Action and Cognitive Processing

Functional Links between Action Planning and the Processing of Perceptual, Semantic and Mathematical Information

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Chapter 1

Introduction

1.1 Brain and Body

Why has evolution equipped us with a brain? What is the purpose of our cognitive system? When trying to answer these questions, it might be interesting to have a closer look at species in nature which have developed brains or brain-like structures and compare their capabilities with existing organisms which have no brains. In doing so, it becomes immediately obvious that all species that can perform any kind of movement or action such as insects, fishes or mammals have at least a rudimentary brain, while biological organisms that cannot act, re-act or move, like for example trees or corals, have no functioning brain-like structure. An illustrative example in this context is the ontogenetic development of sea squirts. At the beginning of their lives, sea squirts are able to swim. They have a simplified central nervous system consisting of a cerebral ganglion that controls movements. In other words, sea squirts have simple brains. At a certain point of time, however, when the animal finds a suitable place to stay, it stops swimming, attaches itself to a permanent object on the sea ground and does not move anymore. Interestingly, after settling down, the nervous system previously used to control movements breaks down immediately and the sea squirt starts digesting its own brain. Apparently, without the requirement to move, there is not need for having a brain. One might therefore provocatively hypothesize that the basic function of the brain is to control motor behavior, or from a psychological perspective, that the purpose of cognition system is to serve actions.

Certainly, the example of the degradation of the sea squirts' nervous system is merely just an anecdote and does not represent any scientific argument for the importance of actions in human information processing. Nevertheless, many theorists in the last decades have proposed action-oriented views on cognition, which share the basic assumption that the central function of the mind is to guide actions (for a recent review see, e.g., Wilson, 2002). For example, Churchland, Ramachandran, and Sejnowski (1994) mention that "vision has its evolutionary rationale rooted in improved motor control" (p. 25). Glenberg (1997) argue similarly and emphasize that "memory evolved in service of perception and action in a three-dimensional environment" (p. 1). Moreover, Clark (1998) even states that the traditional distinction between perception, cognition and action may sometimes obscure our view for a better understanding of the cognitive processes and functions. He proposes conceptualizing cognitions as body-related processes, because "the brain is revealed not as (primarily) the engine of reason or quiet deliberation, but as the organ of *environmentally-situated control.* Action, not truth and deductive inference, are the key organizing concepts." (p. 268) Following this embodied view on human information processing, each cognitive mechanism has to be considered in terms of its function in serving adaptive behavior and its contribution to control motor behavior.

However, a glimpse inside almost every available cognitive psychology textbook reveals that most information-processing theories are still dominated by the traditional assumption that perception, cognition, and action are three independent stages in a serial chain of processes (see Donders, 1886; Sternberg,1996). In these classical approaches, actions are implicitly conceived as a mere consequence of information processing, that is, as stimulus-inducted re-actions or as "trivial appendages to the seemingly more sophisticated operations subserving 'higher-level' cognition" (Fischer & Zwaan, in press). Researchers in this tradition have consequently put much more emphasis on the receptive than on the productive side of human behavior and aimed in their empirical work to reduce movement-related processes as far as possible (e.g., by using simple button press response tasks) in order to isolate them from processes of perception and cognition. However, the strict separation of motor action from perception and cognition does not adequately capture the goal-directed nature of human information processing and intentional behavior (Hommel, 2005; see also Rosenbaum, 1983, and Abrams & Balota, 1992, for earlier critiques of this approach). The new generation of cognitive scientists should therefore focus, as for example suggested by Lakoff & Johnson (1999), on approaches of embodiment and the close interaction between mind and body and between cognition and action (cf. Garbarini & Adenzato, 2004).

In the following I will describe four influential theoretical concepts—the ideomotor principle, the common coding principle, the principle of motor simulation and the principle of motor resonance—which have inspired in recent years many empirical studies and which all suggest a strong coupling between perception and action on the one hand and between cognition and action on the other.

1.2 Perception and Action

1.2.1 Principle of Ideomotor Action

The notion that action and perception are mutually dependent processes is not new and dates back to the early days of experimental psychology. Theorists at the end of the 19th century searched for an answer to the question how voluntary actions are possible at all and proposed the so-called ideomotor principle, which basically holds that actions are represented in terms of their sensory effects in the environment. According to this assumption, human actions are initiated by nothing other than the idea of the sensorial consequences that typically result from them. Merely thinking about an action and its intended consequences prompts and instigates a motor response. Thus, the central mechanism underlying the planning of actions is an anticipation of their perceptual effects. The principle of ideomotor actions has been most dominantly proposed by James

(1890), whose considerations were strongly influenced by the British and German psychologists Carpenter (1852) and Lotze (1852; for an overview of the historical roots of ideomotor theories see Stock & Stock, 2004). According to James, learning is a precondition for the control of voluntary actions. Since every performed movement goes along with a perceivable change in the environment, the actual motor action and the sensory consequences become associated. Once the bidirectional connection between action and consequences is established, the motor response can be initiated by the mere activation of the intended action effect in the mind (i.e., "*Vorstellung des Gewollten*"; Lotze, 1852).

The ideomotor theory as it was originally formulated by James represents a purely introspective approach. Almost a century later, however, Greenwald (1970a) provided an extension of these considerations, which allows empirical and experimental validations. He hypothesized that if responses are coded by representations of their sensory feedback, it implies that the perception of a stimulus, which closely resembles the consequences of a previously learned action, should result in a priming of this particular motor response. And in fact, Greenwald (1970b) demonstrated that stimuli representing well-known action effects primed responses that typically produce them. For example, verbal responses were found to be faster to auditory stimuli then to visual stimuli, because speaking produces auditory but not visual effects. Several studies have investigated since then effects of ideomotor compatibility and demonstrated experimental evidence for an influence of anticipated or perceived action effects on motor response (e.g., Stürmer, Aschersleben, & Prinz; 2000; Brass, Bekkering, Wohlschläger, & Prinz, 2000; Kunde, 2001; Elsner & Hommel, 2001; Koch & Kunde, 2002; Drost, Rieger, Brass, Gunter, & Prinz, 2005). For example, Brass et al. (2000) demonstrated that the observation of a finger-lifting movement facilitates the equivalent finger movement even in a simple response task. Interestingly, Elsner & Hommel (2001) demonstrated that associations between actions and their effects are automatically and incidentally learned. Participants experienced, in an initial learning phase, the co-occurrences between left and right keypress responses and low- and high-pitched tones, and subsequently made keypress responses in a free- or forced-choice paradigm. As the reaction times indicate, the presentation of tones facilitates the execution of left or right key presses, depending on the previously acquired response-stimulus association. Thus, research in the last decades has accumulated empirical support for the ideomotor hypothesis and demonstrated that participants use automatically acquired associations between motor responses and perceived consequences for the planning and initiation of actions.

The notion that the voluntary control of actions involves an anticipation of intended effects implies that action planning is seen as goal-driven process—a central assumption that can be also found in some theories of motor control (e.g., Jeannerod, 1997; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Glover;

2004) and imitation (e.g., Bekkering, & Wohlschläger, 2002). Anticipatory action control implies furthermore that action and perception are two functionally linked cognitive processes. This notion has been adopted in particular by the framework of common coding (Prinz, 1990; Hommel, Müsseler, Aschersleben, & Prinz, 2001), which tried to integrate the ideomotor principle with concepts and ideas of modern cognitive psychology. The next section will therefore describe the common coding principle in greater detail.

1.2.2 Principle of Common Coding

Prinz (1990; 1997) suggested a common coding theory, which aimed at understanding the linkages between the "late" products of perceptual processing and the "early" cognitive antecedents of motor actions. The central assumption of this model is that perception and action share and operate on common cognitive codes within one representational domain. The common coding principle has been recently elaborated in greater detail by the Theory of Event Coding (TEC; Hommel et al. 2001). The model holds that perceived and to-be produced events, such as intentional actions, are represented by a network of linked codes of relevant features of the event (the so called 'event file'). Thus, in line with many theories on perception, attention, and memory (e.g., Allport, 1987; Singer, 1994, Kahneman, Treisman, & Gibbs, 1992, Treisman, 1996), it is assumed that stimulus representations are feature-based. However, since perception and action are entirely commensurate, TEC states furthermore that also action plans are represented in a distributed fashion and comprise in the same way temporary composites of cognitive codes (i.e., action-feature codes). Evidence for a feature-based action representation can be found, for instance, in classical motor control experiments showing that movement initiation times decrease if subjects have the opportunity to partially make up their action plan in advance (Rosenbaum, 1980, 1987). In these experiments, participants were required to perform speeded hand movements consisting of different action features (e.g., with the left or right hand, for a short or long distance, toward or away from the body). Movement precues were presented before the actual go signal and informed about some or all response parameters. As the response latencies indicated, movements were faster initiated with an increasing number of precued action features, suggesting that subjects are able to specify the features of their action relatively independently.

Importantly, according to TEC, the common representation of perception and action is characterized by a distal coding of event features. That is, feature codes of perceptual objects and action plans refer to external, that is, distal features of stimuli or action-generated effects. The model shares this notion with other approaches to action planning assuming that movement planning is goal-directed and guided by the desired movement end-states (Rosenbaum et al., 2001). However, in contrast to these approaches, TEC holds that motor behavior is not only guided by proximal action effects such as proprioceptive and visual feedback of a performed movement. Rather, the common coding principle suggests that action-generated effects refer to the highest level of representation and to the remote consequences that the action is supposed to have on the environment. For example, if one intends to decrease the volume of the music by turning a knob of the stereo amplifier, the cognitive representation of the planned action does not refer merely to the muscle contractions or visual feedback of the rotational movement, but involves instead also the actual intended effect in the environment, namely, the change of volume. From a theoretical point of view, the crucial advantage of a distal reference system is that perception and action can operate on commensurate representations. This does not only simplify many cognitive processes, like for example the transformation of visual object properties (e.g., object size) into appropriated motor commands (e.g. grip aperture) as required while grasping, it also enables the cognitive system to abstract from domain- and modality-specific coding characteristics by referring to the informational content of the action or event (Prinz, 1997). The idea of distal coding of event features is supported by numerous reports in the literature on both perception and action planning (for a review see Hommel et al., 2001) and also receives evidence from research on ideomotor actions (see above). As one recent example, Rieger (2004, 2007) compared participants who were able to type fluently using the 10-finger-system with participants doing hunt-and-peck typing with two fingers only. She found that expert typists had built up an integral representation of fingers movements and the corresponding letters, resulting in an automatic bidirectional association between motor responses and distal action effects.

Taken together, the common coding principle holds that representations of perceived events as well as representations of actions and action-generated effects are based on the same cognitive codes referring to distal event features. In this way, perception and action planning can be understood to be functionally equivalent, because, as argued by Hommel et al. (2001), “they are merely alternative ways of doing the same thing: internally representing external events” (pp. 860).

1.3 Cognition and Action

The notion that perception and action operate on shared representations raises the question whether the common coding principle is restricted to the perceptual domain. Alternatively, it might be possible that the close bidirectional coupling of mental representations with motor codes is a generalized principle of how the brain processes and represents information. Indeed, research in the field of neuroscience and cognitive psychology has recently indicated that motor representations are involved in a wide range of cognitive tasks and contribute even to rather complex processes such as the understanding of other's actions (Wilson & Knoblich, 2005), the processing of language (Glenberg, 1997) and numerical information (Walsh, 2003). This section will elaborate these ideas in the light of two further coding principles emphasizing the role of action in cognition.

1.3.1 Principle of Action Simulation

Many studies in animal research and cognitive social psychology have suggested that motor processes are strongly involved in understanding the behavior of conspecifics (Wilson & Knoblich, 2005; Prinz, 1997; Rizzolatti & Craighero, 2004). The rationale behind these models can be summarized by the principle of action simulation: People, who observe somebody else performing an action, activate the same neural substrates that are recruited when they performed that action themselves. In other words, action understanding implies an internal, covered imitation of the observed motor behavior.

Action simulation received recently a lot of attention due to the discovery of the so called mirror neurons in macaque monkeys, which are sensitive to action execution as well as action observation (Gallese, Fadiga, Foggassi, & Rizzolatti, 1996; for review, see Rizzolatti & Craighero, 2004). That is, single-cell recordings in monkeys' premotor cortex (in particular area F5) revealed that this type of neurons increase their firing when the monkey performed an action (e.g., grasping a food item) as well as when it observes an experimenter or conspecific performing a similar action. Importantly, it could be shown that the mirror system is responsive to the understanding of the action goal and not merely to the perception of the motor movement. Specifically, the monkey mirror neuron system was shown to respond to goal-directed grasping movements, even if the final goal (food) was occluded (Umiltà, Kohler, Gallese, Fogassi, Fadiga, Keysers, & Rizzolatti, 2001). As shown by a large number of neuroimaging studies, a mirror-neuron system similar to that of the monkey likely also exists in humans (Iacoboni, Woods, Brass, Bekkering, Mazziotta, & Rizzolatti, 1999; Buccino, Binkofski, Fink, Fadiga, Fogassi, Gallese et al., 2001; Decety, Chaminade, Grezes, Meltzoff, 2002). This research demonstrates that the observation of actions performed by others activates a complex network including the Broca's area, an inferior frontal brain area considered to be homologous to area F5 in the macaque monkey, and other cortical regions whose functions are predominantly motor related (cf. Rizzolatti & Craighero, 2004).

The notion of action simulation implies furthermore that the observation and understanding of other's actions involves previously acquired motor experiences. In line with this reasoning, it has been shown the activation of the human mirror system strongly depends on motor knowledge and expertise. For example, Calvo-Merino, Glaser, Grèzes, Passingham and Haggard (2005) studied experts in either classical ballet or capoeira dancing (i.e., a Brazilian fight-dance) and found greater activity in the premotor and parietal brain regions when dancers watched their own dance style. A follow-up study (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2006) ruled out that the differences in motor activation were not merely the result of visual familiarity. It can be thus concluded that the motor system is more strongly engaged during action understanding when participants have a specific motor representation of the behavior they observe.

In addition to this neuropsychological work, the idea of action simulation receives support from behavioral studies. The above described finding of ideomotor compatibility effects during action observation (Brass et al. 2000; Stürmer et al. 2000) is just one example. Kilner, Paulignan, & Blakemore (2003) provide further evidence by showing that people's attempts to perform an arm movement become more variable when watching an incompatible arm movement. Similarly, interference effects of action simulation have been found during the observation of mouth movements. People are faster to pronounce a printed syllable when they see a mouth pronouncing the same syllable than when they see a mouth pronouncing a different syllable (Kerzel & Bekkering, 2000).

In sum, empirical research shows that the observation of body movements automatically triggers a sort of covert imitation resulting in an activation of motor-related brain areas and a facilitated execution of similar motor responses. These findings suggest that action simulation is a cognitive principle subserving the conceptual understanding of other's behavior. Action simulation reflects thus another example for the involvement of motor representations in cognitive processing.

1.3.2 Principle of Motor Resonance

The important role of motor representations as it has been described above clearly points to an embodied information processing approach in perception and action understanding. This raises the general question whether embodiment can be understood as a universal coding principle also valid for high-level cognitive processes such as the word reading and the coding of abstract semantic information. Some recent studies on grasping actions provide evidence for this notion and showed that semantic information effect the planning of actions. Gentilucci, Benuzzi, Bertolani, Daprati, and Gangitano (2000) reported, for instance, that reach-to-grasp movements are influenced by the semantic properties of distracting words. They showed that Italian words denoting *far* and *near* reprinted on to-be-grasped objects had comparable effects on movement kinematics as actual greater or shorter distances between hand position and object. Automatic word reading effects have also been observed for words implying explicitly or implicitly size-related semantic information. For example, the maximum grip aperture during reaching has been found to be enlarged after reading the word *large* as compared to the word *small* (Gentilucci & Gangitano, 1998; Glover & Dixon, 2002) or after reading the word *apple* as compared to the word *grape* (Glover, Rosenbaum, Graham, & Dixon, 2004).

Beside this work on motor control, also theoretical work on language comprehension has recently highlighted the role of motor information in high-level cognitive processing (e.g., Lakoff & Johnson, 1999, Glenberg, 1997; Clark, 1998; Gallese & Goldman, 1998). These approaches are motivated by the problem of symbol grounding—a problem that is faced by each theory on semantic knowledge and that represents the basic question of how linguistic symbols such as words, numbers, or syntactic constructions acquire meaning. Although embodied approaches to cognition differ widely on the emphasis that is put on separate cognitive subsystems and on the way in which conceptual knowledge is organized (for recent overviews see Fischer & Zwaan, in press; van Elk, van Schie, Lindemann & Bekkering, in press; Barsalou, in press), they all share the assumption that symbols can become meaningful only when they are somehow mapped to non-linguistic perceptual experiences and bodily activities. The cognitive system operates accordingly on representations that are grounded in perception and action, or in other words, cognition is based on embodied knowledge. Following this line of reasoning, theories of semantic representations have been proposed, which relate abstract concepts to perceptual experiences (Barsalou, 1999) and motor actions (Glenberg, 1997; Zwaan, 2004). Sharing the assumption that the comprehension of meaning is a fundamentally body-related process that involves sensorimotor representations, these models predict that the processing of linguistic stimuli causes a reactivation of perceptual and motoric representations of the objects and actions that underlie this abstract semantic information. This automatic activation of embodied representations represents a form of mental resonances (cf. Zwaan, 2006), which can be subdivided according its modality into perceptual resonance and motor resonance (see Schütz-Bosbach & Prinz, 2007, for this distinction in the context of social cognition).

Perceptual resonance refers to sensory activation due to mental imagination. Evidence for this phenomenon is provided by several behavioral experiments on sentence comprehension (Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002; Pecher, Zeelenberg, & Barsalou, 2003; Kaschak, Madden, Therriault, Yaxley, Aveyard, Blanchard & Zwaan, 2005). For example, Stanfield and Zwaan (2001) required participants to verify that a picture (e.g., a pencil) depicted an object mentioned in a sentence (e.g., "The pencil is in a cup"). They observed faster responses if the object on the picture was presented in the same orientation as implied by the sentence (in this case a vertically depicted pencil). Thus, understanding the sentence appears to call on real perceptual experience.

The notion of motor resonance refers to motor activation in semantic processing due to mental simulation or re-enactment (cf. Prinz, 2006). This coding principle represents therefore the most straightforward conceptualization of the coupling of action and high-level cognition as it is in the focus of the present thesis. Importantly, the concept of motor resonance goes far beyond the phenomenon of action simulation, because it does not reflect merely the matching of perceived actions with existing motor repertoire. Rather, motor resonance stands for a coding principle to deal with semantic knowledge on an abstract level of representation and is expected to cause therefore interference also when processing symbolic information. Evidence for this idea comes from neuroimaging studies showing that reading of action words activates motor-related brain areas (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, Hauk, Nikulin, & Ilmoniemi; 2005; Rüschemeyer, Brass, & Friederici, 2007) as well as from behavioral research demonstrating the presence of priming effects on motor responses while sentence comprehension (Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006; Borreggine & Kaschak, 2006; Taylor, Lev-Ari, Zwaan, in press). For example, Glenberg and Kaschak (2002) found that sentences describing simple motor actions facilitate the execution of compatible motor responses (i.e., Action Sentence Compatibility effect). They asked participants to judge the sensibility of sentences such as “You gave Andy the pizza” or “Andy gave you the pizza” by moving the hand from a start button to the Yes button. The location of the buttons required a literal movement either toward the body or away from the body. Participants were faster to execute the motor responses when the direction of the response matched the direction of the motion described by the sentence (e.g., making a response towards the body to the sentence “Andy gave you the pizza”).

1.4 Summary and Aims

Taken together, psychological research offers several ideas and theoretical concepts that suggest that motor representations are involved in different cognitive functions ranging from low-level cognitive processing such as visual perception up to high-level cognitive processing such as language processing. Surely, the four principles of embodied cognitive processing described above—the ideomotor action principle, the common coding principle, the action simulation principle and the motor resonance principle—represent only a selection of views on action-perception and action-cognition coupling among many others in the literature. They also should not be understood a four disjunctive independent concepts, since they are interrelated and to some extent even mutually conditional. For example, action simulation can be conceptualized as a special case of motor resonance, the common coding principle implies the principle of ideomotor actions and the notion of motor resonance can be derived following a few assumptions from the Theory of Event Coding.

As described above there are ample studies providing support for the interference effects between action and cognition in different domains. However, it is still unclear to what extent action intentions affect cognitive coding and whether there are any limits of motor involvement in information processing. One might therefore assume that embodiment and the involvement of motor representations is a generalized universal coding principle, which applies in theory to all cognitive processes and to the coding of all types of information. Guided by this hypothesis, the present thesis sought for evidence of motor effects in a wide range of cognitive domains and aimed to address within this context some open questions. The following chapters therefore investigated action effects in the domain of visual processing (Chapter 2), word reading (Chapter 3) and number processing (Chapters 4 & 5).

Since most of the research on action effects has focused on rather simple one-dimensional actions like button press responses or bare grasping movements, a specific aim of this thesis was to explore whether motor interference effects can be also observed for more complex natural actions, which are directed on an specific goal and which consist of more than just a single movement. The first three chapters investigated effects of object manipulations such as the grasping and turning of an object and the use of a familiar tool. In particular with respect to the idea that actions are goal-directed and represented by their intended distal effects (cf. ideomotor and common coding principle), it is interesting to explore the role of actions goals that are on a higher level in the hierarchy of possible subgoals. The thesis intends therefore to shed some light on the impact of motor features that occur at the end of complex motor sequences, like for instance the intended manipulation after grasping an object or the goal location of the use of an object. At the end of this introduction I present a short overview of the empirical work in the following four chapters.

1.4.1 Action and Visual Processing

Chapter 2 focuses on the coupling between perception and the preparation of natural grasping actions. In three experiments, we established an experimental paradigm, which allows to investigate cognitive interference effects in the context of object manipulations and which can be later utilized to study effects on other cognitive processes. We assumed that the intention and preparation to manipulate an object affects visual processing. Since each object manipulation results in a perceivable motion as an action consequence, Chapter 2 aimed in particular to find evidence for action-inducted effect on motion perception.

1.4.2 Action and Semantic Processing

Chapter 3 aimed to provide support for the notion that effects of motor preparation are not restricted to the visual domain. The major question to be addressed was whether the planning of goal-directed actions interferes with the language-related processes. We conducted therefore four experiments, which examined the impact on the preparation to reach out, grasp and use a meaningful object (i.e., household tool) on the processing on semantic information in different word reading tasks (e.g., lexical decision task and semantic categorization task).

1.4.3 Action and Number Processing

Chapter 4 aimed to further support the notion of embodiment as a generalized coding principle and sought for evidence for motor involvement in a high-level cognitive domain that has not been studied so far. A promising candidate is the domain of mathematical cognition, because the coding of numbers and the planning of motor responses (e.g., object grasping) are two cognitive tasks, which both depend essentially on the same type of information, namely, an accurate knowledge about size and quantity. In line with this consideration, a study on the interference between grasping actions and number processing was conducted, in which participants judged the parity of presented digits and indicated their decisions by performing either a power or precision grip action.

1.4.4 Intention and Number Processing

Chapter 5 further investigates the representation of numbers and addresses the phenomenon of the interaction between numerical magnitude information and lateralized motor responses (i.e., the SNARC effect). Again, we aimed to investigate the impact of intentions on cognitive processes. With this study, however, the focus of attention is shifted from the effects of motor intentions to the effects of coding intentions and cognitive strategies. Two experiments are reported, which examined whether number representations are influenced by implicit task requirements in order to test the hypothesis that coding strategies are responsible for the cognitive coupling between numbers and spatial response features.

Chapter 2

Action and Visual Processing

Effects of Object Manipulation on Motion Perception

Abstract. Three experiments investigated the coupling of perception and action in the context of object manipulation. Participants prepared to grasp an X-shaped object along one of its two diagonals and to rotate it in a clock- or counterclockwise direction. Action execution was triggered by a visual go signal, consisting of a circle (neutral) or a tilted bar that afforded either the same (grip-consistent) or an orthogonal type of grip (grip-inconsistent) as the prepared action involved. Experiment 1 indicates that action preparation facilitates the detections of grip-consistent and end-state consistent stimuli. In Experiment 2, the appearances of the go signals induce apparent rotational motions in a clock- or counterclockwise direction. Interestingly, stimulus detections were faster when apparent motions were consistent with the manual object rotation. Motion perception was also facilitated when detections had to be indicated with a foot response (Experiment 3). In sum, we present evidence for motor-visual priming of prepared object manipulations on the perception of visual motions, which suggests a close link between motor and perceptual representations that goes beyond visuomotor associations between object properties and afforded actions.

