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# Specific Interference Effects Between Temporally Overlapping Action and Perception

# Specific Interference Effects Between Temporally Overlapping Action and Perception

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# Contents

# Chapter 1

# Introduction

> *The men of experiment are like the ant, they only collect and use: the reasoners resemble spiders, who make cobwebs out of their own substance. But the bee takes a middle course: it gathers its material from the flowers of the garden and the field, but transforms and digests it by a power of its own.*
> Francis Bacon, 1620: The New Organon , XCV

The quote of Bacon at the beginning is in my view about the substance of psychology which allows to combine theory and empiricism and by digesting it creates new knowledge. The following dissertation is my way of digesting and I hope the outcome resembles more that of a bee.

Progress in science is often achieved by dissecting a complex task in its components and by dealing with these components separately. Despite this has proved to be a successful strategy for research, the effort breaks down if the two components behave differently when combined. This dissertation investigates one example of such an interference between two components that traditionally have been treated separately, perception and action. By looking at the combined temporally overlapping functioning of action and perception a closer resemblance to everyday life is gained. Understanding better the interplay between action and perception will allow to improve working environments and thereby avoid errors. The relevance of this endeavor can be seen in the growing need of high precision working. For example, knowing the influence that actions will have on perception and thereby predicting the direction of errors in an endoscopic operation might distinguish between healing and harming a patient.

In the paradigm of this dissertation two tasks are performed at the same time which leads to a temporal overlap of a continuous movement[1] production and a continuous motion perception. The observed interference between action and perception is used as an indicator of underlying coding principles and used to evaluate two models.

In the following, I address the rather general question whether interactions should be expected at all and introduce the paradigm by discussing overlapping task situations. Then, I distinguish between specific and unspecific interference and discuss how the aim of this study differs from typical dual-task experiments. This is followed by a discussion of paradigms that measured specific interference, the topic of this dissertation. Discussing findings in these paradigms then leads to two models that motivated the experiments of this thesis. These experiments allow to evaluate the two models. Finally, I discuss the relevance of these results for models of specific interference between action and perception more generally.

## 1.1 Mutual Interactions Between Action and Perception

Intuitively many people believe that certain percepts lead to certain actions and that therefore perception influences action. Also many people might agree that acting and perceiving at the same time is more difficult than performed in isolation (for scientific evidence see e.g., De Jong, 1993). Less intuitive however seem to be influences between action and perception that are not required by the demands of the task. For example, when I want to grasp a cup, it seems trivially true that perceptual information of the cup informs my movement and therefore perception influences action. Further, reading the text on the cup might be much easier when the grasping hand does not perform a complicated trajectory across obstacles to it. This speaks for a better performance when the perception occurs in isolation. Surprising however at first seems to be that the cup can be detected faster when the hand is already preshaped to grasp it (see for related phenomena Hommel & Prinz, 1997). This influence on performance that depends on the relationship between features of both tasks (e.g., the features of a graspable object and a corresponding hand posture) will be discussed under the term of specific interference below.

Interactions between action and perception have been ignored to some extent in the scientific literature (e.g., Ward, 2002). One reason might be that these effects seem surprising as mentioned in the cup example. Additionally, the long adopted information-processing approach (see Massaro, 1990 for an overview) tried to disentangle cognitive processes into

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[1] In the following the terms "movement" and "action" are used in a similar way. While the former puts more stress on execution, the latter also stresses the planning and the goals of the movement (see Prinz, 1990). This distinction, however, will not be used in this thesis.

separate stages from stimulus to response (Sanders, 1983; Sternberg, 1969) and thus separated action from perception. A third reason for a neglect of interactions between action and perception might be the influential finding of two separate visual processing streams, one for action and one for perception (Goodale & Milner, 1992). Separate processing of information for action and for perception might have led to a more general view of separate systems, one dedicated to action and one to perception.

