of an additional characteristic of transformation rules which are incorporated in simple mechanical tools: These are evidently afforded by the tool's structure. In Experiment 5 the main differences between compatible and incompatible tools were replicated with abstract rule cues which cued a compatible or an incompatible transformation rule. Still, less controlled processing seemed to be required for movement selection in response to tool pictures as compared to movement selection in response to abstract rule cues. The same was true in Experiment 6 in which written tool names instead of abstract rule cues were contrasted which tool pictures. We concluded that movement selection in the tool-switching condition was an on-line process based on visual information and on a lifelong experience with mechanical devices, and not primarily a process based on the retrieval of explicit knowledge. It was suggested that compatible tools obviously extended the fingers and movement selection could take place directly upon effect anticipation as if the desired effect was achieved by the hand only, without the involvement of a tool. For incompatible tools, it was proposed that the correct operating movement could be derived from the tool picture by anticipating the desired effect along with imagining the associated tool movement.

Finally, in Experiment 7, the application of transformation rules in the tool-switching paradigm was investigated by event-related fMRI. The contrast of incompatible versus compatible tools revealed activation in the IPS, the precuneus, the dorsal premotor cortex, the lateral cerebellum and the extrastriate cortex. These areas can be associated with visuomotor imagery. Furthermore, activation in the ACC, the IFJ, the inferior frontal cortex and the medial aspect of the pallidum provided evidence that movement inhibition and cognitive control were required for movement selection in order to achieve a desired effect with incompatible as compared to compatible tools. These findings strengthen the notion of a default status of compatible movement-effect associations and of a process of visuomotor imagery for the realization of incompatible movement-effect transformations. The contrast of transformation rule switch as compared to repetition trials yielded activation in the anterior vermal area and the dentate nucleus. Activation in both regions can be associated with a process of motor integration between the tool and the operating fingers. With reference to research on the application of explicit mapping rules it was concluded that updating a transformation rule in the tool-switching paradigm differed from updating an explicit mapping rule in important aspects.

Taken together, the experiments of this dissertation provided evidence for an independent and functionally relevant representation of tool-associated transformation rules in the cognitive system, for the advantage of high ideomotor compatibility between movements and their associated effects at the tool's distal tip, as well as for the capacity of a simple mechanical tool to afford a specific transformation rule. These seem to be important characteristics of transformation rules inherent in simple mechanical tools and in the present experiments, they had an impact on movement selection.

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Lepper, M., Massen, C., & Prinz, W. (2008). What to do and how to do it: Sequence learning of action effects and transformation rules. *Acta Psychologica, 128*, 139–152.

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Hiermit erkläre ich,

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- Professor Dr. Wolfgang Prinz, Max-Planck-Institut für Kognitions- und Neurowissenschaften, Abteilung Psychologie
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