This chapter is based on: Lindemann, O., & Bekkering, H. (under review). Object manipulation and motion perception: Evidence for an influence of action planning on visual processing. *Journal of Experimental Psychology: Human Perception and Performance.*

2.1 Introduction

Recent behavioral and neuropsychological research suggests a close and bidirectional link between perceptual and motor processes (see e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). Several cueing experiments have shown that visual images of graspable objects (Tucker & Ellis, 1998; Craighero, Fadiga, Rizzolatti, & Umiltà, 1998) or film sequences of actions of others (Brass, Bekkering, & Prinz, 2001; Vogt, Taylor, & Hopkins, 2003) prime the motor system and speed up the initiation of an action when the cue and the motor response are congruent (*visuomotor priming*). More recent studies report evidence for an effect of the opposite directionality, i.e., an impact of motor actions on visual processing (here referred to as *motor-visual priming*). Action-induced effects on visual attention have been observed in participants performing rather simple actions like button-press responses (Müsseler & Hommel, 1997; Wühr & Müsseler, 2001; Kunde & Wühr, 2004), pen movements (Zwickel, Grosjean, & Prinz, 2007), pointing movements (Deubel, Schneider, & Paprotta, 1998; Bekkering & Pratt, 2004; Linnell, Humphreys, McIntyre, Laitinen, & Wing, 2005) or changes in hand postures (Hamilton, Wolpert, & Frith, 2004; Miall, Stanley, Todhunter, Levick, Lindo, & Miall, 2006).

Interestingly, only few studies reported motor-visual priming effects for more complex and natural motor behaviors like reaching for and grasping an object (Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Craighero, Bello, Fadiga, & Rizzolatti, 2002; Fagioli, Hommel, & Schubotz, 2007). Yet, Craighero et al. (1999) demonstrated that the processing of a visual stimulus is facilitated if it affords the same type of grasping response as the subject concurrently intends to perform. In their paradigm, differently oriented wooden bars had to be grasped without the aid of sight. A word cue informed the participants about the orientation of the bar and instructed them to prepare the corresponding grasping action. However, the actual execution of the prepared motor response had to be delayed until a visual go signal had been presented. Craighero et al. (1999) observed faster response if the go signals afforded the same type of grasping response as the concurrently prepared action. Interestingly, this effect was also observed when the participants prepared a manual grasping response but signaled their detection of the visual stimulus with another motor effector (e.g. by a foot response). These results suggest that the preparation of a grasping movement facilitates the visual processing of stimuli sharing the same intrinsic properties and supports the notion of motor-visual priming.

The idea of action-induced attentional effects has received further support from studies that compared grasping and pointing movements (Bekkering & Neggers, 2002; Hannus, Cornelissen, Lindemann, & Bekkering, 2005; Fagioli et al., 2007; Fischer & Hoellen; 2004). For example, it is has been shown that the intention to grasp an object selectively enhances the processing of object properties such as size (Fagioli et al., 2005) and orientation (Bekkering & Neggers, 2002; Hannus et al., 2005), which indicates that the planning of an action automatically modulates visual attention toward those object dimensions that are relevant for the selection and programming of that particular motor response.

In sum, most of the studies that investigated motor-visual priming effects either examined rather simple actions and focused on the perception of object features, which are associated with a particular kind of hand posture and which are required in each visuomotor transformation for grasping. However, in everyday life, we reach out and grasp an object in order to use it for a specific purpose. For instance, depending on whether we wish to open or close a faucet we grasp it with the intention to rotate it afterwards clock- or counterclockwise. In other words, almost all our grasping movements are instrumental and directed toward an action goal[1], which involves a certain manipulation of the grasped object. Although it is widely recognized that the planning of grasping actions strongly relies on the visual information we receive about the spatial characteristics of the target object (for review see, e.g., Castiello, 2005) recent research in the field of motor control demonstrates that an intended object manipulation plays a crucial role in the selection of an initial reach-to-grasp movement (see e.g., Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Empirical support for this view was derived from the observation that most subjects grasped an object they intend to manipulate in a way that allowed them to finish their action with a comfortable end state even if this implied having to adopt an awkward initial grip (the so-called end-state comfort effect; see e.g., Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990; Weigelt, Kunde, & Prinz, 2006). However, until now, the relevance of the desired manipulation and the role of action goals have been largely neglected in research investigating the interaction between attentional and motor processes in grasping.

Given that grasping actions are goal-directed and generally guided by the intention to use, displace or control the grasped object, the present study aimed to investigate the nature of motor-visual priming in the context of object-manipulations. Because such a motor action always implies a visually perceivable movement and taking into account the importance of visual feedback for the control of manual actions (cf. Glover, 2004), it is plausible to assume that especially the domain of visual motion perception is characterized by an close coupling of action planning and perception. Surprisingly, however, as yet

[1] We use the term *action goal* to describe any kind of cognitive representation of changes in the environment that a person intends to achieve with a motor action. Behavioral goals can vary in terms of their remoteness, e.g. from proximal goals like *grasping the faucet* to more distal goals like *filling the bathtub with water* or *having a bath*. In this respect, action goals are here understood as proximal goals at the level of motor intentions (cf. Jacob & Jeannerod, 2005).

little is know about the interference between action and visual motion perception. It has been shown, for example, that the perception of moving objects automatically activates responses that correspond spatially to the direction of the observed motions (Michaels, 1988; Proctor, Van Zandt, Lu, & Weeks, 1993; Bosbach, Prinz, & Kerzel, 2004). Nevertheless, the only indication so far for an effect of the reversed directionality, i.e., an impact of action planning on motion perception, is coming from the finding of action-induced motion biases reported by Wohlschläger (2000). In his study, participants had to indicate the direction of ambiguous rotational motion displays while they were turning a knob either clock- or counterclockwise. Wohlschläger (2000) observed that participants tend to judge the ambiguous motions in the rotational direction of their current action and interpreted this as evidence that visual motion perception is biased by actions. Thus, the finding of judgment biases provides some first indications that action planning may indeed facilitate the perceptual processing of visual motion.

Based on these preliminary findings we conducted three experiments to test our hypothesis that a prepared object manipulation would modulate visual attention and particularly facilitates the perceptual processing of visual motion in line with the intended action. In Experiment 1 we established a paradigm to investigate motor-visual priming effects of object manipulations. Experiment 2 further investigated this effect and tested whether action planning has an impact on the perception of visual motions. Experiment 3 was conducted to exclude the possibility that our findings reflect a facilitated action initiation and rather represent an action-induced effect on motion perception.

2.2 Experiment 1

The aim of our first experiment was to study motor-visual priming effects in the domain of object manipulation. To this end, we compared the priming effects of two actions. Following the delayed-response paradigm proposed by Craighero et al. (1999), we asked participants to prepare themselves to reach out and grasp an object (object grasping) but added a second action condition in which participants were additionally required to subsequently rotate the object in a given direction (object manipulation). However, in both conditions response execution had to be delayed until the appearance of a visual go signal. The go signal was either a solid circle (neutral stimulus) or a tilted bar that afforded the same type of grip as the prepared action involved (grip-consistent stimulus) or an orthogonal grip (grip-inconsistent stimulus). For both action conditions we predicted a motor-visual priming effect, i.e., faster responses toward grip-consistent stimuli as compared to neutral stimuli.

We assumed that the process of planning to grasp an object in order to manipulate it afterwards is strongly influenced by the purpose of the movement, e.g. the required end position of the object (see e.g., Rosenbaum et al., 2001). Assuming that the goal of an action already affects the process of motor preparation in its earliest stages, we hypothesized that the reach-to-grasp movements prepared for different purposes (i.e., merely holding the object or rotating the object) would affect visual attention differently. Hence, for the present experiment we predict faster detections of grip-consistent stimuli in both action conditions. Since we assume that in the manipulation condition the grasping and rotation of the object is considered and prepared while the initial reach-to-grasp movement is being planned, in this condition we additionally expected to find a facilitated processing of visual features corresponding to the end state of the object rotation.

2.2.1 Method

Participants

Twenty-eight students from the Radboud University Nijmegen participated in the experiment in return for 4.50 Euros or course credits. All were naive to the purpose of the study, had normal or corrected-to-normal vision and were free of any motor problems that could have affected their task performance.

Apparatus and Stimuli

Participants were required to perform grasping movements toward an X-shaped object (manipulandum; see Figure 2.1B) consisting of two perpendicularly intersecting wooden bars (8 by 1.1 by 5 cm each) mounted on a base plate (30 by 15 cm). The manipulandum could be rotated around its crossing point with the rotation axis being parallel to the Cartesian y-axis. Owing to small pegs underneath the manipulandum and holes inside the base plate, it clicked into place after rotating it for a multiple of 90°. This mechanism enabled us to keep the orientation of the manipulandum at the beginning of each trial constant even when participants were required to rotate the object. A small pin placed on the base plate at a distance of 15 cm from the manipulandum's rotation axis marked the starting position for the grasping movements (see below). The manipulandum, which was oriented such that the crossing bars were aligned 45° diagonally to the subject's midsagittal plane, was positioned behind a wooden screen (height: 44 cm, width: 45 cm) allowing the participants to reach it comfortably with their right hand but obscuring it and their hand from view (see Figure 2.1A).

All stimuli were presented in the center of a computer screen that was placed at a viewing distance of approximately 70 cm in front of the participants, allowing

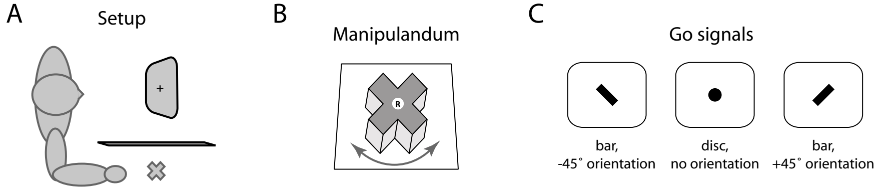

Figure 2.1: A: Illustration of the experimental setup. Participants were seated in front of a computer screen. The starting position and the manipulandum were obscured from the participant's view by means of a wooden screen. B: Illustration of the X-shaped manipulandum that could be rotated along the rotation axes indicated by *R*. C: Visual stimuli that served as go signals in all three experiments.

them an unobstructed view of the monitor. The Dutch words LINKS (left) and RECHTS (right) served as action cues to indicate the required motor response (a left or a right grasp) in a particular trial. Black bars (subtending a visual angle of 4.1° by 1.3°) tilted from the vertical for either -45° or +45° or a solid circle (visual angle of 2.7°) served as go signals (see Figure 2.1C). Thus, depending on the required motor response, a go signal could afford the same type of grip as currently prepared action involved (grip-consistent) or it could afford the orthogonal grip (grip-inconsistent). The solid circle, which did not afford any specific type of grip, served as neutral go signal.

Procedure

Participants were randomly assigned to one of two action conditions. Participants in the condition 'object grasping' had to grasp the object and hold it for a second without lifting it before returning the hand to the starting position. Participants in the condition object manipulation, however, were additionally required to rotate the object 90°, either clockwise (CW) or counterclockwise (CCW). In both conditions the manipulandum had to be grasped along one of its two crossing bars: either with the index finger at the top-left and thumb at the bottom-right leg (called *left grasp*) or with the index finger at the top-right and thumb at the bottom-left leg (*right grasp*). In the manipulation condition a left grip needed to be followed by a CW rotation and a right grip by a CCW rotation.

Prior to the actual experiment participants performed two short pre-experimental blocks. In the first block participants were required to reach out and simulate to grasp different bars, presented at different location on the computer screen. The bars were oriented -45° or +45° similar to the go signals in the experimental block and had always to be grasped with thumb and index finger to be placed at the bars' ends. With this block, we ensured that all participants associated with each bar orientation the same particular type of grip. In the second block, participants practiced grasping and rotating the manipulandum in the way described above. When the responses were carried out incorrectly, the experimenter corrected the participants and again demonstrated the correct action. Only when participants were able to carry out the movements fluently without vision was the experimental block started.

At the beginning of each trial the participants fixated their eyes on a gray cross presented on the monitor and positioned their hand in the starting position by placing their index finger and thumb around the start peg after which the cross disappeared and the action cues were presented for 2,000 ms. At this point the participants prepared the required action but needed to withhold its initiation. After a random interval between 250 ms and 750 ms the go signal appeared and remained visible for 1,000 ms. After appearance of the go signal participants' had to initiate their prepared motor response as soon as possible. After holding or rotating the manipulandum they returned their hands to the starting position.

Design

Apart from 10 randomly determined practice trials at the beginning, the experimental block comprised 144 trials presented in a random order. They were composed of all possible combinations of the two manual responses (left grasp, right grasp) and the three types of go signals (circle, bar tilted -45°, bar tilted +45°). Depending on the prepared response, each go signal could be considered as grip-consistent, grip-inconsistent or neutral. Additionally, the experimental design contained the between subject factor Action Condition (object grasping, object manipulation).

Data acquisition and analysis

To record the hand movements we used an electromagnetic position tracking system (miniBIRD 800^{TM}, Ascension Technology Corporation). Three sensors were attached to the thumb, index finger, and wrist of the participant's right hand. The hand movements were recorded with a sampling rate of 100 Hz and analyzed off-line. We applied a fourth-order Butterworth lowpass filter with a cut-off frequency of 10 Hz on the raw data. The onset of a reach-to-grasp movement was defined as the moment when the tangential velocity of the index-finger sensor first exceeded a threshold of 10 cm/s. For the movement offsets we used the reversed criteria, i.e. the time when the tangential velocity first dropped below this threshold. For both experimental conditions we computed the mean reaction times (RT; i.e., mean time elapsed between the appearance of the go signal and the onset of the ensuing reach-to-grasp movement).

Table 2.1: Mean Reaction Times (in ms) in Experiment 1. The Values in Parentheses Represent Standard Errors.

	Object Grasping			Object Manipulation		
Response	GC	GI	N	GC	GI	N
Grasping "Left"	336 (17)	344 (18)	353 (17)	367 (17)	369 (18)	388 (17)
Grasping "Right"	323 (15)	339 (16)	332 (15)	361 (15)	368 (16)	377 (15)
Mean	*330 (16)*	*341 (16)*	*342 (15)*	*364 (16)*	*368 (16)*	*383 (15)*

Note. GC = grip consistent; GI = grip inconsistent; N = neutral.

In all experiments reported in this chapter, anticipation responses (response ahead of onset of the go signal and RTs<150 ms), missing responses (no reactions and RTs>800 ms) and incorrect actions (e.g. wrong grip, cessations of movement while reaching, incorrect rotation) were considered errors and excluded from the statistical analyses. A type-I error rate of α=.05 was used in all statistical tests. Whenever appropriate, pairwise post-hoc comparisons were conducted using the Bonferroni procedure.

2.2.2 Results

Anticipations occurred in 10.4% of all trials (6.1% concerned responses ahead of the go signal and 4.3% RTs <150 ms). The rate of missing (< 1%) and incorrect responses (2.5%) was low reflecting that the participants had carefully complied with the instructions concerning planning and execution of the required responses.

We applied a repeated measures multivariate analysis of variance (MANOVA)[2] with the within-subject factors Manual Response (left grasp, right grasp) and Grip Consistency of the go signal (consistent, inconsistent, neutral) and the between-subject factor Action Condition (object grasping, object manipulation) on the RT data (see Table 2.1). The analysis revealed a simple main effect for the factor Manual Response indicating faster initiations of right grasps (350 ms) than of left grasps (360 ms), $F(1, 26) = 3.57$, $p < .05$. Apparently, right grasps were easier to perform as this is the natural manner to reach out for the manipulandum with the right hand. Importantly, the main effect of Grip Consistency was significant, $F(2, 25) = 9.95$, $p < .001$. As anticipated, the response latencies to grip-consistent stimuli (346 ms) were shorter than those to grip-inconsistent (354 ms), $t(27) = -2.28$, $p < .05$ and neutral stimuli (362 ms), $t(27) = -4.57$, $p < .001$. The main effect for Action Condition, $F(1, 26) = 2.39$, $p = .13$, and the interaction of Action Condition and Grip Consistency, $F(1, 25) = 1.79$, $p = .18$, did not reach significance.

[2] We used the multivariate F-test based on the Pillai-Bartlett V criterion for all within-subject factor analyses reported here (cf. O'Brien & Kaiser, 1985).

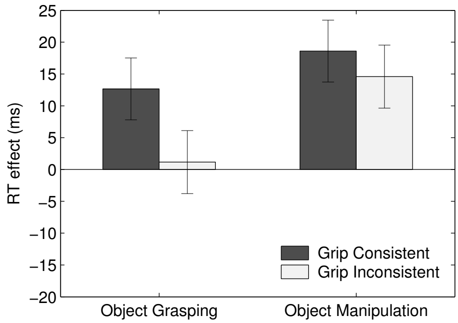

Figure 2.2: Mean effects in the response latencies of Experiment 1 as a function of the factors Action Condition and Grip Consistency. Effects are defined as the deviation from the participant's mean RT in the neutral condition. Error bars represent standard errors.

To examine the grip consistency effects in more detail, we calculated for each subject in the two action conditions the deviation of the mean RT to grip-consistent and inconsistent stimuli from the mean RT to neutral circles. The resulting RT effects are depicted in Figure 2.2 and tested with one-sample t-tests for reliability. As expected, in the object grasping condition action preparation resulted in a significant facilitory effect on the detections of a grip-consistent stimuli, $t(13) = 2.96$, $p < .05$, and did not affect the detections of grip-inconsistent stimuli, $|t(13)| > 1$. Interestingly, however, the pattern of effects in the object manipulation condition was different. When intending to manipulate the object not only grip-consistent, $t(13) = 3.45$, $p < .01$, but also grip-inconsistent stimuli—which are here consistent with the end state of the manipulation—were processed faster, $t(13) = 2.16$, $p < .05$.

2.2.3 Discussion

Taken together, the perceptual processing of visual bars was facilitated (as compared to neutral solid circle) when participants prepared an action that involved the same type of grip as afforded by the go signal. Hence, a motor-visual priming effect for grip-consistent stimuli was present in both the object grasping and the object manipulation condition. Interestingly, however, besides the finding of priming induced by prepared object manipulations, Experiment 1 also revealed differences in the effect patterns of the two conditions. Whereas, in the object grasping condition the detection times for bars in a grip-inconsistent orientation did not differ from the detection times for neural circles, in the object manipulation conditions RTs showed faster processing of bars in both grip-consistent and inconsistent orientations relative to neutral circles. For an adequate interpretation of these results it is important to note that grip-inconsistent stimuli in the manipulation condition were always consistent with the hand posture after having rotated the object by 90°, or, in other words, grip-inconsistent stimuli were always consistent with the end state of the required object manipulation.

We therefore conclude that the faster responses in the manipulation condition reflect an impact of the prepared object manipulation and indicate a facilitated processing of visual features consistent with the required action end states.

Taken together, the dissociation of RT effects between the two action conditions of Experiment 1 suggest that the participants prepared the manual rotation of the manipulandum in advance and provides a first indication that motor-visual priming effects are not restricted to the processes of visuomotor transformation required for the grip selection and is influenced the intended object manipulation. However, since this interpretation is based on multiple t-tests of the effects in the two action conditions and because of the weak statistical interaction between the factors Action Condition and Grip Consistency in the MANOVA, additional empirical evidence is clearly warranted. Thus, to test our hypothesis that motor-visual priming depends on the intended object manipulation we performed a second experiment, which is detailed next.

2.3 Experiment 2

Experiment 1 had yielded faster responses to stimuli affording the same type of grip as the currently prepared action and hence suggested that motor-visual priming effects not only depend on the selection of the initial grip but are also influenced by the end state of the intended movement. With our second experiment we aimed to test the idea that motor-visual priming indeed goes beyond visuomotor associations between intrinsic object properties and afforded grip. Given that the most basic function of any manual action is to cause changes in our physical world and that the use of an object generally involves an object displacement, the visual perception of motions should be sensitive to the planning of manual object-directed actions. Thus, when people intend to rotate an object and prepare the manipulation in advance this should result in a motor-visual priming of motions related to the intended object displacement.

In Experiment 2 we again used the object manipulation of Experiment 1 but made a crucial modification: before the go signal appeared participants were presented with a stimulus either consisting of a horizontal or a vertical bar. Due to that initial stimulus, the go signal could induce an apparent 45° CW or CWW rotation (see Figure 2.3). Assuming that the participants prepare the actual manipulation before the onset of the reach-to-grasp movement, we predicted a facilitated processing of the rotational motions in the same direction as the intended object rotation.

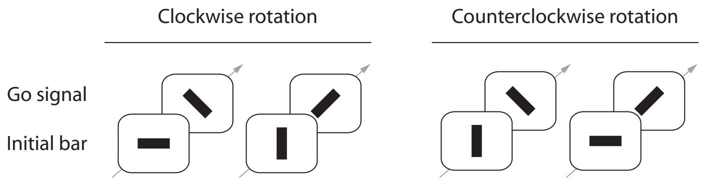

Figure 2.3: Apparent visual motions caused by the sequence of stimuli in Experiment 2 and 3. Depending on the orientation of initial bar (i.e., horizontal or vertical) the appearance of the go signal (i.e., -45° or +45° tiled bar) induced an apparent rotational motion in a clock- or counterclockwise direction. The neutral condition, in which the go signal (i.e., a solid circle) did not induce an apparent motion, is not depicted in this figure.

2.3.1 Method

Participants

Thirty students from the Radboud University Nijmegen participated in exchange for 4.50 Euros or course credits. All had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Apparatus and stimuli

The apparatus was the same as in Experiment 1. Also the go signals were unchanged. In contrast to Experiment 1, in all trials an initial stimulus consisting of either a horizontal or vertical bar was presented in the center of the screen that remained visible until the go signal appeared. The initial stimulus had the same size and was presented at the same location as go signals. Note that the go signals were identical to the ones used in Experiment 1. However, due to the presence of an initial bar the appearance of a go signal could induce an apparent rotational motion (see Figure 2.3 for an illustration). For example, the presentation of a +45° tiled bar resulted in apparent CW motion if initial stimulus was oriented vertically and in a CCW motion of it was oriented horizontally. When the circle served as go signal, there was no apparent motion (no rotation). Additionally, we didn't cue the action preparation by words, as we did in Experiment 1, because the appearance of a word stimulus would have masked the initial stimulus strongly. Instead, now we presented as action cue a small blue or yellow cross (0.9° of visual angle) on top of the vertical or horizontal bar.

Procedure and design

The procedure was basically the same as in Experiment 1, including the pre-experimental and practice blocks. Participants were instructed to always grasp

Table 2.2: Mean Reaction Times (in ms) in Experiments 2 and 3. The Values in Parentheses Represent Standard Errors.

	Vertical Initial Bar			Horizontal Initial Bar		
Manual Response	RC	RI	NR	RC	RI	NR
Experiment 2						
Left-CW	324 (21)	354 (24)	334 (20)	322 (21)	344 (24)	332 (20)
Right-CCW	337 (21)	339 (23)	354 (24)	307 (21)	340 (23)	330 (24)
Mean	*331 (21)*	*347 (23)*	*344 (22)*	*314 (21)*	*343 (23)*	*331 (22)*
Experiment 3						
Left-CW	328 (17)	341 (15)	330 (18)	327 (18)	322 (15)	323 (19)
Right-CCW	326 (16)	334 (19)	340 (19)	311 (16)	326 (19)	330 (15)
Mean	*327 (16)*	*338 (17)*	*335 (18)*	*320 (17)*	*324 (16)*	*327 (17)*

Note. RC = rotation consistent; RI = rotation inconsistent; NR = no rotation; Left-CW = grasping "left" & turning clockwise; Right-CCW = grasping "right" & turning counterclockwise.

and rotate the manipulandum. Half of the participants were presented with the horizontal and the other half with the vertical bar as initial stimulus. Each trial began with the presentation of a gray cross projected on top of the initial stimulus. As soon as the participants had placed their hand in the starting position, the color of the cross changed to cue the preparation of the object manipulation (remaining visible for 2,000 ms). Blue indicated a left grasp (the index finger at the top-left and the thumb at the bottom-right leg of the manipulandum) and a 90° CW rotation, whereas yellow prescribed a right grasp (index finger at the top-right and thumb at the bottom-left leg) and a 90° CCW rotation. After a random interval (250-750 ms) the initial stimulus disappeared and the go signal was presented for the duration of 1,000 ms.

The experimental block again comprised 144 trials consisting of all possible combinations of the two manual response (left grasp/CW rotation, right grasp/CCW rotation) and the three types of go signals (circle, bar tilted -45°, bar tilted +45°). The orientation of the initial bar (horizontal, vertical) was balanced between subjects. Depending on the induced apparent rotation, the go signals were either consistent or inconsistent with the prepared object rotation.

Data acquisition and analysis

Data acquisition and analysis were identical to Experiment 1.

2.3.2 Results

As in Experiment 1, participants had the tendency to anticipate the go signals (14.9% anticipations; 4.9 % of RTs<0 ms and 10.4% of RTs<150 ms). 8.4 % of

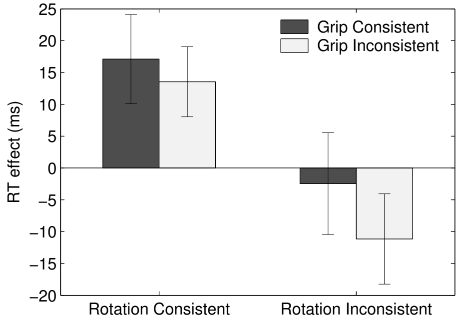

Figure 2.4: Mean effects (i.e., deviations from the neutral condition) in the response latencies of Experiment 2 as a function of the factors Rotation Consistency and Grip Consistency. Error bars represent standard errors.

the actions were performed incorrectly (i.e., no response or wrong grip or wrong object rotation).