### 1.1.1 Two Separate Processing Streams for Action and Perception

The division of visual processing in streams for action and for perception goes back to findings of Ungerleider and Mishkin (1982) who divided visual processing in a dorsal or "where" stream (from primary visual cortex to superior parietal cortex) and a ventral or "what" stream (from primary visual cortex through inferior portions of occipital and temporal cortex). This division was refined by Goodale and Milner (1992) to a dorsal stream for manipulating objects that therefore is mainly concerned with location information (the action stream) and a ventral stream that allows to recognize objects and to verbally report them (the perception stream). This conjecture was grounded in double dissociations of patients who could either recognize or manipulate objects. For example, Milner et al. (1991) reported a patient (D.F.) who had acquired a damage to the ventral stream. Even though D.F. had no problems when placing a card inside a slot at varying orientations, her performance was lower or at chance when she should match the orientation of the slot by manipulating a second slot. As matching two slots in orientation is seen as a perceptual task and inserting a card into a slot as a motor task the dissociation fits well to the proposal of independent processing streams. The opposite pattern was found for a patient with a posterior parietal lesion (Jeannerod, Decety, & Michel, 1994) what ruled out that the single dissociation was caused by differences in task difficulty alone. The patient A.T. could reach correctly to targets but was unable to fulfill the motor demand of adjusting grip aperture to the objects sizes. On the other hand, when performing a perceptual task, e.g., match the distance between the thumb and index finger to the object size either with the objects visually presented or object size inferred from memory, A.T.'s impairment was much less severe. Based on these data, Jeannerod et al. (1994) distinguished between "pragmatic" and "semantic" representations, but the location of the lesion and its behavioral consequences were also consistent with the ventral/dorsal model above. Similar examples of a dissociation between motor behavior and explicit visual judgments is provided by blindsight patients. These patients though reporting to have no conscious perception of some stimuli perform above chance when acting on them (e.g., Stoerig & Cowey, 1997). This double dissociation was considered as evidence for two independent processing streams. Before I come back to why double dissociations between these streams do not rule out interactions between action and perception processing streams, I introduce another often-cited dissociation in visual illusion paradigms.

A further argument for separate streams of action and perception has been that in healthy humans perceptual but not manual measures seem to be influenced by visual illusions. For example, Aglioti, DeSouza, and Goodale (1995) used the Titchener circles illusion to show that perceptual but not motor responses are influenced by the illusion. In the Titchener illusion the perceived size of a circle depends on the size of the circles surrounding it. In these stimuli, small surrounding circles lead to a larger perceived central circle than large surrounding circles. In the perceptual task, participants had to judge whether two central circles, each surrounded by circles of different sizes appeared to be of the same size. This perceptual decision was delivered by picking up either the right or left circle. The picking movement was then analyzed as the motor task. The perceptual measure showed that the circles were perceived as different when they physically had the same sizes and perceived as of the same size when actually their diameter differed. Maximum grip aperture however corresponded to the physical sizes and was not affected by the illusion. This finding has been interpreted as evidence for different representations underlying the perceptual and the motor response. Nevertheless, these results have been questioned by others (e.g., Franz, Gegenfurtner, Bülthoff, & Fahle, 2000). In fact, when the perceptual and the motor tasks where made more comparable to each other, similar illusion effects in both tasks were observed. For example, Pavani, Boscagli, Benvenuti, Rabuffetti, and Farnè (1999) argued that during the grasping task the second stimulus could be ignored while during the perceptual task both stimuli had to be considered. By using only one stimulus at a time the Titchener illusion could be obtained in the motor and the perceptual task. What is more the illusion affected both the motor and the perceptual task more with large than with small surrounding circles. This correlation between the size of the illusion influence in the motor and the perceptual task argues for similar percepts underlying the motor and perceptual task.

Further, it has been suggested that when the perceptual and the motor measure dissociate, this is because the action relies on different information than the perceptual measure. For example, the action might rely on information about the grip position which is not influenced by the illusion while the perceptual measure might rely on size information that is influenced by the illusion (Brenner & Smeets, 1996). Brenner and Smeets (1996) asked participants to pick up disks. When the perceived weights were manipulated by a visual size illusion, grip aperture was not affected by the illusion. Still, the illusion influenced the time it took to pick up the disks probably as an result of a higher expected weight. Brenner and Smeets (1996) interpreted the finding of an illusion effect on one variable of the motor task but not on the other as evidence that the illusion affects action but whether the influence can be measured depends on the variable tackled by the measurement method.

Taken together these experiments suggest that when proper experimental conditions are met influences of visual illusions can also be obtained in motor tasks. Therefore, these visual illusions provide no conclusive evidence for a separation between action and perception streams of visual processing.

In addition, a dissociation or even a double dissociation in the lesion studies above do not mean per se that both streams cannot interact. For example, it could well be that manipulating and recognizing an object both rely on the same internal representation and the damage is somewhere "upstream" in the processing. For instance, the information flow from the representation to the motor commands could be disturbed in patients with manipulation problems and the flow to comparison processes could be disturbed in patients with problems in the perceptual tasks. This would still allow for interactions prior to or via the common object representation. What is more, even in the case of separate object representations interactions could arise at an earlier stage. Finding dissociations between two tasks thus is also neutral to the question of interactions. What is more, evidence for an interactive view between the dorsal and the ventral stream based on anatomical data of macaque monkeys was reported by Merigan and Maunsell (1993). Also experimental support for interactions between the two streams is growing (Dassonville & Bala, 2004; Helbig, Graf, & Kiefer, 2006; Schenk & Milner, 2006).