A three-way MANOVA was performed on the mean RTs with the within-subject factors Manual Response (left grasp/CW rotation, right grasp/CCW rotation) and Rotation Consistency (consistent, inconsistent, neutral) and one between-subject factor Initial Bar Orientation (horizontal, vertical). The mean RTs are shown in Table 2.2. As hypothesized, there was a simple main effect for Rotation Consistency, $F(2, 27) = 9.75$, $p < .001$. All other effects failed to reach significance. Post-hoc t-tests yielded shorter RTs to go signals that were consistent with the rotational direction of the action (322 ms) than inconsistent (345 ms), $t(29) = -4.16$, $p < .001$, or neutral signals (338 ms), $t(29) = -3.31$, $p < .01$.

Since the go signals were identical to the ones used in Experiment 1, they could also be regarded as consistent, inconsistent or neutral with respect to the required grip. To be precise, with the horizontal bar all rotation-consistent stimuli were simultaneously consistent with the required grip, whereas with the vertical bar grip and rotation consistencies were opposed. A separate MANOVA with the factor Grip Consistency was performed and did not yield any effects in the mean RTs toward grip-consistent (327 ms), grip-inconsistent (326 ms) and neutral go signals (329 ms), $F(2, 31) = 1.05$.

In order to compare the effects of Rotation and Grip Consistency directly and to see whether the two factors interacted, we analyzed the RT effects further. For each subject we calculated the deviations of the mean RTs to the grip-consistent and grip-inconsistent bars from the mean RTs to the neutral solid circles. The resulting RT effects were submitted to a univariate analysis of variance (ANOVA) with the factors Rotation Consistency (consistent, inconsistent) and Grip Consistency (consistent, inconsistent). Averaged RT effects are depicted in Figure 2.4. As could be expected from the results of the analyses above, the main effect for Rotation Consistency was highly significant, $F(1, 56) = 9.61$, $p < .003$, whereas there was no effect for Grip Consistency, $F < 1$. This indicates a facilitated detection of stimuli eliciting consistent apparent rotations but, in contrast to Experiment 1, no impact on the detection of grip-consistent stimuli. Interestingly, the two factors did not interact, $F < 1$, showing that the rotation consistency effects were independent from the orientation (i.e., grip affordance) of the go signal.

2.3.3 Discussion

In Experiment 2 responses were speeded up when the appearance of the go signal induced an apparent rotational motion in the same direction as the prepared object manipulation. Intriguingly, the priming effects of grip-consistent stimuli as found for the static stimuli in Experiment 1 had disappeared. Possibly, the apparent motions were more salient, and had therefore a stronger impacted on the detection of the go signals, than a static intrinsic stimulus feature like orientation.

We conclude that the observed perception-action interferences reflect motor-visual priming and indicate a perceptual benefit for consistent visual motions. That is, we interpret our findings as evidence of an impact of action planning on the visual processing of motions. However, since in Experiment 2 the execution of the manual actions was coupled with the motion detections we cannot rule out an alternative explanation in terms of a stimulus-response priming effect. In other words, rather than an action-induced effect on perception, the response latency differences might reflect an accelerated initiation of manual object rotations consistent with the visual motion, i.e., visuomotor priming (cf. Craighero et al., 1998; Vogt et al., 2003) at the level of response execution, which would be an effect of opposite directionality. Thus, we conducted a third experiment to distinguish between these two possible interpretations.

2.4 Experiment 3

With this third experiment we sought to substantiate our assumption that the RT differences in Experiment 2 reflected a motor-visual priming of motion perception rather than stimulus-response priming. Again, participants prepared one of two object manipulations. However, this time the onset of the visual stimulus did not prompt the execution of the grasping response. Instead, participants were asked to signal the motion detections by pressing a foot pedal and to postpone the execution of the prepared object manipulation until the presentation of later in the trial (i.e., following a second auditory go signal).

The rationale of Experiment 3 was as follows: if, as hypothesized, the preparation of a manual response indeed facilitates the perception of consistent motions, we should observe a similar priming effect when the motion detections to be indicated with another effector system, in this case the foot (cf. Craighero et al., 1999; Fagioli et al., 2007). By contrast, if the alternative explanation holds that in Experiment 2 the perception of motions accelerated the initiation of object manipulations in the same direction, we should not find any effects on the execution of the foot responses, because they were identical in all trials and unrelated to the rotational stimulus motions.

2.4.1 Method

Participants

Fifteen students from the Radboud University Nijmegen participated in exchange for 6 Euros or course credits. All had normal or corrected-to-normal vision and were naïve to the purpose of the experiment.

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 2. To record the foot responses we placed a foot pedal (conventionally used by percussionists to play the bass drum) under the table and attached a motion-tracking sensor to the end of the pedal's drumstick (17.5 cm long). When the pedal had been pressed a sinusoid 440-Hz tone (50 ms duration) sounded to indicate a correct response. However, when participants responded before the onset of the visual go signal they were given negative auditory feedback (4400 Hz lasting 200 ms). The auditory go signal triggered the execution of the prepared manual action and consisted of a 900-Hz tone (150 ms duration).

Procedure and design

Comparable with the previous experiment, the participants were again visually cued to prepare to grasp and rotate the manipulandum. However, in contrast to Experiment 2, they were now required to make a foot response with their right foot as soon as the visual stimulus appeared. The auditory go signal indicating the initiation of the manual action was presented 600 ms after the foot response had been given.

Experiment 3 was divided into four blocks of 48 trials each. In contrast to Experiment 2, the orientation of the initial bar was now varied blockwise within subjects: half of the participants saw a horizontal bar in blocks 1 and 3 and a vertical bar in blocks 2 and 4 and for the other half the order was reversed.

Data acquisition and analysis

Data acquisition and analysis were identical to those employed in Experiment 2 with the exception that we used a fourth motion-tracking sensor to measure the

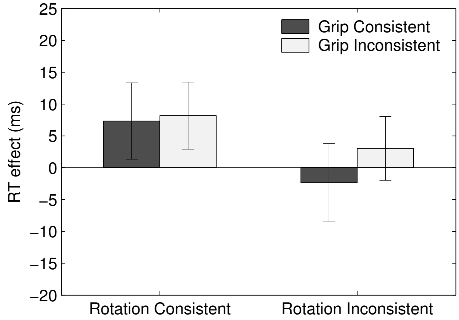

Figure 2.5: Mean effects (i.e., deviations from the neutral condition) in the foot response latencies of Experiment 3 as a function of factors Rotation Consistency and Grip Consistency. Error bars represent standard errors.

foot responses. We used the same method (i.e., velocity threshold of 10 cm/s) to determine the foot response latencies as for the hand response in Experiment 1 and 2.

2.4.2 Results

Due to an incorrect execution of the delayed object manipulation 4.7% of the foot responses were excluded from the analysis. Anticipatory foot responses occurred in only 2.6%.

The three-way MANOVA of the foot RTs with the within-subject factors Manual Response (left grasp/CW rotation, right grasp/CCW rotation) and Rotation Consistency (consistent, inconsistent, neutral) and Initial Bar Orientation (horizontal, vertical) revealed a simple main effect for Rotation Consistency, $F(2, 13) = 4.34$, $p < .05$ (see Table 2.2 on page 27). Post-hoc t-tests yielded shorter RTs for responses following visual go signals that were consistent with the planned rotation (320 ms) than for inconsistent (332 ms), $t(14) = -3.08$, $p < .01$, and neutral signals (332 ms), $t(14) = -3.30$, $p < .01$. Additionally, there was a trend to an interaction between the factors Manual Response and Rotation Consistency, $F(2, 13) = 3.0$, $p = .08$, which reflects the tendency to smaller rotation-consistency effects when a left grasp and CW rotation was required. There were no further significant effects (all Fs< 1.8).

To compare rotation and grip consistency effects we performed a separate analysis. Like in Experiment 2, we calculated the RT effects of the presentation of the tilted bars (defined as deviations from the RT for the neutral stimulus) per subject for all conditions and entered this data into a two-way MANOVA with the factors Grip Consistency (consistent, inconsistent) and Rotation Consistency (consistent, inconsistent). Again, there was no effect for Grip Consistency, $F(1, 14) < 1$, but a significant effect for Rotation Consistency, $F(1, 14) = 5.46$, $p < .05$, indicating a facilitated perception of consistent rotational motions relative to the neutral, no motion condition, while no differences were found for inconsistent motions.

2.4.3 Discussion

The foot-response latencies of Experiment 3 replicated the effects of Experiment 2, i.e., faster foot responses were made toward stimuli inducing an apparent rotation consistent with the prepared object manipulation. Because the detection of the motions and their signaling took place before the manual action had to be executed, and since the foot responses were unrelated to the visual stimuli, we can exclude the existence of stimulus-response priming at the level of response initiation. Thus, the results of Experiment 3 support the assumption of motor-visual priming: a facilitated perceptual processing of visual motions in the same direction as the intended object manipulation. This shows furthermore that motor-visual priming occurs already after action preparation and even in the absence of the execution of the response.

2.5 General Discussion

The results of the present study indicate that action planning has an impact on the perceptual processing of visual motions. Experiment 1 showed action-related effects of object manipulation on visual perception. Whereas in the object grasping condition only a grip-consistency effect was found, we observed in the object manipulation condition a grip-consistency effects as well as a facilitated processing of stimuli consistent with the end state of the required object manipulation. The data demonstrated that the preparation to manipulate an object facilitates the perception of stimuli that afford the same type of grip as the currently prepared action involved. Moreover, it indicated that motor-visual priming might not be restricted to the perception of grip-consistent stimuli but could also affect the processing of stimuli related to other states and features of the intended action. Experiment 2 investigated further the nature of motor-visual priming. When the appearance of the visual go signal induced an apparent rotational motion we observed a benefit for the perception of rotation-consistent motions. The effects of grip and end-state consistency disappeared. Importantly, the same effects on motion perception were also present in Experiment 3 in which the manual response was unrelated to the motion detection and participants indicated the detection of the visual stimuli by pressing a foot pedal. This finding clearly rejects the alternative interpretation of stimulus-response priming. In conclusion, the present findings demonstrate that planning an action facilitates the processing of visual motions if they are consistent with the intended action. The observed action-induced effects on perception indicate a modulation of visual attention as a result of motor-visual priming and suggest a bidirectional link between motor and perceptual representations that goes beyond the visuomotor association of superficial motor-object characteristics.

As mentioned in the introduction section, we are not the first to demonstrate action-induced effects on visual attention (cf. Craighero et al., 1999; Müsseler & Hommel, 1997; Wohlschläger, 2000; Bekkering & Neggers, 2002; Hannus et al., 2005; Fagioli et al.; 2007). These earlier studies, however, reported effects for simple motor responses (i.e., key presses or mere grasping actions) on the visual processing of intrinsic object properties (e.g. location or orientation) that are relevant for the programming of an object-directed motor action (e.g. grasping or pointing). The present study extends these findings to the domain of object manipulations. Furthermore, we demonstrate that action planning not only has an impact on the processing of visual object properties but also on the perception of visual motions. Although there is evidence that the perception of motions facilitates the selection of compatible motor responses (cf. Bosbach et al., 2004), to date little was known about the reversed effect. Wohlschläger's study (2000) gave some indications for an action-induced priming of motion perception by showing that the participants' direction judgments of ambiguous apparent motion were systematically biased toward the rotational direction of a simultaneously performed turning action. Although it cannot be excluded that the effects in such a paradigm may have been caused by a guessing bias in perceptually unclear situations rather than a perceptual bias, Wohlschläger's (2000) observations were in line with the idea that the planning and execution of motor actions affect the visual processing of motions. With the present paradigm we excluded the possibility of biases caused by guessing. The observed differences in the detection latencies of apparent motions thus provide new evidence for action-induced effects on motion perception. Furthermore, our experimental design allowed the detection of attentional effects induced by goal-directed actions consisting of more than just a single movement: the data showed a motor-visual priming of motions when participants prepared a more complex motor sequences such as reaching, grasping and manipulating an object. Note that the effects occurring in the onset of the reaching movements were driven by a movement (i.e., the object rotation) that had to be performed later in the motor sequence. This indicates that participants prepared the actual object manipulation before the reach-to-grasp movement was initiated. Consequently, the effects of the object manipulation can be interpreted as evidence for a goal-directed action planning and they stress the impact of action intentions (e.g. rotating the object) on the process of early movement selection (see Jeannerod, 1999). This would underpin the recent model of motion control proposed by Rosenbaum et al. (2001), which states that grip selection depends on the intended object manipulation and is mainly affected by the desired end position of the movement. The relevance of end postures in action planning might then also account for our observation in Experiment 1 that visual detections were facilitated when stimuli were consistent with the end state of the required rotation (i.e., grip inconsistent stimuli).

Craighero et al. (1999) had earlier reported priming effects of prepared reach-to-grasp movements. The present experiment replicates their findings and additionally controls for a potential confounding that made it difficult to interpret their reaction-time differences as action-related effects. In contrast to our study in which we used a single object in a constant orientation, Craighero and colleagues (1999) required participants to grasp bars positioned in different orientations that were each associated with one specific type of grip. The authors observed faster responses when the go signals afforded the same action as the to-be-grasped object. Since the actions were determined by the object orientation, it is unclear whether the stimulus detections interacted with the prepared action or with the representation of the to-be-grasped object. That is, it might be possible that priming effects were fully independent from the concurrent motor intention and were instead driven by an overlap of visual object properties (e.g. object orientation or grip affordances) between the go signal and the object. With the present paradigm, however, we can clearly reject this alternative account because participants had to grasp one object, whose orientation remained stable, in two different ways. That is, the same manipulandum was always associated with both grasping responses. Consequently, the grip-consistent effects in Experiment 1 were not triggered by the to-be-grasped object but emanated from the prepared action. This interpretation received additional empirical support from our findings of visual motion priming in Experiments 2 and 3, which indicated the presence of an impact of the intended rotation and ruled out the possibility of a consistency effect between the object and go signal.

A facilitatory motor-visual priming effect seems to conflict with studies that reported an impaired accuracy in the identification of stimuli that shared features with a prepared action (the so called action-effect blindness; Müsseler & Hommel, 1997; Wühr & Müsseler, 2001; Kunde & Wühr, 2004). For example, Müsseler and Hommel (1997) presented left- and right-pointing arrowheads shortly before the execution of a manual left or right keypress response and found impaired identifications for arrows that corresponded to the action (e.g., if a left-pointing arrowhead appeared while planning a left keypress). A crucial difference between the findings of motor-visual priming and action-effect blindness is that the former effect represents a reaction-time effect in a speeded task, whereas the latter effect was found in the accuracy of unspeeded perceptual judgments. Although there is evidence that these methodological differences could account for the disparate perceptual effects (Santee & Egeth, 1982), we argue that also from a theoretical point of view the two findings are not in contradiction. The impaired accuracy in the perception of action-consistent stimuli has mostly been explained within a common coding framework (cf. Theory of Event Coding; Hommel et al., 2001), which suggests that perception and action planning use shared codes that can represent the features of both perceived stimuli and prepared actions (see e.g., Wühr & Müsseler, 2001). Accordingly, the preparation of an action and its maintenance in memory results in an integration of all required feature codes into one coherent action plan. Once a feature code becomes integrated it is bounded and, as a consequence, less available for another integration such as required for the representation of a perceptual event. However, the likelihood that a certain feature code has to be integrated when an event is perceived depends on the feature's relevance for the task (Hommel, 2004). Thus, unattended task-irrelevant features might become activated but will not become part of any binding. In contrast to code integration, the mere activation of feature codes is assumed to facilitate the processing of events sharing these features. Consequently, the planning of an action and the resulting integration of feature codes should only cause inhibitory effects on the attempt to integrate this code in a second representation. It is important to discern that in our paradigm the direction of the motion was irrelevant to the participants' task and no short-term memory representation of the perceptual event had to be created for later recall. We therefore did not expect action-effect blindness to occur. Instead, our data indicated a facilitation of motion detections sharing features with the intended action. Whether the encoding of visual motions into a cognitive representation is impaired, as predicted by the Theory of Event Coding (Hommel et al., 2001), can not be answered at this point and requests additional investigations of action effects on the accuracy of motion perception.

As recently argued by Fagioli et al. (2007), actions cannot only affect visual attention in terms of feature-based interferences but also in terms of a bias towards an entire stimulus dimension, which results in a facilitated processing of all features defined in this dimension. This notion is supported by studies that compared the impact of grasping and pointing actions on the ability to detect a target object among distractors (Bekkering & Neggers, 2002; Hannus et al., 2005) or to identify deviants in sequences of visual events (Fagioli et al., 2005). With these paradigms it could be shown that the intention to grasp selectively enhances the visual discrimination of the grasp-relevant dimensions size and orientation. Noteworthy, from research on object perception we know that it is exactly these two stimulus dimensions that are directly associated with specific types of motor responses (Ellis & Tucker, 2000; Tucker & Ellis, 1998). For example, Ellis and Tucker (2000) demonstrated that the perception of big and small objects automatically potentiates the related grasping action, that is, either a response with the whole hand (power grip) or with the thumb and index finger only (precision grip). Apparently, effects of object affordances on response execution reflect the same close bidirectional link between object and action representation as the effects of action planning on object perception described above.

Taken together, previous studies on the interference between grasping actions and perception—including the work of Craighero et al. (1999)—focused on the two perceptual dimensions size and orientation, both crucial for the visuomotor transformation process and thus for the selection and programming of reach-to-grasp movements. The current study demonstrates an action-induced effect that cannot be explained by the visuomotor association between intrinsic object properties and selected grip. Rather, we argue that the visual motion priming originates from the relation between the action goal (i.e., the object manipulation) and the expected visual-action effects (i.e., a rotational motion). We base our interpretation on the concept of ideomotor action (cf. Greenwald, 1970a; Stock & Stock, 2004), which basically holds that actions are represented and planned in terms of their sensory outcome. Action planning is accordingly understood as a goal-driven process that involves an anticipation of the desired action effects at a sensory level. Since motor preparation is accompanied by an activation of sensory information, it can be predicted that motor preparation affects visual processing. In line with this reasoning, we interpret our results as an enhanced processing of events that are consistent with the expected action outcome. In sum, the motor-visual priming of motion perception supports the idea that action planning involves an anticipation of sensory consequences and furthermore suggests that attention is modulated toward changes in the environment that represent the potential consequences of the intended action.

Chapter 3

Action and Semantic Processing

Semantic Activation in Action Planning

Abstract. Four experiments investigated activation of semantic information in action preparation. Participants either prepared to grasp and use an object (e.g., to drink from a cup) or to lift a finger in association with the object's position following a go/no-go lexical-decision task. Word stimuli were consistent to the action goals of the object use (Experiment 1) or to the finger lifting (Experiment 2). Movement onset times yielded a double dissociation of consistency effects between action preparation and word processing. This effect was also present for semantic categorizations (Experiment 3), but disappeared when introducing a letter identification task (Experiment 4). In sum, our findings indicate that action semantics are activated selectively in accordance with the specific action intention of an actor.

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3.1 Introduction

In the area of motor control, many sophisticated models have been developed during the last couple of decades that specified the parameters of control for making object-oriented hand movements (Rosenbaum, 1991). However, a long neglected issue concerns the role of semantic knowledge in the process of action planning and control (see Creem & Profitt, 2001). That is, we do not only attune our motor system to the physical properties of a stimulus, but we also use our knowledge of what to do with an object and how to use it.

Recently, several behavioral and neuroimaging studies demonstrated that the visual perception of graspable objects and preparing for action are mutually dependent processes. For example, it has been shown that passive observations of tools evoke neuronal activation in different cortical motor areas (Martin, Wiggs, Ungerleider, & Haxby, 1996; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Chao & Martin, 2000) and facilitate motor responses that are consistent with these objects (Tucker & Ellis, 1998; Ellis & Tucker, 2000). Interestingly, other studies assume effects of a reversed directionality, that is, they assume effects of action on perception (e.g., Müsseler & Hommel, 1997; Wohlschläger, 2000; Müsseler, Steininger, & Wühr, 2001; Creem-Regehr, Gooch, Sahm, & Thompson, 2004). Several studies, for instance, showed that the planning or preparation of a motor action is able to facilitate visual processing, such as the detection of a visual stimulus that is consistent with the intended action (e.g., Craighero, Fadiga, Rizzolatti, & Umilta' 1999; Bekkering & Neggers, 2002; Hannus, Cornelissen, Lindemann, & Bekkering, 2005).

Despite the increasing evidence of the direct coupling between visual perception and action in motor control, the underlying mechanisms and representations are not well understood (see Hommel, Müsseler, Aschersleben, & Prinz, 2001 for recent review and theoretical considerations). In particular, not much is known about the role of semantic knowledge in action planning. Several neuropsychological studies have shown that there are patients with apraxia who have a selective deficit in object use but spared semantic knowledge about those objects (e.g., Buxbaum, Schwartz, & Carew, 1997; Rumiati, Zanini, Vorano, & Shallice, 2001). On the other hand, patients have been reported with semantic loss but with the ability to manipulate objects accordingly (e.g., Buxbaum et al., 1997; Lauro-Grotto, Piccini, & Shallice, 1997). This indicates that the two domains, action planning and semantic knowledge, are at some level independent from each other and that the accessibility of conceptual knowledge is not necessarily required for an appropriate object-directed action. Comparable findings led Riddoch, Humphreys, and Price (1989) to conclude that there is a direct route from vision to action that bypasses semantics. This notion received additional support from experiments with neuropsychological intact adults (Rumiati & Humphreys, 1998). Interestingly, however, a recent study by Creem and

Proffitt (2001) indicated that action planning and semantic processing cannot be considered under all circumstances as two independent processes. They found in a dual-task experiment that normal subjects often used inappropriate grasping for household tools when object grasping was paired with a semantic dual task, but less so when paired with a visuospatial dual task. As the authors argued, this finding indicates that semantic processing is involved when preparing to grasp a meaningful object. The notion of the important role of functional knowledge in object-directed motor action is also supported by behavioral and developmental studies in children and adults indicating that in our everyday life, we build up strong associations between objects and hand shapes (Klatzky, Pellegrino, McCloskey, & Doherty, 1989; Klatzky, Pellegrino, McCloskey, & Lederman, 1993) and the purpose or function for which objects are typically used (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976; McGregor, Friedman, Reilly, & Newman, 2002).

The importance of semantics for action is furthermore reflected by the results of behavioral studies that showed that semantic properties of distracting words (Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Gentilucci & Gangitano, 1998; Glover & Dixon, 2002; Glover, Rosenbaum, Graham, & Dixon, 2004) or objects (Jervis, Bennett, Thomas, Lim, & Castiello, 1999) influenced the kinematics of reach-to-grasp movements. For instance, Gentilucci et al. (2000) reported that Italian words denoting *far* and *near* printed on to-be-grasped objects had comparable effects on movement kinematics as the actual greater or shorter distances between hand position and object. Glover and Dixon (2002) reported that maximum grip aperture was enlarged when subjects grasped an object with the word *large* printed on top, as compared to grasping of an object with label *small*. Another effect indicating an interaction between semantics and action was reported by Glenberg and Kaschak (2002). They instructed their participants to judge whether sentences were sensible by making a motor response that required moving toward or away from their bodies and found faster response latencies when the sentence implied an action in same direction (e.g., "Close the drawer", which implies an action away from the body) as the direction of the required motor response (e.g., moving their hand away from their body to indicate "yes"). According to the authors, this directly supports the notion that language comprehension is grounded in bodily actions.

The studies previously mentioned nicely demonstrate the impact of semantic information on the action system, showing the readiness in which semantic content, for example, from words, may interfere with and influence ongoing behavioral performance. It is typically not the case that mere activation of semantic information will in itself result in the execution of a stereotypical action, however (with the exception of patients that display utilization behavior; Archibald, Mateer, & Kerns, 2001). Rather, human behavior, in unaffected cases, shows the ability to withstand many of the automatic tendencies or affordances that may be present in the environment and to control action selection in accordance with immediate and long-term behavioral goals (Norman & Shallice, 1986; see Humphreys & Riddoch, 2000; Rumiati et al., 2001 for neuropsychological cases in which there is a deficit in supervisory attentional control).

Although it is clear that executive processes that regulate the coherence of goal-directed behavior over time, must at some point, modulate the influence of action semantics on behavior, the exact interaction between the two mechanisms remains to be determined. One possibility is that semantic information on the functional use of objects is activated automatically upon presentation of those objects and that the control mechanisms for action subsequently select the most favorable course of action from the available alternatives (Buxbaum, 2001). Another possibility is that the activation of semantic information is selectively modulated in accordance with the behavioral goals of the task that the person is involved in. In this case, the semantic properties of the object will not be activated in full, but only those aspects that are relevant for the ongoing task. This hypothesis would be consistent with a selection-for-action viewpoint (Allport, 1987) in which information, whether perceptual or semantic, is selected in accordance with the action intention of the person that is about to act. In partial support for this possibility, electrophysiological studies indicate that providing subjects with specific task instructions to attend and respond to certain object properties, determines the type of semantic information that is activated to those objects (Coltheart, Inglis, Cupples, Michie, Bates, & Budd, 1998).

Whereas interactions between perception and action have been studied in both directions (effects of perception on action and influence of action preparation on perception; see information previously mentioned), there have been hardly any studies that looked into the influence of action preparation on the level of semantics. In the present study, we attempt to learn more about the activation of semantic information in the course of action preparation and tested the hypothesis that semantic action knowledge is activated in accordance with the specific action intention of the actor.

Traditionally, language tasks have been used to investigate semantics. A typical finding is that the semantic context (e.g., provided by a prime word) facilitates the processing of semantically related words (for review, see Neely, 1991). Priming effects have often been studied with a lexical-decision task in which participants have to judge whether a visually presented letter string is a lexically valid word or not. The semantic priming effect is very robust and has been supposed to occur automatically (Neely, 1991). It is plausible to assume that semantic preactivation is not restricted to the linguistic domain (e.g., from prime word to target word). Semantic effects have been reliably found between linguistic and nonlinguistic stimuli (e.g., Lucas, 2000; Van Schie, Wijers, Kellenbach, & Stowe, 2003). Additionally, priming studies have indicated facilitation for a variety of prime-target relations, including script relations, functional relations, and perceptual relations (overview in Lucas, 2000).

To investigate effects of action preparation on semantics, four experiments were conducted in which the preparation of an action provided the semantic context for a subsequently presented word. In all experiments, participants prepared a motor action (e.g., drink from a cup) and delayed its execution until a word appeared on a screen. In Experiment 1, participants were required to execute the action (go) if the word was lexically valid, but withhold from responding if a pseudoword was presented (no-go). The size of interference between action preparation and lexical decision was estimated by comparing the movement onset times in trials with action-consistent words (e.g., *mouth*) and action inconsistent words (e.g., *eye*). To ensure that the expected action word-processing interaction depended on the relation between prepared action and processed words and not on the sequence of the presented stimuli (i.e., picture-word priming, cf. Vanderwart, 1984; Bajo & Canas, 1989), a control condition was introduced in which participants were required to perform simple finger-lifting movements instead of grasping responses. Assuming that the semantic concepts associated with the goal location of the object use are only activated with the preparation to grasp the objects, interactions between action planning and word processing were only expected in the grasping condition. The preparation of finger-lifting responses, however, should not activate these semantic concepts.

3.2 Experiment 1

The aim of Experiment 1 was to investigate the activation of action semantics in association with action preparation. We required our subjects either to grasp and use one of two objects (cup or magnifying glass) or to lift one of two fingers related to the object positions. Subsequently presented words in a go/no-go lexical decision task (Gordon, 1983) determined whether the prepared motor action should be executed (go) or not (no-go). In line with the hypothesis that action semantics are activated conform the action intention of the subjects, we expected faster responses in the object grasping condition for trials, in which words were consistent with the goal location of the object use, as compared to trials with inconsistent words. In contrast, no latency differences between consistent and inconsistent words were expected for finger lifting responses.

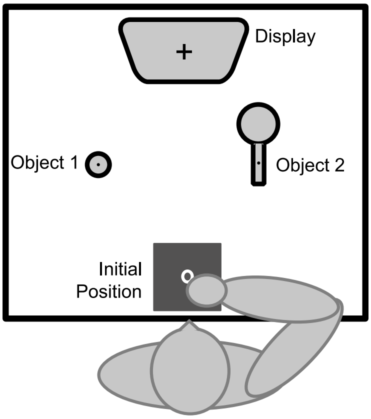


Figure 3.1: Illustration of the experimental setup. A cup (Object 1), a magnifying glass (Object 2) and a computer display were placed on the table. Participants placed their right hand on the starting position.

3.2.1 Method

Participants

Twenty-four students (18 females and 6 males) from the University of Nijmegen took part in the experiment. All were right-handed and Dutch native speakers.

Setup

Figure 3.1 illustrates the experimental setup. In front of the participants, we placed a computer display and a touch sensitive response box with markers to indicate and control the starting position of the right hand. Additionally, a cylindrical cup without any handle (diameter 7.5 cm, height 10.0 cm) and a round magnifying glass (diameter 7.5 cm) with a handgrip (length 9.0 cm) were situated on the table, both at a reaching distance of 33 cm. To keep the object positions constant we used a desk pad with drawings of the object contours. The object positions (left side/right side) were counterbalanced between the participants.

Procedure

All participants were randomly assigned to one of two action conditions (object grasping or finger-lifting). At the beginning of each trial, a picture of one of the two objects appeared on the screen for 500 ms. In the object-grasping condition, participants were instructed to prepare actions associated with these objects. None of these actions was described verbally, nor were actions or their endpoints mentioned in the task instructions. Instead, the experimenter performed the associated actions in presence of the subject to instruct the required motor responses at the beginning of the experiment. For example, if a cup was shown, the required action was to grasp the cup and to bring it to the mouth. The motor response associated with the magnifying glass was to grasp the object and move it to the right eye. By contrast, in the finger-lifting condition, the participants prepared a lifting of either the index or middle finger of the right hand depending on which side the depicted object was situated on the table. Importantly, the action in association with the object had to be delayed until the presentation of a word on the screen. After a variable delay of 500 ms to 2,000 ms either a valid Dutch word or a pseudoword was presented for 1,000 ms. We instructed our subjects to initiate the prepared action as soon as the word was identified as a lexically valid word (go), and to place back the object after the action was finished. Whenever a pseudoword was displayed, participants were instructed to withhold from responding (no-go). In the object-grasping condition, a cross appeared on the screen 2,500 ms after word offset and extinguished when the subject returned the hand correctly to the starting position. Because the time needed to execute a simple finger movement is relatively short, the cross in the finger-lifting condition was presented 1,000 ms after word offset.

Stimuli and design

The target words used for the go/no-go lexical decision task were the Dutch words *MOND* [mouth] and *OOG* [eye] representing the goal locations of the action associated with the cup and the action associated with the magnifying glass, respectively. In addition, two unrelated filler words, *DEUR* [door] and *TAS* [bag], were selected to match the target words with respect to word category, word length (three or four letters, monosyllabic) and word frequency in written Dutch language (CELEX lexical database, Burnage, 1990). Thus, in go trials, the presented words were either consistent with respect to the prepared action, inconsistent with the action (that is, associated with the other object), or unrelated fillers. Additionally, five legal pseudo-words were constructed for the no-go trials. These were derived from the targets by replacing all letters (vowels by vowels and consonants by consonants) so that the syllable structure and the word length were identical to those of targets. All pseudo-words obeyed the Dutch phonotactics.

Thus, there were two action conditions (object grasping and finger lifting) varied between subjects. Each condition consisted of 96 target trials (50% action consistent words, 50% action inconsistent words), 48 filler trials, and 30 (17.2%) no-go trials (2 objects × 5 pseudo-words × 3 repetitions). All trials were presented in a randomized sequence. The experiment lasted about 30 minutes.

Data acquisition and analysis

To record hand and finger movements we used an electromagnetic position tracking system (miniBIRD 800^{TM}, Ascension Technology Corporation). In the object grasping condition, three sensors were attached to the participants' thumb, index finger, and wrist of their right hand. Only two sensors, one attached to the right index finger and one to the middle finger, were needed in the finger lifting condition. Sensor positions were tracked with a sampling rate of 103.3 Hz.

Movement kinematics were analyzed off-line. We applied a fourth-order Butterworth lowpass filter with a cut-off frequency of 10 Hz on the raw data. Two criteria were chosen to detect onsets and offsets of the reach-to-grasp and finger lifting movements. An onset was defined to be the first moment in time when the tangential velocity exceeded the threshold of 10 cm/s and remained above this level for the minimum duration of 400 ms (object grasping condition) or 50 ms (finger lifting condition). For the offsets, we used the reversed criteria, taking the time of the first sample where the velocity decreased below the threshold for the predefined time.

The time differences between word onset and hand movement onset (determined by the wrist sensor) were used to calculate response latencies in the object grasping condition. We additionally calculated the following kinematic parameters of the first movement after word presentation: reach time, peak velocity, and percentage of time to maximum grip aperture with respect to reach time (TMG). In the finger lifting condition the analysis was restricted to the response latencies determined by the onset of the first finger movement after word presentation. All trials with incorrect response (i.e., incorrect lexical decisions and wrong actions) or with response latencies more than 1.5 standard deviations from each participant's mean were excluded from the statistical analysis (cf. Ratcliff, 1993).

A type I error rate of $\alpha = .05$ was used in all statistical tests reported in this chapter. Given $\alpha = .05$ and $n = 12$ participants in both action conditions, contrasts between consistent and inconsistent trials of the size $d_3' = .9$ (cf. Cohen, 1977) could be detected with a probability of $(1 - \beta) = .81$ for object grasping as well as for finger lifting[1].

3.2.2 Results

For both action conditions, the percentages of correct lexical decisions to Dutch words (hits) were greater than 98.4%. No false alarm responses occurred. Wrong

[1] All statistical power analyses reported here were performed using the G*Power 2 program (Erdfelder, Faul, & Buchner, 1996)

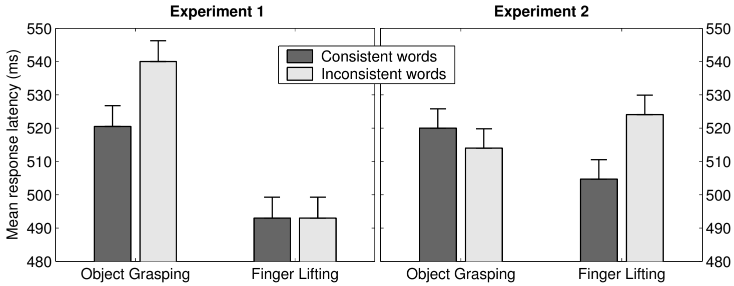


Figure 3.2: Mean response latencies in the go/no-go lexical decision task of Experiment 1 (goal locations) and 2 (spatial descriptions) as a function of the factors action condition and word consistency. Error bars represent the 95% within-subject confidence intervals (cf. Loftus & Masson, 1996).

actions (i.e., lifting the wrong finger or grasping the wrong object) occurred in less than 1% of all hit trials.

The response latencies to target words (i.e., consistent and inconsistent words) and filler words did not differ significantly, neither for object grasping, $t(11) = -2.00$, $p > .05$ nor for finger lifting, $|t(11)| < 1$. For further analyses we focused on the contrast between consistent and inconsistent trials.

The mean response latencies to target words in the lexical decision task are shown in Figure 3.2. A mixed-model analysis of variance (ANOVA) with one between-subject factor (action condition: object grasping or finger lifting) and one within-subject factor (word consistency) was computed. The data showed an overall trend for the factor word consistency, $F(1, 22) = 3.91$, $p = .06$. Most important, the interaction between the two factors was significant, $F(1, 22) = 4.72$, $p < .05$. Post-hoc 2-tailed t-tests showed that for object grasping the latencies to consistent words (521 ms) were shorter than to inconsistent words (538 ms), $t(11) = -3.35$, $p < .01$, $d'_3 = 1.36$ (cf. Cohen, 1977), whereas no significant difference was observed in the finger lifting condition (consistent: 493 ms vs. inconsistent: 492 ms), $|t(11)| < 1$.

For the object grasping condition, we calculated the kinematic parameters reach time, peak velocity and the percentage of time to maximum grip aperture (TMG). They were entered separately into three 2 (object) $\times$ 2 (word consistency) repeated measures ANOVAs (see Table 3.1). When grasping the cup, peak velocity was slower, $F(1, 11) = 12.58$, $p < .01$, and TMG was later, $F(1, 11) = 15.04$, $p < .01$, as compared to trials in which the magnifying glass was grasped. The reach times didn't differ significantly. More important, no effects of the word consistency were found in any kinematic variable, all $F < 1$.

Table 3.1: Means of the Kinematic Parameters Reach Time (RET), Peak Velocity (PV), and Percentage of Time to Maximum Grip Aperture with Respect to Reach Time (TMG) in Experiment 1 as a Function of the Word Consistency.

	Cup		Magnifying Glass	
	Consistent	Inconsistent	Consistent	Inconsistent
RET (ms)	592	597	585	582
PV (cm/s)	123.9	123.4	137.1	137.7
TMG (%)	76.5	75.8	51.8	50.6

3.2.3 Discussion

In summary, response latencies to words consistent with the action goal of the movements were faster if object grasping was prepared. On the contrary, no consistency effects were found when subjects prepared for finger lifting. This dissociation suggests that the action word-processing interaction did not merely arise from presenting the object pictures or from attention being selectively directed to one of the two objects. Both action conditions were identical in these aspects. We can also exclude the alternative explanation that simple picture-word priming (cf. Vanderwart, 1984; Bajo & Canas, 1989) caused the response latency differences, because pictures and words were identical in both conditions. Rather, the results suggest that action-specific semantic information was selected in association with the action goal of the movement that was prepared. Only when subjects had the intention to grasp and use the objects, a relative advantage was found for words that specified the goal location of the object use. Furthermore, the absence of priming effects in the finger-lifting condition argues against the hypothesis that action semantics are activated automatically and independent from the behavioral goal upon the presentation of objects.

Nevertheless, there is a possible alternative account for the lack of response latency differences in the finger-lifting condition. In Experiment 1, the preparation of simple finger movements appears much easier than the preparation of reach-to-grasp movements, which are motorically more complex. As a consequence, participants may have been more efficient in cognitively separating action preparation and word recognition tasks, resulting in the absence of an action word-processing interaction for the finger-lifting condition.

3.3 Experiment 2

Experiment 2 was conducted to exclude the possibility that the differences in the motor complexity in the two action conditions (object grasping and finger lifting) may have affected interactions between action preparation and lexical decision.

In order to test that the effects reported in Experiment 1 were independent of movement complexity and the result of an interaction between the semantic representations involved in motor preparation and word processing, we sought to reverse the pattern of effects between the two conditions. Instead of using words related to the goal locations of grasping movements, we presented the Dutch words for *left* and *right*, as representatives of action features believed to be important in the finger-lifting condition. We hypothesized that these spatial descriptions were much more relevant for the finger-lifting condition than for the object-grasping condition. In other words, we predicted an action word-processing interaction primarily for the finger-lifting condition and much smaller or no effects for object grasping.

3.3.1 Method

Participants

Again, twenty-four students (16 females and 8 males) from the University of Nijmegen were tested. All were right-handed and Dutch native speakers.

Setup and procedure

The experimental setup and procedure was the same as compared to Experiment 1.

Stimuli and design

For the go/no-go lexical decision task we used as consistent and inconsistent words (target words) the Dutch words for the spatial relations left and right (i.e., *LINKS* and *RECHTS*). The unrelated filler words were *BLAUW* [blue] and *SCHOON* [nice, clean], selected to match target words in word category, word length (i.e. number of letters and syllables) and word frequency in written Dutch language. For the no-go trials, five legal pseudo-words with the same word lengths and syllable structure as the target words were constructed from the targets by replacing all letters. The experimental design was identical to Experiment 1.

Data acquisition and analysis

Data acquisition and analysis was unchanged. Also, the statistical power to detected consistency effects was identical to those in Experiment 1.

Table 3.2: Means of the Kinematic Parameters Reach Time (RET), Peak Velocity (PV), and Percentage of Time to Maximum Grip Aperture with Respect to Reach Time (TMG) in Experiment 2 as a Function of the Word Consistency.

	Cup		Magnifying Glass	
	Consistent	Inconsistent	Consistent	Inconsistent
RET (ms)	628	635	637	638
PV (cm/s)	128.6	127.6	141.2	143.0
TMG (%)	77.7	78.5	41.0	38.7

3.3.2 Results

Hit rates for both action conditions were higher than 98.8%. No false alarm responses occurred. The percentages of wrong actions were 2.8% for object grasping and 0.8% for finger lifting. In both action conditions, response latencies to filler words were statistically not different from the latencies to target words, both $|t(11)| < 1$.

Mean response latencies to target words in the lexical decision task are shown in Figure 3.2 on page 46. The 2 (action condition) × 2 (word consistency) mixed-model ANOVA yielded no main effects. Again, a significant interaction between word consistency and action condition was found, $F(1, 22) = 10.48$, $p < .001$. Interestingly, in the finger lifting condition response latencies to inconsistent words (524 ms) were longer than to consistent words (504 ms), $t(11) = 2.82$, $p < .05$, $d'_3 = 1.15$. However, no significant differences were found in the object grasping condition (consistent: 520 ms vs. inconsistent: 514 ms), $t(11) = 1.58$, $p > .05$.

The three two-factorial repeated measures ANOVAs (object × word consistency) of the kinematic parameters revealed that grasping the cup led to slower peak velocities, $F(1, 11) = 8.43$, $p < .05$, and later TMG, $F(1, 11) = 30.02$, $p < .001$ (see Table 3.2). However, there was no influence of the word consistency on any kinematic variable, all $F(1, 11) < 1$.

3.3.3 Discussion

In summary, consistent with the results of the previous experiment, Experiment 2 showed an action word-processing interaction using the spatial descriptions *left* and *right*. Again, no effect of the word consistency was found in the analysis of kinematics. Importantly, however, in contrast to the first experiment, consistency effects were now present in the finger-lifting condition, whereas the response latencies in the object-grasping condition were unaffected by the word meaning. Overall, there is a double dissociation of effects between Experiment 1 and 2, which indicates that the action word-processing interaction cannot be explained by the complexity of the motor response. Rather, the results of Experiment 1 and 2 are consistent with the hypothesis that action semantics were specifically activated in association with the action intended by the subject.

Although it is difficult to imagine an explanation for the action word-processing interaction without including semantics, there is a possibility that the repeated use of the same words in the experiment may have led participants to perform the lexical-decision task on the basis of the visual word forms alone, without involving semantics. To control for this possibility and to provide further support for the idea that the interaction between action preparation and word processing critically depends on semantic processing, two additional experiments were performed, in which we introduced a semantic categorization and a letter identification task.

3.4 Experiment 3

In order to better understand the nature of the action word-processing interaction, we introduced a semantic categorization task instead of a lexical-decision task for the current experiment. We cannot exclude the possibility that the participants in the first two experiments did read the words, but relied only on the visual word forms and did not process words to a semantic level. Clearly, a semantic categorization task cannot be performed without deep semantic processing. Thus, Experiment 3 allows collecting further evidence for the assumption that the relevant processing level for the action word-processing interaction is the semantic processing level.

3.4.1 Method

Participants

Fifteen students (13 females and 2 males) from the University of Nijmegen participated in Experiment 3 in return for 4 Euros or course credits. All were right-handed and Dutch native speakers.

Setup and procedure

The experimental setup was the same as in Experiment 1. Only, instead of using a touch sensitive response box, we implemented an online control function in the motion tracking software to control whether the hand was positioned correctly at the beginning of each trial. A white and tangible circle (3 cm) on the desk pad served as marker for the initial position.

Table 3.3: Word Stimuli Used in Experiment 3 (Semantic Categorization Task, SC Task) and Experiment 4 (Final Letter Identification Task, FLI Task).

Word Stimulus (Dutch)	English Translation	Stimulus Category Experiment 3 (SC Task)	Experiment 4 (FLI Task)
mond	mouth	target	target
oog	eye	target	target
heup	hip	filler	no-go
rug	back	filler	filler
nek	nape	filler	no-go
buik	stomach	filler	no-go
mug	mosquito	no-go	filler
mier	ant	no-go	no-go
eend	duck	no-go	filler
kat	cat	no-go	no-go
vis	fish	no-go	no-go
hond	dog	no-go	filler

The procedure was basically identical to Experiment 1. That is, each trial started with a picture of one of the objects, which indicated the action to prepare. After a variable delay a word appeared, which triggered the action initiation. In contrast to the previous experiments, a semantic categorization task was used for the go/no-go decisions. Participants were instructed to decide whether the displayed word represents a human body part or an animal. In the case of a body part the prepared action had to be initiated immediately; in the case of an animal no response was required. The semantic categorizations had to be performed as fast and accurate as possible. Since the aim of this experiment was to replicate the action word-processing interaction in object grasping, we could refrain from varying the type of action. Thus, all participants were required to prepare and execute reach-to-grasp movements to use the objects.

Materials

The twelve Dutch words that were used for the semantic categorization task are printed in Table 3.3. As in Experiment 1, the words *MOND* [mouth] and *OOG* [eye] were the target words, which were consistent or inconsistent with respect to the goal location of the prepared action. Additionally, we used four action unrelated words, all members of the natural category of the *human body* as filler words and six members of the natural category of *animals* as no-go stimuli. Both categories were part of the supracategory *natural* and were chosen so that they were roughly comparable in category size. All words were selected to match the two target words with respect to word length (3 or 4 of letters and

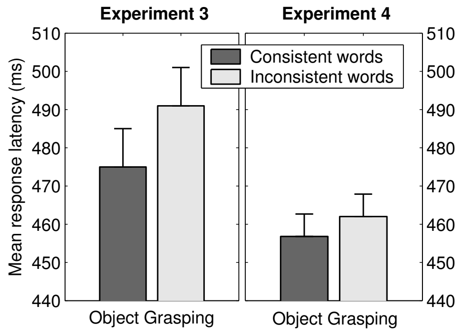


Figure 3.3: Mean response latencies in Experiment 3 (semantic categorization task) and in Experiment 4 (final letter identification task) as a function of the factors action condition and word consistency. Error bars represent the 95% within-subject confidence intervals (cf. Loftus & Masson, 1996).

monosyllabic), word category and word frequency in written Dutch language (cf. CELEX lexical database, Burnage, 1990). Both target words were repeated 20 times in combination with each of the two object pictures indicating the respective action. In order to obtain an equal amount of trials with target words and filler words, the four fillers were presented ten times per object. All six no-go stimuli were repeated four times per object.

The experiment consisted of 80 target trials (50% action consistent words, 50% action inconsistent words), 80 filler trials and 48 (23.0%) no-go trials. All trials were presented in a randomized sequence. The experiment lasted about 40 minutes.

Data acquisition and analysis

Data acquisition and analyses of latencies and kinematics were as described in Experiment 1. Given $\alpha = .05$ and $n = 15$ participants, consistency effects of size $d'_3 = .8$ could be detected with a probability of $(1 - \beta) = .82$.

3.4.2 Results

The percentage of correctly categorized body-parts (hits) was 98.2%. Incorrect categorizations of animals (false alarms) occurred in average in less than 1% of all trials. Incorrect actions were observed in less than 1% of the hit trials. Response latencies to action-unrelated filler words (499 ms) were slower than to target words (482 ms), $t(14) = -6.10$, $p < .001$. This difference is not surprising, because filler words were presented less frequently than target stimuli.

Mean response latencies to consistent and inconsistent target words for the semantic categorization task are shown in Figure 3.3. As expected, the responses to action-consistent words (474 ms) were significantly faster as compared to action-inconsistent words (490 ms), $t(14) = 2.37$, $p < .05$, $d'_3 = 0.87$.

Table 3.4: Means of the Kinematic Parameters Reach Time (RET), Peak Velocity (PV), and Percentage of Time to Maximum Grip Aperture with Respect to Reach Time (TMG) in Experiment 3 as a Function of the Word Consistency.

	Cup		Magnifying Glass	
	Consistent	Inconsistent	Consistent	Inconsistent
RET (ms)	522.1	522.0	517.2	515.8
PV (cm/s)	117.6	117.1	125.7	125.1
TMG (%)	76.1	76.5	71.8	71.9

The 2 (object) × 2 (word consistency) repeated measures ANOVAs of the reach time, peak velocity, and percentage of time to maximum grip aperture (TMG) yielded no influence of word meaning on any kinematic variable, all $F(1, 15) < 1$ (see Table 3.4). Merely effects of the objects were present, that is, grasping the cup led to slower peak velocities, $F(1, 15) = 7.97$, $p < .05$, and later TMG, $F(1, 15) = 5.72$, $p < .05$.

3.4.3 Discussion

The aim of the present experiment was to provide further evidence for a semantic nature of the action word-processing interaction observed in Experiment 1. Unambiguously, the categorization task in the present experiment required deep semantic processing and the low number of errors in this task indicates that semantic processing was indeed successfully performed by the participants. Similar to the results of Experiment 1 response latencies were faster for conditions in which the word semantics were consistent with the prepared action, without there being any effects in movement kinematics. The results of Experiment 3 indicate the reliability of the action word-processing interaction and support our assumption that the effect reflects an interaction at a semantic level.

Still, one additional test may be applied to strengthen the present conclusions. If the interaction between action preparation and word processing indeed critically depends on semantic processing, the effect should disappear under conditions where the activation of word semantics is not required to solve the task.

3.5 Experiment 4

Previous studies using a word-to-word priming paradigm have shown that the semantic priming effect is reduced or eliminated when participants perform a letter identification task on the prime word (prime-task effect, e.g., Henik, Friedrich, Tzelgov, & Tramer, 1994; Stolz & Besner, 1996). Similarly, Stroop interference can be reduced or eliminated when only a single letter is colored instead of the whole word, as in the standard version of the task (Besner, Stolz, & Boutilier, 1997). In both tasks, allocating attention to low-level features of the word is assumed to hinder semantic processing.