In sum, while earlier studies seemed to suggest that action and perception follow two separate streams that do not interact, these studies can be challenged on empirical grounds. What is more, newer studies provide evidence for interactions between the visual processing streams for action and for perception. In the following I discuss further arguments for close connections between action and perception in general. I will start with neuropsychological data and then turn to behavioral studies.

### 1.1.2 Empirical Evidence for Interactions Between Action and Perception

Particular strong neuropsychological evidence for a close interaction between action and perception was found in the monkey lateral intraparietal region (LIP). This was shown by Shadlen and Newsome (1996) in a motion direction detection task. In the task, the monkeys observed dynamic random dot motions with differing amounts of overlaid coherent motions. After motion offset, the monkeys signaled the perceived direction by moving their eyes to one of two targets on the screen. During performance of the task, the discharge rate of LIP neurons was recorded. Three features of these discharge rates are remarkable because they suggest that the neurons do not reflect simple sensory processing. First, the discharge rate correlated highly with the target choice, which argues for a close connection of the neurons to the final motor action. Second the discharge rate remained even after the stimulus disappeared which rules out a purely stimulus driven activity. Third neuronal activity still predicted the following eye-movements when only a random dot motion was presented. This predictive value of discharge rates for movements even in sensory non-discriminative situations adds further support for a close link between LIP neurons and actions. On the other hand some patterns of discharge also excluded a strict motor-related behavior of LIP neurons. First, the predictive power of LIP neurons increased with an increase in motion coherence. If LIP neurons were simply related to motor activity, firing rates should only correlate with the performed movement but not with the amount of sensory information for one direction. Second, predictivity was reduced on error trials. This suggests that LIP neurons coded the motor decision but also included sensory information that was in opposite to the motor decision. Taking these results together, Shadlen and Newsome (1996) described LIP neurons as neither strictly motor nor sensory but reflecting a decision process. This combination of motor and sensory information in one area provides a direct link between action and perception not mediated by some "central-controlling process" and therefore is compatible with a highly interactive view between action and perception.

An interference between action and perception is made more plausible if the same areas in the brain are found to be in charge for action and for perception. Some plausible locations have indeed been found. The clearest evidence for a common brain location for action and perception has been gathered with monkeys. By placing electrodes to single neurons in area F5 of the monkey premotor cortex, some neurons have been identified that discharge when an object-directed action is either observed or executed by the monkey (Rizzolatti & Craighero, 2004). Consequentially, these neurons have been called "mirror neurons". Some mirror neurons called "strictly congruent" respond only if the executed and observed actions correspond in goals and means. "Broadly congruent" neurons on the other hand generalize across different goals and means. The important point is that mirror neurons discharge when the action is performed and therefore show motor properties but also discharge when an action is observed which indicates perceptual properties.

Similarly, evidences for motor cortex activation during action observation have also been found in humans using brain activity related measures like electro-encephalography (EEG; Rizzolatti & Craighero, 2004), magnet-encephalography (MEG; Rizzolatti & Craighero, 2004) and functional magnetic resonance imaging (fMRI; Buccino et al., 2001). For instance, in the study of Buccino et al. (2001) participants watched actions performed with different effectors. A change in brain activity relative to static effector images was found for areas that would be active during performing the task, i.e., perception of different effectors was associated in a somatotopic pattern with premotor areas. Rizzolatti, Fogassi, and Gallese (2002) reported further evidence for a mirror neuron system in humans. For example, Area 44 is more strongly activated in fMRI when a movement is observed that corresponds to the concurrently performed movement (Iacoboni et al., 1999). Interestingly, Area 44 is seen as homologue to monkey Area F5. This facilitation of activity in the brain by perceived corresponding movements is contrasted by findings of inhibition at peripheral motor neurons that would be active during execution of the observed action (Baldissera, Cavallari, Craighero, & Fadiga, 2001). This was interpreted as evidence that peripheral inhibition allows the cortex to "re-act" an observed movement without running the risk of producing movements.

Another technique used to detect motor areas in humans that are also activated by perception is transcranial magnetic stimulation (TMS). TMS allows to stimulate certain brain regions non-invasively by applying a strong magnetic field to the brain location. Applying TMS to motor areas leads to motor-evoked potentials (MEPs) in the corresponding limbs. By looking at the change in MEPs in response to different visual information the influence of visual information on the areas to which TMS was applied can be observed. It turned out that the location at which the change in MEPs occurred corresponded to the muscles involved in the observed action (Rizzolatti & Craighero, 2004). This is consistent with the notion of a mirror system also in humans that activates motor areas that are in charge of the observed movement.