In the present experiment, we transferred this logic to the paradigm involving action preparation and word reading. We used the same experimental procedure and the identical stimulus set as in Experiment 3, although, the go/no-go criterion was whether a given letter was present in the final position of the word form. If the observed consistency effects require semantic processing, the response latency differences should disappear or become significantly smaller using a low-level letter-identification task.

3.5.1 Method

Participants

Twenty right-handed and Dutch native speaking students (14 females and 6 males) from the University of Nijmegen were tested.

Procedure

The experimental setup and procedure was identical to Experiment 3. The only modification was that the go/no-go decisions were based on the final letter of the word that was presented. To be precise, participants were instructed to initiate the prepared action as soon as possible only if the word ended with either the letter "D" or "G", and not to respond if the word ended with any other letter.

Materials

The same twelve Dutch words as in Experiment 3 were used for the letter identification (see Table 3.3 on page 51). Again, the two goal locations of the actions *MOND* [mouth] and *OOG* [eye] served as target words. Four action unrelated words (filler words) also ended with a "D" or a "G" and served as go stimuli. The remaining six words, which did not end with "D" or "G" served as no-go stimuli. The frequencies of presentation of targets, fillers, and no-go stimuli were the same as described in Experiment 3. Thus, there were 80 target trials (50% action consistent words, 50% action inconsistent words), 80 filler trials and 48 (23.0%) no-go trials. All trials were presented in a randomized sequence. The experiment lasted about 40 minutes.

Table 3.5: Means of the Kinematic Parameters Reach Time (RET), Peak Velocity (PV), and Percentage of Time to Maximum Grip Aperture with Respect to Reach Time (TMG) in Experiment 4 as a Function of the Word Consistency.

	Cup		Magnifying Glass	
	Consistent	Inconsistent	Consistent	Inconsistent
RET (ms)	508.0	508.3	527.2	523.9
PV (cm/s)	118.8	118.6	123.5	125.9
TMG (%) 70.1	70.7	59.8	59.6	

Data acquisition and analysis

Data acquisition and analyses of latencies and kinematics were as described in Experiment 1. In order to interpret a potential non-significant result, as hypothesized, an a priori power analysis was performed. Given $\alpha = .05$ and $(1-\beta) = .80$, $n = 20$ participants were needed to detect a consistency effect with somewhat smaller size ($d'_3 = .7$) than the effects in the first three experiments.

3.5.2 Results

The percentage of correct identifications of the final letter "D" and "G" (hits) was greater than 98%. False alarms occurred in less than 1% of all trials, wrong action in less than 1% of the hit trials. Response latencies to filler words (475 ms) were longer than to targets words (459 ms), $t(19) = 5.33$, $p < .001$, which reflects the fact that filler words were presented less often than target words.

Mean response latencies to target words for the final letter identification task are shown in Figure 3.3 on page 52. Importantly, there was no statistical difference between the response latencies to consistent words (457 ms) as compared to inconsistent words (462 ms), $t(19) = 1.29$.

Again, the three kinematic parameters were analyzed with separate 2 (object) × 2 (word consistency) ANOVAs (see Table 3.5). Grasping of the cup led to later TMG, $F(1, 19) = 6.80$, $p < .05$. No effects were observed in peak velocities and reach times. As in the three experiments before, we did not find effects of the word meaning on any kinematic variable, all $F(1, 19) < 1.4$.

3.5.3 Discussion

In summary, no reliable action word-processing interaction was observed with the letter identification task. There were no significant differences in response latencies for action-consistent words as compared to inconsistent words. Because the statistical power was satisfactory, we can exclude the presence of an interaction between action intention and word semantics in the present experiment. These results are in line with our assumption that when semantic processing is not required for the go/no-go task, no action word-processing interaction can be observed. Although some degree of automatic semantic processing of word forms cannot be excluded in the letter identification task, when attention was directed to low-level features of the target words, the interaction effects disappeared. Accordingly, the activation of semantic representations from the visual word form seems to be a prerequisite for the observed interaction, which emphasizes the semantic nature of the action word-processing interaction effect.

3.6 General Discussion

The results of the present study demonstrate an interaction effect between processes involved in action preparation and processes involved in word reading. Response latencies were sped up if words presented in a go/no-go decision task were consistent with the features of a concurrently prepared action. In Experiment 1, when subjects prepared to grasp the objects, reaction times were faster when words consistently described the goal location (i.e., *mouth* or *cup*) of the prepared action. When subjects prepared finger-lifting movements on the basis of the object positions instead of performing object-directed actions, however, reaction time effects were found to disappear. These results suggest that functional semantic information regarding the purpose or action goal for which an object is typically used does not become activated automatically upon presentation of the object, but only when subjects intend to use the object with that specific purpose.

Experiment 2 further supported the hypothesis that semantics are activated in association with the action intention of the actor and ruled out possible alternative explanations for the difference between the two action conditions in Experiment 1. Changing the words to describe relevant action features for the finger-lifting condition (*left* and *right*) resulted in an action word-processing interaction for this condition, whereas no effect was found in the condition in which subjects grasped and used objects. Both the dissociations between conditions within each experiment and the reversal of effects between experiments are consistent with our hypothesis that action semantics about objects are selectively activated and depend on the actor's intention.

Experiments 3 and 4 further supported the suggestion that the action word-processing interaction critically depends on the depth of semantic processing required by the go/no-go task. In Experiment 3, in which subjects made semantic decisions about word category instead of the lexical decisions, the action word-processing interaction between the two tasks was found unchanged. As Experiment 4 demonstrates, however, the mere presentation of a visual word form is obviously not sufficient to cause this effect, which indicates the semantic nature of this effect. Therefore, we consider the use of a secondary language task as a successful approach to investigate semantic action representations and the use of functional object knowledge in the context of action preparation.

In line with the results of Experiments 3 and 4, which show that the activation of semantic concepts was critically involved in establishing the interaction between the two tasks, contemporary models of motor control (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Glover, 2004) suggest that conceptual knowledge is involved in the selection of appropriate action plans. Consistent with this notion, recent experiments in the field of motor control demonstrated that presentation of irrelevant semantic information (via words) has a direct impact on movement kinematics of reach-to-grasp actions (Gentilucci & Gangitano, 1998; Gentilucci et al., 2000; Glover & Dixon, 2002; Glover, 2004). For example, Glover and Dixon (2002) reported that maximum grip aperture was enlarged while grasping an object with the word label *large* as compared to grasping an object with the word label *small*. Interestingly, Glover et al., (2004) reported an automatic effect of word reading on grasp aperture using words for objects that either afford a large grip (e.g., *apple*) or a small grip (e.g., *grape*). In both studies, Glover and colleagues performed a detailed analysis of the movement kinematics, which showed that word semantics affected the motor action only very early in the movement. As the hand approached the target, the impact of word semantics was found to decline continuously. In line with these results, the authors concluded that semantic information interferes only with motor planning but not with motor control once the action is initiated. This view is consistent with the present findings in which word meaning only affected reaction times but not the online control of movement execution. Concerning the absence of kinematic effects, our study notably differs from earlier studies on semantics in motor action. To be precise, in our paradigm, it was required to prepare the action before word onset and to execute it after word processing. In other words, motor action and word reading did not take place at the same time. This may explain the absence of kinematics effects in the present study and suggests that the reaction time differences reflect effects in the word-processing performances caused by action preparation.

Although the absence of kinematic effects is consistent with the assumption that actions were prepared effectively, an alternative account that may partly explain our results is that, instead of preparing a motor response, participants represented the upcoming motor task verbally in short-term memory and recalled these verbal descriptions for the grasping or finger-lifting actions after picture onset. It must be emphasized, however, that in the present study, subjects were never instructed in words such as "grasp the left object and bring it to the mouth." Instead, subjects just saw the relevant actions once before the experiment started. Furthermore, the short reaction times, minimal error rates, and absence of kinematic effects in all experiments indicate that subjects prepared the upcoming actions well before word onset and do not suggest that participants memorized the motor task verbally and prepared the action only after word onset. This assumption is also supported by several studies on motor control (e.g., Rosenbaum, 1983; Leuthold, Sommer, & Ulrich, 2004), which indicate that, in delayed response conditions, subjects tend to prepare the motor response as far as possible in advance instead of maintaining cueing information in memory or recalling the task instruction. In light of these arguments, we consider the verbal working memory explanation to be unlikely, and we favor the interpretation that effects reflect semantic overlap between action preparation and lexical semantics.

Hommel and Müsseler (2006) recently investigated the effects of action preparation on the perception of directional words (i.e., *left* and *right*). They required their participants to prepare either a manual left-right keypress response or to say "left" or "right." Later, they briefly presented a directional word. In contrast to the present paradigm, the words had to be recalled after executing the prepared response. Under these conditions, planning vocal actions impaired the perception of directional words, but, interestingly, the preparation of manual responses did not affect word processing. Although it might be difficult to compare accuracy effects in an unspeeded identification task with reaction time effects in a lexical-decision task, these results seem to be in contradiction with the results of the present study. One possible explanation for this discrepancy is that in the study of Hommel and Müsseler (2006), participants were required to maintain a short-term memory representation of the presented words, which was not the case in the present study. According to the feature-integration approach (Stoet & Hommel, 1999; Hommel, 2004), attending a perceptual object as well as planning an action implies an integration of several activated feature codes into one coherent object representation or action plan. The mere activation of feature codes should facilitate processing of all events sharing these features. Once a feature code is integrated into an action plan or object representation, however, it is no longer available for another integration if needed for other cognitive processes. As a result, this process is assumed to be impaired. It has been suggested that the likelihood that a feature code becomes integrated depends on the relevance of the respective feature for the task. That is, unattended or task-irrelevant features may become activated but not integrated into one or more bindings (Hommel, 2004). In line of this reasoning, in the study of Hommel and Müsseler (2006, Experiment 3A), feature integration of the word semantics was required to maintain a short-term memory representation. In the present study, however, semantic features were activated but were not integrated into a short-term memory representation, which had to be maintained while acting. Consequently, we found that the semantic congruency between the two tasks did not result in an inhibitory effect, but in a facilitation of word processing.

Several studies have shown that action preparation as well as action execution can influence visual perception (Craighero et al., 1999; Müsseler & Hommel, 1997; Müsseler et al., 2001; Wohlschläger, 2000). For example, Craighero et al. (1999) required their participants to prepare an action (i.e., to grasp a bar with a specific orientation) but to delay action execution until the appearance of a visual stimulus. Interestingly, they found that movements were initiated faster when the orientation of the go stimulus was consistent with the orientation of the to-be-grasped object. In the same study, consistency effects were found when after preparation of a hand movement, participants were instructed to inhibit the prepared grasping movement and to respond with a different motor effector. Craighero et al. (1999) concluded that the mere preparation of an action is capable to facilitate the processing of visual stimuli if it contains features that are consistent with the preactivated action plan.

In addition to and consistent with the reported perceptual effects of action preparation, the current study suggests that the principles of selection for action are also operational at the level of semantics. Our data suggest that functional semantic information about objects is activated in association with the action intention of the subject. For example, although cups are typically brought to the mouth for drinking, we assume that the concept of mouth is activated stronger when there is the intention to bring the object to the mouth as when some other response is required. In fact, our results suggest that the goal location of the object use is not activated when there is no specific intention to interact with the object. That is, when subjects received the instruction to perform finger-lifting movements, the facilitation of words, which are consistent with the goal locations of the object use, was absent. These results suggest that functional semantic information about how to respond to objects requires motor processing in order to become activated. A theoretically comparable idea in the field of perception and action is expressed by the premotor theory of visual attention (Rizzolatti, Riggio, & Sheliga, 1994), which suggests that allocating visual attention in space involves covert activation of the eye movement system. In this perspective, action preparation no longer just facilitates the selection of perceptual information, but perceptual processes themselves require motor support. A similar mechanism might, in theory, be applicable also to the activation of semantic representations. That is, functional semantic information about the use of objects may require activation of motor representations to enable the semantic information to be addressed. Similar proposals have been made with respect to visual semantic knowledge about the appearance of objects (Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; van Schie, Wijers, Mars, Benjamins, & Stowe, 2005). Lesions in visual areas of the brain (occipitotemporal area) sometimes not only result in perceptual deficits, but may also impair the activation of knowledge about the visual properties of objects (review in Humphreys & Forde, 2001). Comparable ideas have been expressed with respect to functional semantic knowledge in which lesions in motor areas of the brain are held responsible for subjects' impairments to represent the functional properties of objects (review in Saffran & Schwartz, 1994). A growing number of neuroimaging studies furthermore affirm the idea that visual and motor representations support semantic knowledge about the use and appearance of objects (e.g., Pulvermüller, 1999; Tranel, Kemmerer, Adolphs, Damasio, & Damasio, 2003). One advance of the present study is that it provides behavioral support for existing neuropsychological and neuroimaging results, which suggest that accessing functional semantic information about objects involves an activation of specific motor representations.

Whereas an increasing amount of research is directed at the use of motor representations for semantics, the reverse relationship concerning the use of semantic information for actions has received much less attention. As a consequence, the contribution of semantics for use of objects is still not fully understood (see Rumiati & Humphreys, 1998; Creem & Proffitt, 2001; Buxbaum et al., 1997). For example, neuropsychological studies (e.g., Buxbaum et al., 1997; Riddoch et al., 1989) and behavioral studies with time-limited conditions (Rumiati & Humphreys, 1998) suggest that semantic knowledge can be bypassed when selecting an action as response to objects. This shows that an involvement of semantics in action planning is not obligatory and has led Riddoch et al. (1989) to conclude that a direct route from vision to action exists in addition to a semantic route. Nevertheless, some experimental findings support information-processing models for action, which propose that access to stored semantic knowledge about an object is utilized to generate correct object-directed actions (MacKay, 1985). For example, a recent study of Creem and Proffitt (2001) shows that semantic processing is required when grasping ordinary household tools appropriately for their use. They observed that subjects' grasping was frequently inappropriate when the motor task was paired with an additional semantic task but not when paired with a visuospatial task. In congruence with these findings, the present study demonstrates the important role for functional semantic knowledge in action preparation and provides evidence for the notion that action semantics are routinely activated with the preparation and execution of goal-directed actions.

In addition to the rather general conclusion that semantics are involved in object use, the results of the present study clearly indicate that action semantics are activated selectively in accordance with the actor's specific intention. In other words, depending on the person's current behavioral goal, different functional object properties become relevant and activate as a result of different aspects of semantic action knowledge. This conclusion does not contradict the results of neuroimaging experiments that find motor areas activated to the presentation of manipulable objects (Chao & Martin, 2000; Creem-Regehr & Lee, 2005) or the findings of behavioral studies suggesting that the mere perception of tools automatically potentiates components of the actions they afford (Tucker & Ellis, 1998; Ellis & Tucker, 2000). In contrast to these studies, however, the present study points out the modulating role of action intentions on the activation of action knowledge related to an object in a functional-relevant way.

In conclusion, the advance that is made with the present paradigm is that we were able to establish a measure of semantic action knowledge as it is activated in the process of action preparation. Our finding of an action word-processing interaction suggests that the selection-for-action hypothesis is not just restricted to the domain of perception and action, but it is to be extended to the field of semantics. This insight certainly calls for further investigation. More scientific interest into the area of semantic action knowledge is expected to increase our understanding of the cognitive mechanisms that underlie the planning and control of motor actions.

Chapter 4

Action and Number Processing

Numerical Magnitude Priming in Object Grasping

Abstract. To investigate the functional connection between numerical cognition and action planning, we required participants to perform different grasping responses depending on the parity status of Arabic digits. The results showed that precision grip actions were initiated faster in response to small numbers, whereas power grips were faster to large numbers. Moreover, analyses of the grasping kinematics revealed an enlarged maximum grip aperture in the presence of large numbers. RT effects remained present when controlling for the number of fingers used while grasping but disappeared when participants pointed to the object. Our data indicate a priming of size-related motor features by numerals and support the idea that representations of numbers and actions share common cognitive codes within a generalized magnitude system.

This chapter is based on: Lindemann, O., Abolafia, J. M., Girardi, G., & Bekkering, H. (2007). Getting a Grip on Numbers: Numerical Magnitude Priming in Object Grasping. *Journal of Experimental Psychology: Human Perception and Performance, 33*(6), 1400-1409.

4.1 Introduction

In the last few decades many authors have emphasized that cognitive representations of perceptual and semantic information can never be fully understood without considering their impact on actions (Gallese & Lakoff, 2005). In this context interactions between perception and action have been extensively studied (for a review see e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). More recently, researchers also started to focus on the interactions between language and action (e.g., Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006; Lindemann, Stenneken, van Schie, & Bekkering, 2006). However, a cognitive domain that has been hardly investigated in respect to its impact on motor control is the processing of numbers. This is surprising since information about magnitude plays an important role in both cognition and action. Accurate knowledge about size or quantity is not only required for high-level cognitive processes such as number comprehension and arithmetic (Dehaene, 1997; Butterworth, 1999) but also for the planning of grasping movements (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Castiello, 2005). Since magnitude processing in mathematical cognition and in motor control has been studied typically independent from each other, little is known about possible interactions between these two cognitive domains.

Interestingly, some authors have recently argued that the coding of magnitude information may reflect a direct link between number processing and action planning (Walsh, 2003; Göbel & Rushworth, 2004; Rossetti, Jacquin-Courtois, Rode, Ota, Michel, & Boisson, 2004). This idea is so far primarily based on neuroimaging studies that found an overlap in activated brain areas during processes related to numerical judgments and those related to manual motor tasks. In particular, the intraparietal sulcus has been suggested to be the locus of an abstract representation of magnitude information (for a review see Dehaene, Molko, Cohen, & Wilson, 2004).

At the same time, it is widely agreed that this particular brain region, as part of the dorsal visual pathway, is also concerned with visuomotor transformations and the encoding of spatial information required for motor actions (see, e.g., Culham & Valyear, 2006). Based on these findings, Walsh (2003) proposed a neuropsychological model of magnitude representation, which states that space and quantity information are represented by a single generalized magnitude system located in the parietal cortex. Such a system may provide a common metric for all sorts of magnitude information whether this information relates to numerical quantities while counting or to physical sizes of objects while performing grasping actions. In other words, the model claims that number cognition and action planning are linked by a shared abstract representation of magnitude, which is strongly connected with the human motor system.

Indirect behavioral evidence that symbolic magnitude information interferes with motor processes has been provided by language-based studies. For example, Gentilucci et al. (2000) reported that grasping actions are affected by words representing size-related semantic information (see also Glover & Dixon, 2002; Glover, Rosenbaum, Graham, & Dixon, 2004). Gentilucci et al. required participants to grasp objects on which different word labels had been attached, and they observed that the word *large* leads to a larger maximum grip aperture when reaching out for the object than does the word *small*. This finding indicates that the processing of size-related semantic information interferes with action planning. However, as demonstrated by behavioral, neuropsychological, and animal research, semantic knowledge about magnitudes constitutes a very domain-specific cognitive ability that does not require any verbal processing but is based on a language-independent abstract representation of quantity and size (e.g., Brannon, 2006; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2000). Consequently, the findings of an interference effect between semantics and action can hardly be generalized to the domain of numerical cognition, and it remains an open question whether number processing interferes with action planning, as would be predicted by the notion of a generalized magnitude system.

A characteristic property of nonverbal number representations is the direct coupling of magnitude information with spatial features (Fias & Fischer, 2005; Hubbard, Piazza, Pinel, & Dehaene, 2005). Such an association between numbers and space is nicely demonstrated by the so-called SNARC effect (i.e., the effect of spatial- numerical associations of response codes), which was first reported by Dehaene, Bossini, and Giraux (1993). These authors required their participants to indicate the parity status of Arabic digits (i.e., odd or even) by left and right keypress responses, and they observed that responses with the left hand were executed faster in the presence of relatively small numbers as compared with large numbers. Responses with the right hand, however, were faster in the presence of large numbers. The SNARC effect has been interpreted as evidence that numerical magnitude is spatially represented—an idea that has often been described with the metaphor of a "mental number line" on which numbers are represented in ascending order from the left side to the right. Although the origin of spatial numerical associations is still under debate (see Fischer, 2006; Keus & Schwarz, 2005), there is growing evidence suggesting that SNARC effects do not emerge at the stage of motor preparation or motor execution. For example, it is known that spatial-numerical associations are independent from motor effectors, because they can be observed for different types of lateralized responses such as pointing movements (Fischer, 2003), eye movements (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004), and foot responses (Schwarz & Müller, 2006). Additionally, it has been shown that numbers not only affect the initiation times of lateralized motor response but can also induce attentional (Fischer, Castel, Dodd, & Pratt, 2003) and perceptual biases (Calabria & Rossetti, 2005; Fischer, 2001). These findings suggest that space-number interferences occur during perceptual processing or response selection but not in later, motor-related stages of processing. Recently, this interpretation received direct support from electrophysiological experiments on the functional locus of the SNARC effect (Keus, Jenks, & Schwarz, 2005). Regarding the idea of a generalized magnitude system, SNARC and SNARC-like effects can be considered evidence that numbers and space are coded on a common metric, but it appears to be unlikely that they reflect an interaction between number processing and motor control.

However, if numerical cognition and motor control share a cognitive representation of magnitude, numerical information should affect the preparation or execution of motor response. In other words, effects of numerical magnitude should be present not only in movement latencies but also in the kinematic parameters of an action. Moreover, the notion of a generalized magnitude system implies that numerical stimulus-response compatibility effects are not restricted to associations with spatial locations as indicated by the SNARC effect and, rather, predicts a direct interaction between numerical and action-related magnitude coding. Consequently, the processing of numerical magnitudes should affect the programming of size-related motor aspects—an effect that could be described as a within-magnitude priming effect of numbers on actions (see Walsh, 2003). Initial supporting evidence for this hypothesis has come from the observation of an interaction between number processing and finger movements recently reported by Andres, Davare, Pesenti, Olivier, and Seron (2004). In this study, participants were required to hold the hand in such a way that the aperture between index finger and thumb was slightly open. Then participants judged the parity status of a visually presented Arabic digit and indicated their decision by means of a flexion or extension of the two fingers (i.e., a closing or opening of the hand). Electromyographic recordings of the hand muscles indicated that closing responses were initiated faster in the presence of small numbers as compared with large numbers, whereas opening responses were faster in the presence of large numbers. This interaction between number size and finger movements constitutes an interesting example of a numerical priming of size- related action features. Andres et al. (2004) argued that the performed movements may represent mimicked grasping actions and supposed that the observed interaction may point to an interference between number processing and the computation of an appropriate grip aperture needed for object grasping. However, to date, there has been little empirical evidence that numerals affect reach-to-grasp movements. To test this hypothesis directly, we decided to investigate natural grasping movements that involve, in contrast to finger movements, a physical object and that comprise a reaching phase, which is characterized by both an opening and a closing of the hand (see Castiello, 2005).

Thus, the present study investigated the effects of number processing on the planning and execution of prehension movements to test the hypothesis that numerical cognition and motor control share a common representation of magnitude. As mentioned above, previous research has demonstrated that reach-to-grasp movements are sensitive to abstract semantic information (Gentilucci et al., 2000; Glover & Dixon, 2002; Glover et al., 2004). Considering this and the fact that the planning to grasp an object depends to a large extent on magnitude processing, since it requires a translation of physical magnitude information (i.e., object size) into an appropriate grip aperture, grasping responses appeared to us to be promising candidates to study the presumed functional connection between numbers and actions. To be precise, we expected that the processing of Arabic numbers could prime the processing of size-related action features (i.e., a within-magnitude priming effect; cf. Walsh, 2003) and, consequently, affect the initiation times and movements kinematics of reach-to-grasp movements.

4.2 Experiment 1

Experiment 1 investigated whether processing of numerical magnitude information affects the response latencies and movement kinematics of grasping movements. Participants had to judge the parity status of visually presented Arabic digits. Decisions had to be indicated by means of two different reach-to-grasp movements toward a single target object placed in front of the participants. Specifically, participants were required to grasp the object with either a precision grip (i.e., grasping the small segment of the object with the thumb and index finger) or a power grip (i.e., grasping the large object segment with the whole hand). If magnitude representations for numerical cognition and action planning have a common basis, we expected to find a stimulus-response compatibility effect between number magnitude and the prehension act. Thus, power grip actions should be initiated faster in response to relatively large numbers, and precision grip actions should be initiated faster in response to relatively small numbers.

Since it is known from research on eye-hand coordination that participants tend to fixate a to-be-grasped object before initiating the reach-to-grasp movement (Land, 2006), we obscured the right hand and the object from the view of the participants and trained them to grasp the object correctly without visual feedback. There were two major reasons for the use of memory-guided grasping actions in this paradigm: First, if actions have to be executed without visual feedback, participants' visual attention remains constantly directed toward the parity judgment task until the movement is executed and does not alternate between the to-be-grasped object and the monitor. The task requirements as well as the reaction time (RT) measurements are therefore comparable to those in classical number processing experiments using buttonpress responses. Second, online adjustments of memory-guided actions are more difficult to perform than are adjustments of visually guided actions (e.g., Schettino, Adamovich, & Poizner, 2003). As a result, participants are less prone to execute the reaching movements before they have completed their judgment and selected the required grip. This control is crucial for our paradigm, because the hypothesized response latency effects can be only detected if number processing and grip selection are fully completed before the initiation of the reach-to-grasp movement. With respect to the measurement of the maximum grip apertures, it is noteworthy to mention that several studies have shown that hand kinematics during memory-guided grasping actions do not differ from those found during visually guided actions (Land, 2006; Santello, Flanders, & Soechting; 2002; Winges, Weber, & Santello, 2003). It seems, therefore, to be unlikely that the absence of visual feedback influences the appearance of potential number magnitude effects in the grip aperture data.

4.2.1 Method

Participants

Fourteen students of Radboud University Nijmegen, Nijmegen, the Netherlands, participated in the experiment in return of 4.50 Euros or course credit. All were naive regarding the purpose of the study, had normal or corrected-to- normal vision, and were free of any motor problems that would have influenced their performance on the task.

Setup and stimuli

Participants sat in front of a computer screen (viewing distance: 70 cm) and were required to grasp a wooden object consisting of two segments: a larger cylinder (diameter: 6 cm; height: 7 cm) at the bottom and a much smaller cylinder (diameter: 0.7 cm; height: 1.5 cm) attached on top of it (see Figure 4.1). The object was placed at the right side of the table behind an opaque screen (height: 44 cm; width: 45 cm), allowing a participant to reach it comfortably with his or her right hand but without the possibility of visual control (see Figure 4.1A). At a distance of 30 cm from the object center, we fixed a small pin (height: 0.5 cm; diameter: 0.5 cm), which served as a marker for the starting position of the reach-to-grasp movements. As stimuli for the parity judgment task we chose the Arabic digits *1, 2, 5, 8*, and *9* printed in a black sans serif font on a light gray background. They were displayed at the center of the computer screen and subtended a vertical visual angle of approximately 1.8°.

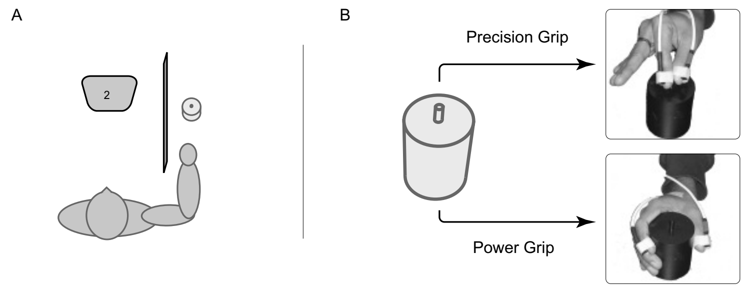


Figure 4.1: Basic experimental setup. A: Participants sat at a table with a computer screen and a manipulandum. An opaque screen obscured the to-be-grasped object and the right hand from view. B: The object consisted of two segments: a large cylinder at the bottom affording a power grip and a small cylinder at the top affording a precision grip.

Procedure

At the beginning of the experiment, participants were required to practice grasping the object with either the whole hand at its large segment (i.e., power grip) or with thumb and index finger at its small segment (i.e., precision grip). Figure 4.1B illustrates the two required responses in the experiment. Only if participants were able perform the grasping movements correctly and fluently without vision was the experimental trial block started.

The participants task was to indicate as soon as possible the parity status of the presented Arabic digit (i.e., even vs. odd) by means of the practiced motor responses. That is, depending on the parity status, the participant was required to reach out and grasp the object with either a power or a precision grip. However, in the case of the digit *5*, participants were required to refrain from responding. This *no-go* condition was introduced to ensure that reaching movements were not initiated before the number was processed and the parity judgment was made.

Each trial began with the presentation of a gray fixation cross at the center of the screen. If the participant placed his or her hand correctly at the starting position, the cross turned black and disappeared 1,000 ms later. After a delay of random length between 250 ms and 2,000 ms, the digit was presented. Participants judged its parity status and executed the corresponding grasping movements. The digit disappeared with the onset of the reach-to-grasp movement or after a maximal presentation time of 1,000 ms. After an intertrial interval of 2,000 ms, the next trial started. If participants moved their hands before the digit was shown or if they responded on a no-go trial, a red stop sign combined with a 4400-Hz beep sound lasting 200 ms was presented as an error signal.

Design

The mapping between digit parity and required grasping response was counterbalanced between participants. That is, half of the participants performed a power grip action in response to even digits and a precision grip action in response to odd digits. For the other half, the stimulus-response mapping was reversed.

The digits *1, 2, 8*, and *9* were presented 50 times. The experiment thus comprised 100 power grip responses and 100 precision grip responses, whereas each grip type had to be performed toward both small and large digits. Additionally, there were 25 no-go trials (i.e., digit *5*). All trials were presented in a randomized sequence. The experiment lasted about 45 min.

Data acquisition and analysis

An electromagnetic position-tracking system (miniBIRD 800^{TM}, Ascension Technology Corporation, Burlington, VT) was used to record hand movements. Two sensors were attached on the thumb and index finger of the participant's right hand. The sampling rate was 100 Hz (static spatial resolution: 0.5 mm). The movement kinematics were analyzed offline. We applied a fourth-order Butterworth lowpass filter with a cutoff frequency of 10 Hz on the raw position data. The onset of a movement was defined as the first moment in time when the tangential velocity of the index finger sensor exceeded the threshold of 10 cm/s. We used reversed criteria to determine movement offset. For each participant and each experimental condition, we computed the mean RT (i.e., the time elapsed between onset of the digit and the onset of the reaching movement) and the mean maximum grip aperture (i.e., average of the maximum Euclidean distances between thumb and index finger during the time between reach onset and offset).

Anticipation responses (i.e., responses before onset of the go signal and RTs < 100 ms), missing responses (i.e., no reactions and RTs $< 1{,}500$ ms), incorrect motor responses (i.e., all trials on which participants failed to hit the object or stopped their reaching and initiated a new reach-to-grasp movement), and incorrect parity judgments were considered errors and excluded from further statistical analyses. In all statistical tests, a Type I error rate of $\alpha = .05$ was used. To report standardized effect size measurements, we calculated the parameter omega squared (ω^2), as suggested by Kirk (1996).

4.2.2 Results

Anticipations and missing responses occurred on 0.3% of trials; 2.7% of the grasping responses were performed incorrectly. The error rate for the parity judgments was 2.2%.

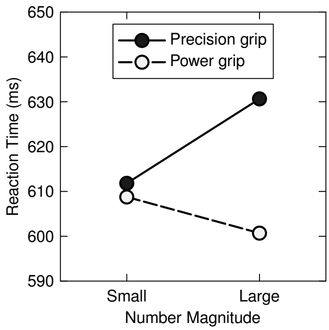


Figure 4.2: Mean response latencies in Experiment 1 as a function of the factors Number Magnitude and Type of Grip.

The mean RT data were submitted to a two-way repeated measures analyses of variance (ANOVA) with the factors number magnitude (small magnitude: *1* and *2*; large magnitude: *8* and *9*) and type of grip (power grip, precision grip). Figure 4.2 depicts the mean RTs. Power grip responses (605 ms) were initiated faster than precision grip responses (621 ms), $F(1, 13) = 5.17$, $p < .05$, $\hat{\omega}^2 = .13$. Most important, however, the analysis yielded a significant Number Magnitude × Type of Grip interaction, $F(1, 13) = 7.13$, $p = .05$, $\hat{\omega}^2 = .10$. That is, precision grips were initiated faster to small numbers (612 ms) than to large numbers (631 ms), $t(13) = 2.30$, $p < .05$. This difference appeared to be reversed for the power grip responses, for which actions were initiated faster to large (600 ms) than to small numbers (609 ms). This contrast, however, failed to become significant, $t(13) = 1.10$, $p = .32$.

The mean maximum grip apertures were analyzed with the same two-way ANOVA as used for the RT data (see Table 4.1 for means). The main effect of type of grip was significant, $F(1, 13) = 376.50$, $p < .001$, which reflects the trivial fact that maximum grip aperture was larger for the power grip responses (120.0 mm) than for the precision grip responses (75.0 mm). Interestingly, we also found a main effect of number magnitude, $F(1, 13) = 5.31$, $p < .05$, $\hat{\omega}^2 = .13$. This finding indicates that grip apertures were somewhat larger in the context of large numbers (97.8 mm) than in the context of small numbers (97.2 mm). The Type of Grip × Number Magnitude interaction did not reach significance, $F(1, 13) = 3.80$, $p = .08$.

4.2.3 Discussion

Experiment 1 demonstrates a magnitude priming effect of numerals on grasping latencies. That is, the grasping responses to small digits were initiated faster if the object had to be grasped with a precision grip, and responses to large numbers were relatively faster if a power grip was required. In addition, we found that number magnitude affected the grasping kinematics (i.e., the maximum

Table 4.1: Mean Maximum Grip Aperture (in mm) During Reach-to-Grasp Movements in Experiment 1 and 3 as a Function of the Factors Number Magnitude and Type of Grip.

	Experiment 1		Experiment 3	
	Small Numbers	Large Numbers	Small Numbers	Large Numbers
Precision Grip	74.6	75.9	73.7	74.2
Power Grip	119.6	119.7	116.3	117.0
Mean	*97.2*	*97.8*	*95.0*	*95.6*

grip apertures were enlarged when the object was grasped in presence of a large number). Although the Type of Grip × Number Magnitude interaction was not significant, the mean maximum grip apertures seem to suggest that the main effect of number magnitude was restricted to the precision grip actions. A possible reason for this dissociation is the fact that many participants had to open their hand to a maximum degree to perform the power grip response and clasp the bottom cylinder, which had a large diameter. Under these circumstances, the processing of large numbers can hardly result in a further enlargement of the grip aperture. The number magnitude effect on the grasping kinematics is therefore less pronounced, for it could be observed for precision grip actions.

The magnitude priming effect on grasping latencies and the number effect on grip aperture indicate that the processing of numbers has an impact on prehension actions. Both findings are in line with the hypothesis that numerical cognition and action planning share common cognitive codes within a generalized system for magnitude representation (Walsh, 2003). A possible objection to the interpretation that the numerical magnitudes primed the size-related motor features of the grasping actions is that the two responses not only varied with respect to the required grip size (i.e., precision or power grip) but were also directed toward different parts of the object. That is, each precision grip was directed toward the small top segment, whereas each power grip was directed toward the large bottom segment. Therefore, the possibility cannot be excluded that the observed response latency differences reflect a compatibility effect between numerical magnitudes and spatial response features along the vertical direction. That is, it might be possible that responses to the top were facilitated for small numbers and responses to the bottom were facilitated for large numbers. Such SNARC-like effects for the vertical direction have been previously shown by different researchers (e.g., Ito & Hatta, 2004; Schwarz & Keus, 2004). However, such studies consistently suggest spatial-numerical associations of upward movements with large numbers and downward movements with small numbers. Although we observed the opposite pattern of effects in Experiment 1, we cannot exclude at this point the possibility that the differences in the latencies of the grasping response might have been driven by a reversed vertical SNARC effect. A second possibility to account for the data of Experiment 1 is the assumption of correspondence effects between the numerical size and the size of the object segment to which the action is directed. That is, reach-to-grasp responses toward the small or large segment could be facilitated in response to small or large numbers, respectively. This possible association between abstract magnitude information and physical object properties would also argue against our interpretation of numerical priming effects on grasping actions. To evaluate these alternative explanations, we conducted a second experiment.

4.3 Experiment 2

The aim of Experiment 2 was to control for a possible confound of the required grip size and the relative vertical goal location of the reaching movements in Experiment 1 and, thus, to exclude the possibility that the observed response latency effects were driven by a spatial association between numerical magnitudes and the vertical dimension (e.g., a vertical SNARC effect). To do so, we required the participants in Experiment 2 to merely reach out for the object without grasping it (i.e., pointing movement). That is, the parity status of Arabic digit had to be indicated by means of pointing movements toward the small top or large bottom segment of the object. If our previous findings reflected a reversed vertical SNARC effect or a compatibility effect between number size and the size of the object segments that served as goal locations for the response, the same response latency effects should be present in pointing movements. However, if the effects reflected a priming effect of aperture size, the intention to grasp should be crucial to finding stimulus-response compatibility effects between numerical information and object-directed actions. In that case, we would expect pointing responses to be unaffected by the presented digits.

4.3.1 Method

Participants

Twenty-two students of Radboud University Nijmegen participated in Experiment 2 in return for 4.50 Euros or course credit. None of them had taken part in the previous experiment. All were naive regarding the purpose of the experiment and had normal or corrected-to-normal vision.

Setup and stimuli

The experimental setup and stimuli were identical to those of Experiment 1.

Procedure

The procedure and the design were virtually the same as in Experiment 1. The only modification was that instead of the previous grasping movements, participants performed pointing movements. That is, depending on the parity status of the presented digit, the participants were required to point either to the small top or to the large bottom segment of the object. Since the pointing movements needed to be performed accurately without sight, the responses were again practiced at the beginning of the experiment.

Design

Half of the participants had to point to the small top segment in response to even digits and to the large bottom segment in response to odd digits. The other half were given the reverse stimulus-response mapping. The experiment again comprised 225 trials (50 repetitions of the digits *1, 2, 8*, and *9* plus 25 no-go trials with the digit *5*) presented in a random order and lasted about 30 minutes.

Data acquisition and analysis

An electromagnetic motion-tracking sensor was attached to the participant's right index finger and used to record the pointing trajectories. Movement onsets were determined and analyzed as described in Experiment 1. In addition, we calculated for each pointing trajectory the path curvature index (PCI), which was defined as the ratio of the largest deviation of the pointing trajectory from the line connecting the movement's start and end locations to the length of this line (see Desmurget, Prablanc, Jordan, & Jeannerod, 1999).

Trials with incorrect parity judgments were excluded from the RT analysis. To increase the chance of finding an effect of number magnitude on pointing, we also considered movements with strongly curved trajectories (i.e., movements with a PCI larger than .50) to be incorrect responses, because in these cases participants may have initiated the pointing movement before having completed their parity judgment, or they may have corrected their judgment during the movement.

4.3.2 Results

Anticipation and missing responses occurred on 0.4% of trials; 2.6% of the pointing movements were performed incorrectly (i.e., PCI>.50).[1] The average error rate for parity judgments was 1.1%.

[1] A two-way repeated measures ANOVA with the factors number magnitude (small, large) and pointing goal location (small top segment, large bottom segment) on the error data (i.e., amount of incorrect performed motor response) yielded no significant effects (all *p*s> .20).

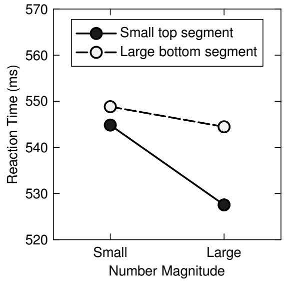


Figure 4.3: Mean response latencies in Experiment 2 as a function of the factors Number Magnitude and Pointing Goal Location.

We applied a two-way repeated measures ANOVA with the factors number magnitude (small, large) and pointing goal location (small top segment, large bottom segment) to the RT data (see Figure 4.3) and the PCI data (see Table 4.2 for means). Pointing movements toward the small top segment (530 ms) were initiated faster than were movements to the large bottom segment (543 ms), $F(1, 21) = 4.80$, $p < .05$, $\hat{\omega}^2 = .08$. Responses to small numbers (541 ms) were faster than responses to large numbers (531 ms), $F(1, 21) = 7.38$, $p < .01$, $\hat{\omega}^2 = .12$. Most important, however, the analysis did not show a significant Number Magnitude × Pointing Goal Location interaction, $F(1, 21) < 1$, even though the statistical power[2] of the performed ANOVA was sufficient to detect an interaction effect that was only half the size of the effect found in Experiment 1–that is, $(1 - \beta) = .83$ for an expected $\omega^2 = .05$ and an assumed population correlation between all factor levels of $\rho = .75$ (conservatively estimated from the observed empirical correlations).

The analysis of the PCI data revealed that pointing movements toward the top segment (PCI < .29) were more curved than the movements toward the bottom segment (PCI < .20), $F(1, 21) = 26.98$, $p < .001$. Importantly, there were no significant effects of number magnitude or the Number Magnitude × Pointing Goal Location interaction, both Fs$(1, 21) < 1.5$, which shows that number processing had no impact on the pointing kinematics.

4.3.3 Discussion

If participants made pointing instead of grasping movements, the interaction between numerical magnitudes and motor responses disappeared. Likewise, the analysis of movement curvature data failed to reveal any influence of numerals. This absence of numerical magnitude effects on the pointing movements excludes the possibility that the priming effects observed in Experiment 1 were

[2] The statistical power analysis was conducted using the *G*Power 3* program (Faul, Erdfelder, Lang, & Buchner, 2007).

Table 4.2: Mean Path Curvature Indices for Pointing Movements in Experiment 2 as a Function of Number Magnitude and Pointing Goal Location.

Segment	Small Numbers	Large Numbers
Small Top	.29	.29
Large Bottom	.20	.21
Mean	*.24*	*.25*

driven by spatial associations between numbers and relative vertical locations or by associations between number magnitude and physical object size. Since other authors have reported numerical associations with locations along the vertical axis, it is possible that the absence of effects for pointing movements was caused by two opposite effects resulting from contrary associations of numerical magnitude with vertical space (i.e., a vertical SNARC effect) and with physical object size (i.e., an association between number and size of object segment). Independent of this speculation, however, the outcome in Experiment 2 shows clearly that numerals did not affect motor actions if responses did not involve a grasping component and consisted only of a pointing movement. Taking these together with the results of Experiment 1, we can conclude therefore that the intention to grasp is a prerequisite for the present of numerical magnitude priming of actions, which in turn indicates that the observed interference effects must have emerged during the selection and preparation of the grip.

Nevertheless, our interpretation of a within-magnitude priming effect between numerical cognition and action planning could still be questioned. The reason is that the motor responses in Experiment 1 differed not only with respect to the size of the required grip but also with respect to the number of fingers that had to be used for grasping. That is, precision grips always implied grasping movements with two fingers (e.g., only thumb and index finger), whereas power grips always involved the use of all five fingers of the hand. Therefore, we cannot exclude the possibility that our findings were driven by the different number of fingers involved in the grasping responses. Such an explanation is not farfetched, and it appears to be even plausible to assume that there is a strong association between the fingers of the hand and the semantic knowledge about numerical magnitudes (see, e.g., Di Luca, Grana, Semenza, Seron, & Pesenti, 2006). This connection is, for instance, nicely illustrated by children's use of finger-counting strategies when learning to deal with abstract quantities. And in fact, empirical evidence for this relation comes from developmental studies indicating that the performance of a child in a finger agnosia test is a good predictor for later numerical skills (Noel, 2005). Moreover, neuropsychological research has shown that symptoms of finger agnosia are often associated with symptoms of dyscalculia (so-called Gerstmann's syndrome; Mayer et al., 1999). Consequently, we conducted a third experiment to control for the number of fingers involved in the grasping responses.

4.4 Experiment 3

In Experiment 3, we sought to provide further evidence that number processing interferes with the processing of action-coded magnitude information for motor preparation, and we aimed to exclude the possibility that this compatibility effect was caused by overlearned associations between numbers and the fingers of the hand. To do so, we tested whether magnitude priming effects of numerals could also be found in grasping movements that required a fixed number of fingers for both required types of grip. As in the first experiment, participants grasped the object in different ways to indicate the parity status of Arabic digits. Now, however, power and precision grips both had to be performed with the thumb and index finger only. Consequently, the two grasping responses differed only in aperture size.[3] To ensure that the ring, middle, and little fingers were not used to grasp the target object, we required participants to hold a little stick with these three fingers. If the response latency differences in Experiment 1 were driven by a number-finger association, we should not observe any magnitude priming effects. If, however, they reflected a magnitude priming of size-related response features of the grasping action, we should be able to replicate our previous findings.

4.4.1 Method

Participants

Eighteen students of Radboud University Nijmegen, none of whom had participated in either of the previous experiments, took part in Experiment 3. The participants were paid 4.50 Euros or received course credits. All were naive regarding the purpose of the study and had normal or corrected- to-normal vision.

Setup and stimuli

The experimental setup and stimuli were identical to those of Experiment 1.

[3]For reasons of simplicity, we keep the label *power grip* here for the grasping of the large segment with the thumb and index finger, although the term is usually reserved for grasping actions with all fingers of the hand.

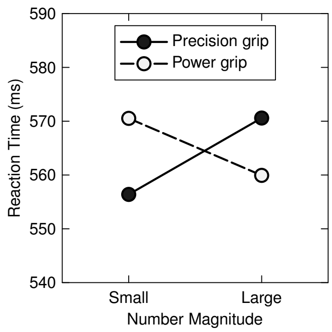


Figure 4.4: Mean response latencies in Experiment 3 as a function of the factors Number Magnitude and Type of Grip.

Procedure and design

The procedure and the experimental design were virtually identical to those of Experiment 1. Again, participants were required to indicate the parity status of the presented digits by performing different types of grasping responses with the right hand. However, in contrast to Experiment 1, the object had to be grasped with thumb and index finger only. That is, depending on the presented digits, participants grasped the object with two fingers either at the large segment (i.e., power grip) or at the small segment (i.e., precision grip). To ensure that no other finger of the right hand were used for grasping, participants had to hold a little stick (length: 5 cm; diameter: 1.5 cm) during the experiment between their right middle, ring, and little fingers.

Data acquisition and analysis

Data acquisition and analysis methods were identical to those used in Experiment 1. An additional motion-tracking sensor was mounted inside the stick and used to make sure that participants held the stick in their right hand during all trials.

4.4.2 Results

Anticipations and missing response occurred on 0.7% of trials; only 0.9% of the grasping movements were performed incorrectly. The error rate for the parity judgments was 1.6%.

The RT and grip aperture data (see Figure 4.4 and Table 4.1 on page 73) were analyzed as in Experiment 1. The 2 (number magnitude: small vs. large) $\times$ 2 (type of grip: precision grip vs. power grip) ANOVA of the RTs revealed no main effects (both Fs<1). Importantly, a significant Number Magnitude $\times$ Type of Grip interaction was found, $F(1,17) = 5.46$, $p < .05$, $\hat{\omega}^2 = .06$. Post-hoc t-tests indicated that the precision grip RTs were shorter to small numbers

(556 ms) than to large numbers (571 ms), $t(17) = -2.13$, $p < .05$, whereas for the power grips, there was a non-significant trend toward the reversed effect—that is, shorter RTs to large (560 ms) than to small numbers (571 ms), $t(17) = 1.95$, $p = .058$. The two-way ANOVA on the mean maximum grip apertures revealed a main effect of type of grip, $F(1, 17) = 292.76$, $p < .001$, which showed that the grip apertures were larger for power grip actions (116.7 mm) than for precision grip actions (73.9 mm). Although the mean grip aperture difference between responses toward small and large numbers was identical to the main effect observed in Experiment 1, the factor number magnitude did not reach statistical significance, $F(1, 17) = 2.11$, $p = .16$.

4.4.3 Discussion

Experiment 3 replicated the RT effect of Experiment 1 and showed an interaction between numbers and grasping actions that involve a fixed number of fingers. These findings exclude the possibility that the observed response latency effects were driven by an association between numbers and the fingers of the hand, and they provide additional support for the idea of numerical priming of size-related motor features.

In contrast to Experiment 1, the size of the maximum grip apertures did not differ for small and large numbers. A possible reason for this might be that the grasping responses in Experiment 3 had to be performed in a rather unnatural manner. Since participants were required to hold a stick with the three remaining fingers while grasping the object with the thumb and index finger, the responses were certainly more difficult to perform and might, thus, have been more disturbed than those in Experiment 1. Evidence for this is provided by the observation that the within-subject confidence interval for the grip aperture data was larger for Experiment 3 than for Experiment 1.[4] It is therefore likely that the increased movement complexity was responsible for the absence of grip aperture effects when objects had to be grasped with two fingers only.

4.5 General Discussion

The present finding of an interaction between representations of numerical information and representations of action-coded magnitude information for grasping provides evidence for a close link between numerical cognition and motor control. We asked participants to indicate the parity status of visually presented

[4]The within-subject confidence intervals (cf. Loftus & Masson, 1994) for the mean maximum grip apertures in presence of small and large numbers were ± 0.56 in Experiment 1 and ± 0.91 in Experiment 3.

Arabic digits by means of different reach-to-grasp movements (Experiments 1 and 1) and observed that precision grip actions were initiated faster in response to relatively small numbers, whereas power grip actions were initiated faster in response to large numbers. This finding indicates a magnitude priming of grasping actions by Arabic numerals. Besides this, we observed that numerical magnitude also had an impact on grip aperture kinematics. With both effects, we provide behavioral support for the idea that number processing and action planning share common cognitive codes within a generalized system for magnitude representation (Walsh, 2003).

Interestingly, the present study indicates that intention to grasp the object was crucial for the interference between number processing and action planning. Numerical magnitudes did not affect actions if they involved no grasping component and consisted merely of a reaching movement (i.e., pointing response) toward the smaller or larger (respectively, upper or lower) part of the object (Experiment 2). These findings clearly excludes the possibility of a compatibility effect between numbers and the reaching component of actions—an effect that could have been caused by an association of number size with the size of to-be-grasped object part or with the end position of the reaching movement along the vertical dimension (a vertical SNARC effect; Ito & Hatta, 2004; Schwarz & Keus, 2004). In addition, we excluded the possibility that interactions between grasping actions and number magnitude were driven by the different number of fingers involved in the two different grasping responses, because the priming effects of the Arabic numerals were also present when the grasping actions were performed with two fingers only (Experiment 3).

Arabic numerals not only affected the time to plan and initiate the grasping action but also influenced the way in which the action was performed. That is, when participants grasped the object without any restrictions concerning the fingers to be used, maximum grip apertures were enlarged in the presence of large numbers. Taking these results together, we conclude that the processing of numerical magnitude information somehow biased the processing of size-related motor features in the preparation of grasping responses. It is possible that this effect originated from processes in the dorsal pathway, where magnitude information needed to select an appropriated grip aperture is computed and represented (see Castiello, 2005).

The present magnitude priming effect in object grasping substantially extends previous findings of numerical stimulus-response compatibility effects caused by an association between numbers and spatial locations. The most prominent example of this relationship is the SNARC effect, reflecting the tendency to respond quickly with a left-side response to small and a right-side response to large numbers (Dehaene et al., 1993; for review, see Hubbard et al., 2005). So far, SNARC effects have been shown for several types of lateralized motor responses (Fischer, 2003; Schwarz & Keus, 2004; Schwarz & Müller, 2006). It is important, however, to note that in the present study, the grasping actions did not differ with respect to a lateralized left-right response feature. Instead, participants always moved with the same hand toward the same object at the same location. Consequently, the observed differences in the latencies of reaching responses cannot be explained by an association between numbers and spatial response features. Rather, our data reveal an interaction between numerical magnitude information and size-related features of the motor response (i.e., the grip aperture). Thus, the demonstrated magnitude priming of grasping actions shows also that numerical stimulus-response compatibility effects are not restricted to an association between numerical values and spatial locations along the mental number line (e.g., Dehaene et al., 1993).

The experiments reported here represent a direct behavioral test of the idea of a generalized magnitude system for number processing and action planning. Importantly, the present findings go beyond the number-finger-movement interaction previously shown by Andres et al. (2004). Although these authors also speculated that the compatibility effects observed between numbers and the extension/flexion of the index finger might be the result of a common representation involved in number processing and hand aperture control, the reported evidence for this was quite indirect in that the task did not require any grasping action. For example, it cannot be excluded that the effects in the study of Andres et al. were the results of an association between numbers and space along the sagittal axis, because each response comprised an index finger movement either toward or away from the body. The findings could be therefore also explained in terms of the more classical idea of the mental number line. Moreover, the assumed connection with grasping behavior appears to be problematic, not only because the actions did not involve objects but also because an opening or closing of two fingers differs in several crucial motor features from natural grasping movements. As is known from several studies of motor control, reach-to-grasp movements always consist of both an opening and a closing of the hand rather than a single change of the grip aperture (for review, see Castiello, 2005). Since hand preshaping is strongly linked to the transport phase of the hand, we argue that magnitude effects in grasping actions cannot be investigated appropriately without considering the whole reaching movement. It is thus important to notice that, in contrast to previous work, the present findings were not driven by finger movements per se and reflect an effect on reach onset times and grasping kinematics during reaching out for the target object. Since the observed numerical magnitude priming is an effect of the intended end postures of the grasping actions, our results indicate that the size of the required grip aperture at the end of reaching is the crucial motor feature responsible for the observed cognitive interference. This interpretation is in line with recent theories in the field of motor control, assuming that the motor planning is guided mainly by the desired end postures of a goal-directed movement (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Taking our results together, the major advance made by studying number effects on natural grasping actions is that our findings provide clear-cut evidence for the presence of within-magnitude priming between numbers and size-related motor features, and they demonstrate furthermore that these effects emerge during action planning well before the object is actually grasped.

Since, broadly speaking, Arabic digits represent an instance of symbolic semantic information, our findings may also contribute to research investigating the relationship between semantic processing and motor actions. Similar to the current number effect on the grasping kinematics, an impact of word meanings on the grip aperture has been demonstrated in several studies (Gentilucci et al., 2000; Glover & Dixon, 2002; Glover et al., 2004). For example, semantic action effects have been found for words representing categorical magnitude relations (e.g., *small*, *large*) as well as for words denoting objects that are associated with a specific physical size (e.g., *grape*, *apple*) and, therefore, also with a specific type of grip (Tucker & Ellis, 2001). The present study extends these findings and provides the first empirical evidence for a comparable grip aperture effect of Arabic numerals. This shows that semantic effects on motor actions are not restricted to words representing physical or relative magnitudes but can be also elicited by stimuli representing knowledge about abstract and absolute magnitudes. Glover and Dixon (2002) performed a very detailed analysis of grip aperture kinematics and found that semantic effects of word reading are only present very early on in the reach. As the hand approaches the target object, this effect gradually declines. These authors concluded that semantic information interferes with motor planning but not with processes of movement control, which become effective only after an action has been initiated. Following this reasoning, it is likely that the present kinematic effects of numbers also occurred during motor preparation. We assume, therefore, that the grip aperture effects of numerals originated from the same cognitive interference during the stage of action planning as the magnitude priming effect found in the reaching latencies.

Several authors have suggested recently that semantic processing and action planning should be understood as two mutually dependent processes (e.g., Gallese & Lakoff, 2005; Glenberg & Kaschak, 2002). This idea implies not only that semantic processing affects action planning but also that action planning may affect semantic processing. Evidence for this has been provided recently by the observation that the planning and execution of an action can facilitate semantic judgments on the meaning of action-related words or sentences (Lindemann et al., 2006; Zwaan & Taylor, 2006). Whether such a reversed effect of action planning on higher cognitive processes also exists for the processing of numbers is an intriguing, open question for future investigations.

In sum, not much is known about the role of magnitude information in the coupling of motor control and other cognitive processes. The present study indicates the existence of a functional connection between numerical cognition and action planning. As the magnitude priming of grasping actions by Arabic digits shows, the coding of numbers interferes with the coding of size-related response features. This finding suggests that number processing and motor preparation share common cognitive codes (Hommel et al., 2001), and it supports in particular the idea of a generalized magnitude system (Walsh, 2003) in which representations of numbers and actions are linked by a common metric for size and quantity information.

Chapter 5

Intention and Number Processing

Coding Strategies Influence Spatial-Numerical Associations

Abstract. The tendency to respond faster with the left hand to relatively small numbers and faster with the right hand to relatively large numbers (SNARC effect) has been interpreted as an automatic association of spatial and numerical information. We investigated in two experiments the impact of task-irrelevant memory representations on this effect. Participants memorized three Arabic digits describing a left-to-right ascending number sequence (e.g., *3-4-5*), a descending sequence (e.g., *5-4-3*) or a disordered sequence (e.g., *5-3-4*) and indicated afterwards the parity status of a centrally presented digit (i.e., *1, 2, 8,* or *9*) with a left/right keypress response. As indicated by the reaction times, the SNARC effect in the parity task was mediated by the coding requirements of the memory tasks. That is, a SNARC effect was only present after memorizing ascending or disordered number sequences but disappeared after processing descending sequences. Interestingly, the effects of the second task were only present if all sequences within one experimental block had the same type of order. Taken together, our findings are inconsistent with the idea that spatial-numerical associations are the result of an automatic and obligatory cognitive process but do suggest that coding strategies might be responsible for the cognitive link between numbers and space.

This chapter is based on: Lindemann, O., Abolafia, J. M., Pratt, J., & Bekkering, H. (2008). Coding Strategies in Number Space: Memory Requirements Influence Spatial-Numerical Associations. *Quarterly Journal of Experimental Psychology, 64*(4), 515-524.

5.1 Introduction

Research in the field of mathematical cognition has accumulated evidence indicating that cognitive representations of numerical magnitudes are closely linked with representations of space. A striking demonstration of this connection is the so called effect of the spatial numerical association of response codes (SNARC effect), which reflects the tendency of participants to respond faster with the left hand toward relatively small numbers and to respond faster with the right hand toward relatively large numbers (Dehaene, Bossini, & Giraux,1993). This interaction between number size and spatial response features has been consistently interpreted as evidence that numerical magnitude information are spatially coded and associated with a mental continuum ("mental number line") on which numbers are consecutively arranged in an ascending order from the left side to the right (for recent reviews see, e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005; Fias & Fischer, 2005).

Several authors have proposed that the spatial representation of numbers along the mental number line can be described as an automatic and obligatory process. In this context, automatic coding of numerical magnitude is understood as a process that occurs without the intentional setting of the goal of the behaviour and does not require any conscious monitoring (see, e.g., Ganor-Stern, Tzelgov, & Ellenbogen, 2007). The idea of an automatic coding of numerical magnitude is supported by the findings showing that number magnitude effects on lateralized motor responses emerge even when the processing of a presented numeral is not required and irrelevant for solving the task (Fias, Lauwereyns & Lammertyn, 2001; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006). Fias et al. (2001), for instance, reported a SNARC effect caused by numerals presented as background stimuli while participants were required to discriminate the orientation of lines and interpreted that both the activation of number meaning and the association of magnitude with space are obligatory cognitive processes. Further support for the idea that merely looking at numbers evokes an activation of spatial cognitive codes is coming from a study on visual-spatial attention reported by Fischer, Castel, Dodd, and Pratt (2003). The authors presented Arabic digits in the centre of the screen while participants preformed a simple detection task and found a shift in covert attention to the left or right side according to the relative size of the number. Although the cueing of visuospatial attention by numerals has often been assessed as important evidence for an automatic activation of the mental number line (Hubbard et al., 2005; Fias & Fischer, 2005), it is important to notice that attentional effects of numbers emerge far slower than effects of other symbolic cues with directional meaning (e.g., the words "left" and "right"; Hommel, Pratt, Colzato, & Godijn, 2001).

There is also a growing body of evidence suggesting that SNARC effects are influenced by top-down factors and that the associations between numbers and space are rather flexible. Since the first report of SNARC effects by Dehaene et al. (1993), it is known that the same number can be linked with either the left or the right side of space, depending on whether it is the smallest or the largest in the used range of numbers. Moreover, it has been shown that the same set of numerals evoke reversed SNARC effects if numbers are intentionally mapped with locations using a different spatial frame of reference (Bächthold, Baumüller, & Brugger, 1998; Vuilleumier, Ortigue, & Brugger, 2004; Ristic, Wright, Kingstone, 2006; Galfano, Rusconi, Umilta, 2006). For example, Bächthold et al. (1998) asked participants to make speeded responses toward numbers ranging from 1 to 11 and instructed to conceive them either as distances on a ruler or as hours on an analogue clock face. Participants in the ruler condition showed a regular SNARC effect. Interestingly, in the clock face condition, where smaller numbers had to be associated with the right side of space (e.g., 3 o'clock) and large numbers with the left side (e.g., 9 o'clock), the SNARC effect reversed. This strong impact of the task instruction on the effects of number reading seems to suggest that the spatial coding of numerical magnitude can be dynamically adapted according to current task demands. Further support for the notion that SNARC effects are flexible and not restricted to a left-to-right oriented continuum can also be derived from the observation of large interindividual variability in the preferred default mapping of numbers and space. For example, we know from studies with English, Arabic, and Japanese participants that the spatial associations with numbers are strongly mediated by culturally acquired reading or scanning habits (Dehaene et al., 1993; Zebian, 2005; Ito & Hatta, 2004) as well as by learned finger-counting strategies (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006). Taken together, there is accumulating evidence that spatial-numerical associations vary across different situations and across different groups of subjects. Thus, the SNARC effect may depend on the spatial frame of reference which is intentionally used or required by the task.

In the same vein, Fischer (2006) recently proposed that the spatial representation of numbers might be the result of an individual's strategic decision in the light of current task demands and not the consequence of an automatic activation of the mental number line. Although there is evidence showing that the selection of a spatial-numerical reference frame for magnitude representation depends on task demands as well as on cultural factors, the literature does not provide consistent evidence whether the activation of spatial codes in number cognition is an automatic obligatory process or, conversely, whether it is the result of a volitionally controlled cognitive strategy to deal with magnitude information.

Importantly, a crucial criterion for describing a cognitive process as being automatic is the absence of any dual task interference (see e.g., Palmeri, 2002). Consequently, if the association between numbers and space can be described as an automatic process, the presence of a SNARC effect should not be affected by requirements of a second unrelated task and should not interfere with spatial-numerical cognitive codes activated at the same time. To our knowledge, there is no definitive empirical evidence showing that the SNARC effect is either sensitive, or insensitive, to interference from an unrelated number task. Given this dearth in the literature, the goal of the present study was to test whether the spatial representations of numbers in one task are modulated by the coding requirements of a second simultaneously performed memory task. If number processing results automatically in an activation of the mental number line, the presence of the SNARC effect should not be influenced by the demands of the second task. If the mental number line represents, however, the current cognitive coding strategy of a person, the SNARC effect should be affected by the sequential order of an activated memory representation and by an activation of spatial mnemonic strategies for the second task.

5.2 Experiment 1

Participants were required to judge the parity status of Arabic numerals (parity task) after they had memorized a short sequence of three digits for later recall (memory task). The digits were arranged so that they formed a left-to-right ascending number sequence (e.g., *3-4-5*), a descending sequence (e.g., *5-4-3*) or a disordered sequence (e.g., *5-3-4*). The type of digit sequence was varied between three experimental blocks. Assuming that the mapping of numbers onto space is the result of a cognitive coding strategy (Fischer, 2006), the SNARC effect in the parity task should be affected by the ordering of the digits in the memory task. Specifically, we expect the SNARC effect to be diminished or even reversed in the experimental block of descending number sequences.

5.2.1 Method

Participants

Twenty-two students of the Radboud University Nijmegen (2 males; average age: 21.2) participated in the experiment in return for course credits.

Apparatus and Stimuli

Participants faced three horizontally aligned square outlines, which served as placeholder boxes for the presentation of the number stimuli. From viewing distance of about 70 cm, each of these frames measured 3.8° of visual angle. All numbers were printed in black sans serif fonts on light gray background and subtended a horizontal visual angle of about 1.3°. Reaction times were measured

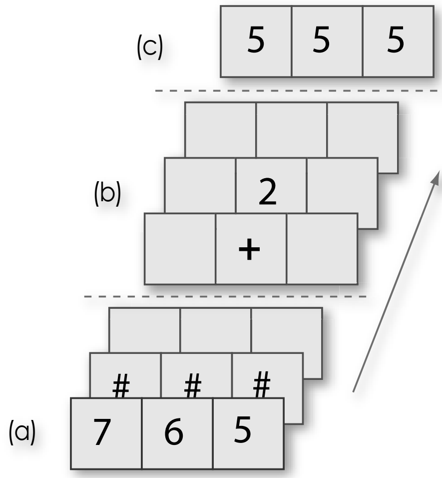


Figure 5.1: Illustration of the sequence of events in Experiment 1 and 2. (a) Participants memorized the locations of three digits before (b) judging the parity status of the centrally presented digit. (c) Each trial ended with a recall of the location of one of the three digits. See text for detailed descriptions.

with using a custom-built external response box with three horizontally aligned buttons.

The to-be-memorized number sequences were composed of three consecutive Arabic digits between 3 and 7. They could be subdivided in three categories: sequences with a left-to-right *ascending order* (e.g., *3-4-5*), sequences with a left-to-right *descending order* (e.g.: *5-4-3*), and sequences with no monotone order (*no order*; e.g., *5-3-4* or *4-5-3*). Only number sequences with no order that did not share any digit location with the corresponding ascending sequence were selected (i.e., sequences like, e.g., *3-5-4* or *4-3-5* were excluded). As target stimuli for the parity task, we used a different set of Arabic digits, namely, the numbers *1*, *2*, *8*, and *9*. Thus, half of the target digits in the parity task were smaller than the digits of the memory task and the other half of the targets were larger.

Procedure

Figure 5.1 illustrates the sequence of events in one trial. All trials started with the presentation of a number sequence, where each digit was displayed in the centre of another placeholder box. Participants were required to memorize all digits and their relative locations (left, central, and right location) for later recall. After a presentation time of 2,500 ms, each digit was replaced by a sharp symbol ('#') that remained visible for 50 ms. 500 ms later, a fixation cross appeared in the central placeholder box and was replaced after 1000 ms by a single digit. Participants' task was to indicate as soon as possible the parity status (odd or even) of this number by means of a left or right hand keypress response (i.e., pressing the left or right button of the response box). The assignment of response keys to odd and even digits was balanced across participants. The digit disappeared after responding or if no response was given after 1000 ms (missing response). Afterwards, one digit of the previously presented number sequence was randomly chosen and displayed in each of the three placeholder boxes. Participants were required to recall the former location of this digit in the sequence and indicate their answer by pressing the corresponding button of the response box (i.e., left, central, or right button). There was no time limit for the location recall. The inter-trial-interval was 2000 ms. In the case of an incorrect response in the parity or memory task, a 4400 Hz beep sound (lasting 200 ms) was presented as acoustic error feedback.

Design

The digit sequence types (ascending order, descending order, and no order) were systematically varied between three experimental blocks. Thus, for all sequences within one block the digits were arranged in the same order. Each block comprised 72 trials presented in random order. They were composed of all possible combinations of the four target numbers and the digit sequences of this particular experimental block. The order of blocks was permutated across participants. Before the actual experiment started, participants performed 38 randomly chosen training trials.

Data analysis

Trials with incorrect parity judgments or incorrect position recalls were identified and removed from the reaction times (RT) analyses. We calculated the mean RT and error rate in the parity task for each participant and each possible combination of the factors Number Magnitude (small: *1* and *2*; large: *8* and *9*), Response Side (left, right), and Sequence Type (ascending order, descending order, no order) and analyzed the data using repeated measures analysis of variance (ANOVA). A one-factorial ANOVA was performed on the error rates in position recall task to test for effects of the sequence type. In all statistical tests reported in this chapter, a Type I error rate of $\alpha = .05$ was used.

The SNARC effect in the present paradigm was represented by an interaction between the factors Number Magnitude and Response Side. In order to obtain in this type of ANOVA design a standardized estimate of the size of the observed SNARC effect, we calculated the effect size parameter η^2 of this interaction and its 95% confidences interval CI (see Smithson, 2001). Since the parameter η^2 provides an estimation of the proportion of variance accounted by the effect, it represents a generalization of the correlation coefficient r^2. The SNARC effect size $\hat{\eta}^2_{\text{SNARC}}$ allows therefore a direct comparison with studies employing regression

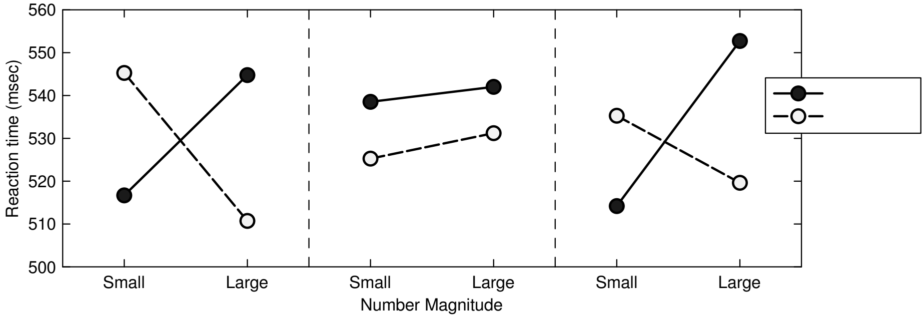

560
550
540
530
520
510
500
Reaction time (msec)
Small
Large
Small
Large
Small
Large
Number Magnitude

Table 5.1: Percentages of Errors in Experiment 1 and 2. Error Rates in Parity Judgment Task are Presented as a Function of the Factors Sequence Type, Response Side, and Number Magnitude. Errors Rates in the Position Recall Task are Presented as a Function for the Factor Sequence Type.

	Experiment 1			Experiment 2		
	Asc	Des	No	Asc	Des	No
Parity Judgment Task						
Left Hand - Small Number	1.28	2.90	1.26	1.83	1.80	1.29
Left Hand - Large Number	1.81	2.55	2.04	7.07	6.86	6.00
Right Hand - Small Number	3.57	1.80	2.27	6.47	5.56	6.80
Right Hand - Large Number	0.52	2.78	1.81	1.91	3.10	0.56
Position Recall Task	1.41	1.18	1.14	3.64	2.46	3.59

Note. Asc = Ascending Order; Des = Desecending Order; No = No Order.

5.2.3 Discussion

A SNARC effect was present if participants memorized an ascending number sequence but vanished completely in the block where the order of descending number sequences had to be recalled. Since a SNARC effect was also found for sequences of no monotonic order, we can exclude that the dissociation of the effect was merely the result of a higher task difficulty in the descending block or a general cognitive effect of the increased memory load. Moreover, the lack of a SNARC effect did not reflect any speed-accuracy trade-off because the analysis of error rates in the parity judgment and position recall task did not reveal any effect of the sequence type. Thus, the results of Experiment 1 clearly show that the SNARC effect is modulated by the cognitive coding of short descending number sequences. More specifically, the spatial representations of numbers in the parity task were affected by the specific spatial coding requirements and the resulting memory traces of the second task.

Since the manipulation of the sequence type was varied only between the three experimental blocks, the internal ordering of the digits was known before the trial started. It is therefore likely that the knowledge about the ordering of the upcoming sequence has been used to simplify the coding and recall of the number locations. That is, participants may have used in the block of descending sequences the concept of right-to-left orientated number line as strategy to code the digit location. This mnemonic strategy of a reversed number line, however, is in conflict with the spatial-numerical coding in the parity task and may therefore explain the vanishing of the SNARC effect. Alternatively, it might be also possible that the mere coding of three digits in a descending order automatically activates a spatially reversed mental number line and interferes therefore with the subsequent spatial coding of numbers. In order to distinguish between these two accounts-automatic activation of opposite number lines versus selected memory strategy-we performed a second experiment.

5.3 Experiment 2

Experiment 1 has demonstrated that the SNARC effect vanishes if the actual memory task required a coding of numbers arranged in descending order. Experiment 2 tests whether the same interference can be observed if the type of ordering is randomized on trial-by-trial basis. If the sequence type is not predictable, participants cannot use their prior knowledge about the sequence ordering to code the digit locations. Consequently, we should expect the SNARC effect to be unaffected by the sequence type in the memory task, if a coding strategy of oriented number lines was responsible for the inhibition of spatial-numerical associations. If, however, the mere representation of three numbers in a descending order results automatically in an activation of a reversed number line, we expect the SNARC effect to be modulated by the sequence coding as it was the case in Experiment 1.

5.3.1 Method

Participants

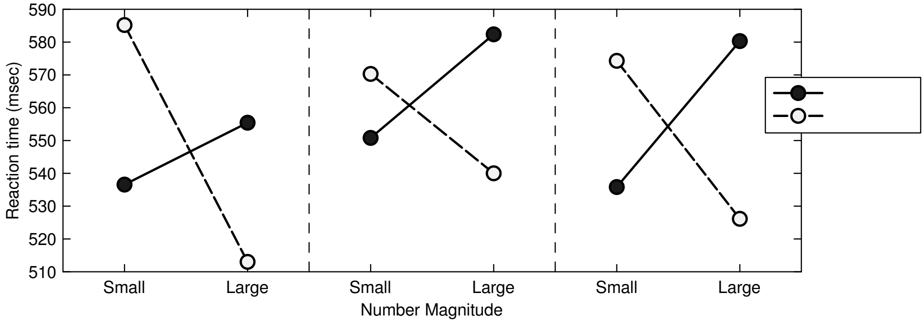
Twenty-two students of the Radboud University Nijmegen (4 males; average age: 22.2; participated in Experiment 2 in return for course credits. None of them took part in the previous experiment.

Apparatus, stimuli, procedure, design and data analysis

The experimental setup, stimuli, procedure and data analysis were identical to Experiment 1. The only modification was related to the order of trial presentation. Again, participants ran through three experimental blocks of 72 trials. However, instead of varying the factor Sequence Type between blocks, all trials were this time fully randomized. Thus, each experimental block comprised trials with all three types of digit ordering.

5.3.2 Results

As found before, there were no effects of the Sequence Type in the error rates of the parity judgment task and position recall task, $F(2, 42) < 1$ and $F(2, 42) = 1.52$, respectively (see Table 5.1). The ANOVA of the judgment errors revealed an interaction between Response Side and Number Magnitude, $F(1, 21) = 15.15$, $p < .001$, $\hat{\eta}^2 = .42$, reflecting a SNARC effect in the accuracy data. That is,


590
580
570
560
550
540
530
520
510
Reaction time (msec)
Small
Large
Small
Large
Small
Large
Number Magnitude

5.3.3 Discussion

Experiment 2 revealed that if digit ordering varied randomly, SNARC effect was not affected by the coding of number locations between trials and was now also present when participants memorized digits in a descending order. It can be therefore concluded that the mere coding of a digit sequence in the memory task was not sufficient to affect the spatial representation of numbers in the parity task. This argues against the explanation that the findings in Experiment 1 were the result of an automatic activation of two oppositely oriented mental number lines. Rather, Experiment 2 suggests that participants were unable to adopt a strong spatial coding strategy for sequences. Apparently, participants represent the sequences under these circumstances as three independent numbers without their inner structure and did not activate the concept of a mental number line. Thus, the results of Experiment 2 support the account that it was the cognitive strategy in the memory task of Experiment 1 that influenced the spatial representation of numbers in the parity task.

5.4 General Discussion

The present study demonstrates that the cognitive association of numbers and space is influenced by current task demands. We observed that the SNARC effect in a parity task is mediated by the specific sequential order involved in a simultaneously performed unrelated numerical task. This finding is inconsistent with the assumption of an automatic obligatory spatial representation of numbers along the mental number line. Since a SNARC effect was found under dual task conditions when the memorized number sequences had no internal monotonic order (Experiment 1), as well as when the number ordering was unpredictable (Experiment 2), the observed interference with the descending sequences in the first experiment cannot be due to an increased task difficulty or a higher cognitive load in general. Moreover, this mediation of the SNARC effect was not due to any sequence-specific speed-accuracy trade-off. We argue consequently that the specific requirement to maintain a short-term memory representation of numbers in a descending order was responsible for the lack of spatial-numerical associations in the parity judgment task.

Interestingly, the SNARC effect was only sensitive to the sequential order of the memory representations if all number sequences within one experimental block were identically ordered (Experiment 1), but not if the sequence type was fully randomized (Experiment 2). This dissociation in the SNARC effect can be explained by the use of different coding strategies when sequences types were blocked or completely randomized. That is, if numbers are repetitively arranged in a descending order, participants seem to use the information about the right-to-left digit ordering to simplify the processing of the number locations. This activated spatial-numerical frame of reference, however, is in conflict with the representation of magnitude along a left-to-right oriented mental number line and seems to result in an absence of spatial-numerical associations. In other words, we interpret that the use of spatial strategies in the memory task modulated the spatial coding of numbers for parity judgments. The outcome of the present study is therefore consistent with the notion that the SNARC effect is driven by top-down processes and provides direct empirical support for the idea of a strategic origin of the mental number line (Fischer, 2006).

In contrast to our interpretation that the SNARC effect depends on the concurrent task requirements, several authors have argued that spatial numerical associations are driven by an automatic activation of the mental number line. This idea received so far support from studies showing that numerical magnitude information activates spatial codes even under conditions in which number processing is irrelevant for the task performance (Fias et al., 2001; Gevers et al., 2006). However, the notion of an automatic SNARC effect implies not only that spatial codes are evoked by task irrelevant magnitude information. It is also important to notice that the assumption of automaticity entails by definition the presence of an obligatory cognitive process, which is immune against the influence of any other task concurrently executed (Palmeri, 2002). With the present paradigm, we now provide a direct behavioural test of this prediction and demonstrate for the first time that SNARC effects are strongly affected under certain dual task conditions. This outcome clearly argues against the idea that spatial-numerical associations are the result of an automatic and obligatory cognitive process.

An interesting aspect of the current data is that the SNARC effect disappeared, but did not reverse, when descending number sequences were memorized. A reason for this might be that the two tasks were functionally unrelated and independent from each other. Apparently, participants do not employ a pre-existing spatial structure that has been activated for one task to process numbers for another task. Instead, they seem to refrain from spatial number processing if it is under dual-task conditions in conflict with concurrently activated and to-be-maintained memory representations. Thus, together with the finding of a SNARC effect for disordered sequences, which demonstrate the participants' preference for a left-to-right mapping of numbers with space, our data indicate that this highly overlearned spatial coding strategy can be ignored in certain situations. The lack of a reversed SNARC effect further suggests that the coding of numbers along a mental continuum oriented differently than the default mental number line is a more effortful process that will not be performed if it is not required or beneficial for solving the task (see Bächthold et al., 1998).

Our report that the spatial coding of numbers is affected by the memory requirements of a second unrelated task substantially extends previous research demonstrating that the SNARC effect is sensitive to contextual task-related information (Dehaene at al., 1993) and affected if participants are explicitly instructed to use a different frame of reference for the spatial mapping of numbers (Bächthold et al., 1998; Vuilleumier et al., 2004; Ristic et al., 2006; Galfano, et al., 2006). In line with these studies, we demonstrate that left-to-right orientation of the mental number line is not obligatory and can be easily adapted or inhibited if the current task requires conceiving numbers differently. Moreover, our findings demonstrate that the SNARC effect is modulated by the sequential order of task-irrelevant memory representations and by the activation of spatial-numerical reference frames in another simultaneously performed task.

Taken together, the present study provides support for the idea that the spatial coding of numbers is the result of a cognitive coding strategy of how to deal with numerical magnitude information.

Chapter 6

Epilogue

Ago Ergo Cogito

Ago ergo cogito: 'I act, therefore I think' (Marsh, 2006)

The purpose of the current thesis was to shed new light on the functional connections between processes involved in the preparation and execution of motoric actions and different types of cognitive representations. The major outcomes of the four different studies consists of the priming of visual motion perception by motor actions (Chapter 2), the interaction of action planning and word processing (Chapter 3), the priming of grasping actions by numbers (Chapter 4), and the effect of coding intentions on spatial number representations (Chapter 5). In the following, I will describe the observed effects in the light of the different experimental paradigms developed for the present thesis. Afterwards, I will briefly discuss the outcome with reference to the principles of embodied coding as they are described in the introduction.

6.1 Summary of Findings

6.1.1 Motor-Visual Priming of Motion Perception

The study reported in Chapter 2 established a delayed grasping paradigm to investigate action-induced effects in natural grasping actions. The three behavioral experiments revealed a facilitated detection of visual motions consistent with a concurrently prepared object manipulation and thus provided evidence for the presence of motor-visual priming effects in motion perception. Interestingly, it could be demonstrated that the intention to manipulate an object had affected visual processing already before the actor's hand had reached out for the target object. The finding indicated furthermore that the coupling between perceptual and motor representations in grasping goes beyond visuomotor associations between object properties and afforded actions.

In the paradigm employed, an action cue instructed participants to grasp an X-shaped object and to rotate it in a clock- or counterclockwise direction. Importantly, however, participants had not to execute the motor response at this point of time and had to delay their response until the onset of a visual go signal. Experiment 1 (Section 2.2) indicated that if the object had to be grasped but not manipulated, stimuli that afforded the same type of grip as the prepared action involved (grip-consistent stimuli) were detected faster than grip-inconsistent stimuli. If the object had to be rotated, also stimuli consistent with the intended end-state of the manipulative action were facilitated in visual processing. In Experiment 2 (Section 2.3), the appearances of the go signals induced an apparent rotational motion in either a clock- or counterclockwise direction. Interestingly, under these conditions, stimulus detections were faster when the induced visual motions were consistent with the intended manual object rotation. This interaction between action and motion detection can be interpreted as evidence for the notion that the processing of action-consistent motions is facilitated as a result of motor preparation. Alternatively, however, it might be possible that the observed effects in the delayed grasping paradigm were the result of a stimulus-response priming at the level of response initiation. We conducted therefore a third experiment, in which participants indicated the detections of visual motions via foot responses. Since the same priming effect was observed in Experiment 3 (Section 2.4), it could be excluded that the reaction time differences reflected a stimulus-induced facilitation of the execution of motion-consistent actions. Thus, the outcome of this study provides straightforward evidence for a new action-induced effect, namely, the motor-visual priming of motion perception.

6.1.2 Action Word-Processing Interaction

Chapter 3 demonstrated that action-induced effects are not restricted to perceptual processes and showed that they also emerge during semantic processing involved in word reading. The four reported experiments provided evidence for an interaction between action planning and word processing. In particular, it could be shown that the preparation of a tool use action facilitates semantic judgments about the meaning of words related to the goal location of the prepared action. This result suggests that semantic knowledge about functional actions becomes selectively activated in the process of motor preparation.

Again, a delayed grasping paradigm was used. Participants in this study, however, grasped and used one of two meaningful objects (e.g., to drink from a cup or use a magnifying glass). Additionally, a control condition was introduced in which participants merely lifted one of two fingers (i.e., index or middle finger) in association with the object's position. Response initiations were triggered by word stimuli in a go/no-go lexical decision task. That is, participants prepared the precued action and executed it as soon as possible, if the presented stimulus represented a valid Dutch word (go trial). In the case of a pseudo word, however, it was instructed to withhold from responding (no-go trial). Word stimuli in Experiment 1 (Section 3.2) were consistent or inconsistent to the action goals of the object use (i.e., *mouth* or *eye*). The analysis of response latencies indicated consistency effects between action preparation and word processing. That is, when participants prepared to use one of the two objects (e.g., the cup) lexical decisions were facilitated for words describing the goal location (e.g., *mouth*) of the intended action. However, in the finger lifting condition, reaction times were unaffected. In Experiment 2 (Section 3.3), in which words were used that described action features primarily relevant of the finger lifting movements (i.e., *left* or *right*), the pattern of effects reversed and the judgments were now affected by the preparation of finger movements but not by tool use actions. Interestingly, two further experiments revealed that the observed actions word-processing interaction crucially depends on the depth of semantic processing required for solving the go/no-go task. When subjects made semantic decisions about the word category (Experiment 3, Section 3.4) consistency effects were present as in the two experiments before. However, when introducing a letter identification task (Experiment 4, Section 3.5)—a task that does not require any semantic processing of the words—action word-processing interactions disappeared completely.

6.1.3 Numerical Magnitude Priming of Actions

Another example for the cognitive interference between grasping actions and semantic processing is provided in Chapter 4, which investigated the functional connection between action planning and mathematical cognition. The described study demonstrates that the processing of numerals affects the coding of size-related motor features (i.e., grip aperture) during the planning of grasping actions. The finding of numerical magnitude priming effects in object grasping supports the notion that the representation of motor actions and the representation of numerical information share common cognitive codes for magnitude-related information.

In three experiments, participants performed object-directed movements (i.e., grasping or pointing) in response to visually presented small or large Arabic numerals. To be precise, the participants' task was to judge the parity status of the numbers and to indicate their decision by performing either a precision or power grip action (Experiment 1, Section 4.2). The analysis of the grasping movements revealed that precision grip actions were initiated faster in response to relatively small numbers (e.g., *1* & *2*), whereas power grips were faster to large numbers (e.g., *8* & *9*). Additionally, the kinematic data showed that maximum grip apertures (i.e., maximum distance between thumb and index finger while reaching out for the target object) were significantly enlarged when the response was made in presence of a relatively large number. Both effects, the numerical magnitude priming effect in the response latencies and the number effect in the grasping kinematics, indicate that the processing of abstract magnitude information has an impact on the planning and execution of prehension actions. Two control experiments were performed to exclude for possible confounds related to the relative vertical end position of the reaching movements and the amount of fingers involved in the two different grip types. Experiment 2 (Section 4.3) demonstrated that number effects in the response latencies disappear when participants perform reaching movements without the intention to grasp the object (i.e., pointing to the top or bottom part of the object). However, as shown in Experiment 3 (Section 4.4), numerical magnitude priming effects were also present when controlling for the number of fingers used for the grasping action.

6.1.4 Effects of Coding Strategies in Number Representations

Chapter 5 further investigated the representation of numerical magnitude information but shifted the focus of attention from effects of motor intentions to the effects of coding intentions. The study provided evidence for the notion that the cognitive link between numbers and space—that is, the representation of magnitude information along a "mental number line"—is the result of a controlled coding strategy and not driven by an automatic stimulus-response association.

Two experiments were conducted showing that the interaction between numerical size and spatial response features (i.e., the SNARC effect) is mediated by concurrent task requirements. Participants memorized three Arabic digits describing a left-to-right ascending, descending, or disordered number sequence and indicated afterwards the parity status of a centrally presented digit by means of left/right keypress responses. As the reaction times revealed, the SNARC effect was only present after memorizing ascending or disordered number sequences but disappeared after processing descending sequences. In other words, the SNARC effect was found to be mediated by the specific sequential order involved in a simultaneously performed unrelated memory task. This observation is inconsistent with the notion that the spatial coding of numbers is an automatic and obligatory cognitive process. Interestingly, the SNARC effect was only sensitive to the sequential order in memory if all number sequences within one experimental block were identically ordered (Experiment 1, Section 5.2), but not if the sequence type was fully randomized and thus number ordering unpredictable (Experiment 2, Section 5.3). This difference suggests that the participants' use of spatial mnemonic strategies to simplify the coding of number sequences have driven the inhibition of the spatial-numerical associations in the parity judgment task.

6.2 Conclusions

The four behavioral studies reported in this thesis examined the involvement of motor representations in cognitive information processing ranging from "low-level" processes such as visual perception up to "high-level" processes such as the coding of abstract semantic information while word and number reading. The findings provide, in line with recent psychological and neuroscientific research, new support for the view that cognition and action are two closely coupled processes. Importantly, however, the present work goes above and beyond previously reported action effects in cognitive psychology and extends the literature at least in four aspects:

1. The reported experiments are based on grasping paradigms, which approach the topic of motor interference in the context of natural goal-directed actions. So far, research in this field has focused mostly on rather simple and one-dimensional motor responses like, for instance, button press responses or mere reach-to-grasp movements without object use. The major advantage of the presented object manipulation paradigms is that they allow a direct investigation of action goals and the actual intended distal effects in the environment.

2. The grasping experiments illustrated that motor behavior has an impact on subsequent cognitive processing. A very clear and reliable example for the existence of action-induced effects represents hereby the motor-visual priming of motion perception—an effect that can be understood as a form of perceptual resonance resulting from motor intentions.

3. The experiments highlight the concept of embodied cognition and the involvement of motor representations in perceptual and semantic processing. In particular, the separation of action planning from execution by delayed responses has shown that actions effects arise already during goal selection and processes of motor preparation. Evidence for this is coming from the finding that action word-processing interference effects occurred at the level of action goals and were caused by merely prepared and not yet executed motor responses. The presented results stress therefore the importance of action goals in motor control and embodied cognition. In this way, they provide strong new evidence for the ideomotor principle, which holds that actions are represented in terms of their intended consequences, and for the common coding principle, which emphasizes in this context the role of distal action effects.

4. The thesis presents straightforward empirical evidence for an action-oriented approach to mathematical cognition—a functional domain that has been until now largely neglected by researcher in the field of embodied cognition. The finding of numerical magnitude priming of grasping actions is in line with the notion that representations of magnitude information for both numerals and actions are base on a shared generalized coding system. The interaction between number processing and object grasping represents additionally an interesting new cognitive effect that provides direct behavioral support for the principle of motor resonance. The performed experiments might thus be a promising starting point for future research on embodied representations in mathematical cognition.

So far, there is no clear-cut empirical evidence in the literature for action-inducted interference effects in high-level cognition. Interestingly, however, the experiments reported here suggest that action-inducted effects seem to exist in semantic processing. First support for this notion is provided by the finding of action word-processing interactions under delayed grasping conditions. Since the study on mathematical cognition aimed to investigate predominantly the effects of numbers on the planning and execution of actions, we cannot say at this point whether similar action-inducted interference effects exist in the processing of symbolic magnitude information. Future studies on action effects in semantic processing of words and numbers should therefore focus more strongly on the directionality of observed interference effects. The involvement of a second motor effector, as demonstrated in the study on visual motion perception (Chapter 2), seems to offer in this connection a promising method to test the directionality of action effects in high-level cognition.

Taken together, the present thesis demonstrates that functional connections between motor actions and cognitive processes are not restricted to certain response complexities or motor effectors and not to specific types of information or representational domains. All reported experimental findings thus support the hypothesis initially formulated in the introduction that the involvement of motor representations reflects a universal coding principle of the brain to deal with different kinds of cognitive demands. Abstract cognition and motor action can be consequently understood as two mutually depended processes, which presuppose each other. One might therefore reverse the intuitively plausible notion that "*motor behavior requires cognition*" and end the thesis with the statement that "*cognition requires motor behavior*".

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Summery in Dutch

Nederlandse Samenvatting

Dit proefschrift probeert de relatie tussen de processen betrokken bij het voorbereiden van motorische acties en cognitieve informatieverwerking te doorgronden. De meeste klassieke cognitief psychologische theorieën nemen impliciet aan, dat actie puur als het gevolg van cognitieve informatieverwerking ontstaat of zelfs dat actie een triviaal aanhangsel is aan de lange keten van cognitieve processen tussen de stimulus en de reactie. Een strikte scheiding tussen motorische actie aan de ene kant en perceptie en cognitie aan de andere zou echter niet een juist beeld geven van de werkelijke aard van de doelgerichte informatieverwerking en het intentionele gedrag van de mens. Dit proefschrift richt zich daarom voornamelijk op de interacties tussen bewegen en denken met als theoretisch doel empirisch bewijs te vinden voor de veronderstelling dat cognitie direct gekoppeld is aan onze ervaringen in onze omgeving, vaak aangeduid met "embodied cognition". Uit de vier onderzoekslijnen behorende bij dit proefschrift blijkt dat motorische representaties betrokken zijn bij verschillende cognitieve domeinen, van laag (denk bijvoorbeeld aan visuele perceptie) tot hoog cognitief niveau (denk bijvoorbeeld aan het coderen van abstracte semantische informatie, zoals het lezen van woorden en getallen).

De koppeling tussen perceptie en actie in het algemeen en de door actie veroorzaakte effecten in het bijzonder zijn nader onderzocht in **Hoofdstuk 2**. We hebben hier een uitgesteld-respons paradigma ("delayed-response paradigm") ontwikkeld, dat het mogelijk maakte om cognitieve effecten te bestuderen met natuurlijke grijpbewegingen. Omdat elke objectmanipulatie ervoor zorgt dat de waargenomen bewegingen worden ervaren als het gevolg van een actie, hadden wij verwacht dat het plannen van een objectmanipulatie direct de verwerking van visuele bewegingen zou beïnvloeden. De drie experimenten van dit hoofdstuk leveren hier inderdaad bewijs voor. We hebben kunnen laten zien dat het detecteren van visuele bewegingen sneller gaat als deze bewegingen overeenkomen met de op dat moment beoogde en voorbereide motorische actie (bijvoorbeeld het sneller detecteren van een rotatiebeweging met de klok mee als men ook in deze richting het object wil roteren). Deze interactie tussen het plannen van acties en het detecteren van bewegingen (oftewel "motor-visual priming of motion perception" in het Engels) is een duidelijk bewijs voor het bestaan van door actie veroorzaakte effecten in de waarneming in overeenstemming met de verwachting dat het verwerken van actie-consistente bewegingen vergemakkelijkt wordt door motorische voorbereiding.

Ook in **Hoofdstuk 3** hebben we een vergelijkbaar paradigma gebruikt om te demonstreren dat de effecten van motorische voorbereiding niet beperkt blijven tot het visuele domein. De hoofdvraag van deze experimentele lijn was of het plannen van doelgerichte acties interfereerde met talige cognitieve processen. Middels vier experimenten hebben we gekeken naar de invloed van de voorbereiding op het reiken naar, grijpen van en gebruiken van betekenisvolle voorwerpen (bijvoorbeeld een kopje of een loep) op het verwerken van semantische informatie in verschillende woordbenoemingstaken (bijvoorbeeld de opdracht tot een lexicale decisie of een semantische categorisatie taak). De analyse toegepast op de reactietijden liet een interactie zien tussen actieplanning en woordverwerking (oftewel "action word-processing interaction" in het Engels). We hebben laten zien dat de voorbereiding van een beweging met een gebruiksvoorwerp (bijvoorbeeld het grijpen naar een kopje om te drinken) semantische beslissingen bevordert over de betekenissen van woorden die gerelateerd zijn aan de doellocatie van de voorbereide actie (bijvoorbeeld het woord *mond*). Deze bevinding impliceert dat semantische kennis over functionele acties selectief wordt geactiveerd tijdens het proces van motorische voorbereiding en dat deze kennis interacteert met de processen in andere domeinen, in dit geval taal.

Een ander voorbeeld van cognitieve interferentie tussen het grijpen van een object en de daarmee gepaard gaande semantische verwerking is weergegeven in **Hoofdstuk 4**. Hier werd de functionele relatie tussen actieplanning en mathematische cognitie onder de loep genomen. Deze onderzoekslijn laat zien dat de verwerking van getallen invloed heeft op het coderen van grootte-gerelateerde motorische kenmerken (bijvoorbeeld de opening van de hand) tijdens het plannen van een grijpactie (oftewel "numerical magnitude priming of grasping actions" in het Engels). De deelnemers werden geïnstrueerd om de pariteit (even of oneven) van de gepresenteerde Arabische getallen aan te geven door het uitvoeren van een fijne of een grove grijpbeweging. De analyse van de reactietijden liet zien dat het reageren op lage getallen (bijvoorbeeld 1 en 2) sneller van start ging voor fijne grijpbewegingen terwijl het reageren op hogere getallen (bijvoorbeeld, 8 en 9) sneller werd gestart voor de grove grijpbewegingen. Daarnaast hebben we kunnen laten zien dat de maximale handopening (d.w.z., de maximale afstand tussen de duim en de wijsvinger tijdens het reiken naar het doelobject) vergroot was als de grijpbewegingen uitgevoerd werden als reactie op een relatief hoog getal. Samenvattend demonstreert deze onderzoekslijn dat getal- en actierepresentaties een gemeenschappelijke cognitieve metriek hebben voor grootte-gerelateerde informatie. Bovendien ondersteunen deze bevindingen het algemeen idee van 'motorische resonantie' ("motor resonance") uitgelokt door de verwerking van symbolische informatie.

In **Hoofdstuk 5** hebben we verder getallenrepresentaties onderzocht en vooral gekeken naar het fenomeen van de interactie tussen numerieke grootheid en gelateraliseerde motorische responses (oftewel "spatial numerical association of response codes" of afgekort het "SNARC effect" in het Engels). Doormiddel van twee getalverwerkingsexperimenten werd de idee getest dat de cognitieve koppeling tussen getallen en ruimtelijke kenmerken van responses voornamelijk ontstaat door de cognitieve strategie die het individu vormt om te kunnen omgaan met (of een representatie te kunnen maken van) abstracte numerieke informatie. De deelnemers werden gevraagd om een reeks van getallen te onthouden, die van links naar rechts toenam (bijv., 3-4-5), afnam (bijv. 5-4-3) of geen lineaire richting had (bijv., 5-3-4). Direct na de reeks kregen de deelnemer een getal te zien waarvan ze gevraagd werden de pariteitstatus aan te geven door een linker of een rechterknop in te drukken. De analyse van de reactietijden liet zien dat het SNARC effect van de pariteitstaak beïnvloed wordt door de coderingskenmerken van de geheugentaak. Specifiek gesproken hebben we gevonden dat het SNARC effect alleen aanwezig was nadat men een getallenreeks had onthouden die van links naar rechts toenam of geen richting had. Na het onthouden van een afnemende getallenreeks was het effect verdwenen. Deze onderzoekslijn levert dus bewijs op voor de idee dat de cognitieve relatie tussen getallen en ruimte, of de interne representatie van magnitude informatie langs een 'mentale getallijn', ontstaat als gevolg van een gecontroleerde codingsstrategie en niet door een automatische stimulus-respons koppeling.

Al met al leveren de hier beschreven experimentele bevindingen, die in overeenstemming zijn met ander recent gedrags- en neurowetenschappelijke onderzoek, nieuw bewijs op voor de veronderstelling dat de cognitie en actie twee nauw met elkaar verbonden processen zijn. Belangrijker nog, het hier gepresenteerde werk overstijgt de eerder gerapporteerde actie-effecten binnen de cognitieve psychologie en verbreedt de bestaande literatuur minstens op de volgende vier punten:

1. De experimenten in dit proefschrift benaderen het onderwerp van motorische-interferentie-effecten in de context van natuurlijke object manipulaties. Een dergelijk benadering maakt het mogelijk effecten van doelgerichte acties en hun causale gevolgen direct in de omgeving te bestuderen.

2. De grijpexperimenten illustreren dat het plannen van motorische acties gevolgen heeft voor andere daaropvolgende cognitieve processen.

3. De experimenten bevestigen het concept van embodied cognition en de betrokkenheid van motorische representaties in de perceptuele en semantische verwerking van de omgeving.

4. Dit proefschrift laat empirisch bewijs zien voor een actie-georienteerde benadering van mathematische cognitie; een functioneel domein dat tot op heden genegeerd werd door onderzoekers binnen het onderzoeksveld van embodied cognition.

Kort samengevat tonen de hoofdbevindingen van dit proefschrift aan dat het functionele verband tussen motorische acties en cognitieve processen voor meerdere typen informatie (bewegingswaarneming, talige en grootte waarneming) geldt en betrekking heeft op verschillende representationele domeinen (taal, perceptie en mathematiek). Met andere woorden, de bevindingen ondersteunen de idee dat de betrokkenheid van motorische representaties een universeel coderingsprincipe van de hersenen is, dat toegepast wordt op verschillende typen cognitieve taken. Op grond hiervan is het mijn overtuiging dat de abstracte cognitie en die processen die nodig zijn voor motorische bewegingen alleen begrepen kunnen worden als twee van elkaar afhankelijke en zelfs direct op elkaar berustende processen.

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