These neuropsychological findings of close connections between action and perception have been paralleled by behavioral experiments. For example, Mechsner, Kerzel, Knoblich, and Prinz (2001) showed that complex interlimb coordination can be achieved when the associated perceptual information follows an easy rule. In the experiment, participants had to produce circles with both hands at the same time. The non-visible hand movements were translated by a gear system to visible rotating flags. When the transformation led to symmetry between the oscillations of the two flags, even manual relationships that were nearly impossible to perform without the visual aid (e.g., frequency ratio of 4:3) could be performed. This importance of symmetry in the visual feedback was explained with the importance of perceptual goals for motor performance, thus constituting another hint to potential interactions between action and perception. Using different paradigms, other researchers have reported decrements in perception performance that were caused by action (e.g., Jacobs & Shiffrar, 2005; Müsseler, Steininger, & Wühr, 2001; Müsseler, Wühr, Danielmeier, & Zysset, 2005). Jacobs and Shiffrar (2005) reported that when participants had to judge the relative speed of two point-light walkers, their performance was worse during walking compared to standing conditions. Müsseler, Wühr, et al. (2005) showed that increasing the amount of temporal overlap between encoding of a stimulus and a concurrent motor response of a second task decreased encoding performance.

In sum, neuropsychological and behavioral experiments convincingly showed the close connections between action and perception processing in humans.

### 1.1.3 Bridging the Gap Between Action and Perception

In the last section, I discussed evidence for interactions between action and perception. When one has acknowledged the existence of interaction effects then the question arises what type of representations and processes might underlie these effects. What answers different approaches to cognition would suggest will be discussed in the following. These approaches differ mainly in where they propose that the interface between action and perception is located and how perceptual and motor events are coded at that level. One of these approaches, the motor approach suggests that motor properties play a major role for interferences. The perceptual approach on the other hand suggests that perceptual properties interfere. Still other approaches suggest interference at a level were action and perception properties are retained (Common Coding and attentional approach).

The idea that the content of tasks changes performance presupposes that the interference occurs at a level where this content is still coded. Therefore, depending on which representations are assumed to underly the interference effects, different kinds of observations would be expected. For example, a perceptual approach would predict that similarity, i.e., correlation in the sensory data should play a role for the interference effects. Therefore, the approaches differ in how easily they can account for different kinds of interference effects. The following division between the approaches is somewhat artificial and certainly not selective. Still it shows that different approaches lend themselves more easily to explanations of different types of interferences.

#### 1.1.3.1 The Motor Approach

The underlying idea of motor theories of perception is that perception occurs via the activation of motor representations. Therefore, motor theories of perception retain similarity structures of motor properties in the representations that underly the interferences between action and perception because the interface occurs at a motor level. The motor approach of perception can be traced back to Gibson (1979). Gibson attributed a crucial role for perception to the actions that objects allow.

A typical example of a motor theory is given by Liberman and Mattingly (1985) who argued that speech is perceived by coding it with invariant motor commands that would produce the sound. Motor theories have also been developed in detail for language understanding. Glenberg and Kaschak (2002) for instance argued that affordances, i.e., possible ways to interact with an object, are extracted from a percept. These affordances are then activated when a sentence is heard and allow to simulate the sentence action by guide of the sentence grammar. This view is supported by a study in which participants were required to judge whether sentences are sensible by performing a hand movement (Glenberg & Kaschak, 2002). When the implied direction of a sentence did not match the response direction (e.g., the sentence "close the drawer" and a response requiring movements toward the body) participants needed more time to read the sentence. Similarly, Arbib (2005) argued that language is based on the ability to recognize actions.

Support for motor theories of perception comes from neuropsychological and behavioral experiments. For example, mirror neurons as reported above, support a notion of motor involvement in perception. On the behavioral side Tucker and Ellis (1998) argued that affordances of objects automatically activate associated actions during viewing. This argument was based on the finding that participant's manual response to a visually presented object was faster when performed with the hand that corresponded to the affordances of the object. In the experiments, participants judged whether an object was presented inverted or not. Irrelevant to the instruction, affordances of the object could either match to the responding hand (e.g., the handle of a saucepan oriented to the right is responded by the right hand) or mismatch. Participants were faster to respond to objects with the hand that matched the instruction-irrelevant affordance. This effect was however not found when index or middle fingers were used for responding which was taken as further evidence that the affordance and not an abstract spatial code underly the reaction time effect. This automatic activation of actions supports the notion of motor properties underlying perception.

Seen from a functional point, using covert motor acts to represent percepts might lessen the problem of symbol grounding, preserve information for later interaction, and allow for faster motor responding to new situations. Symbol grounding refers to the problem how amodal representations in the brain could be mapped to events outside the body (e.g., Harnad, 1990). By coding objects in terms of possible interactions with them the gap between representation and outer world becomes smaller. A further advantage of motor coding is that the similarity between object and coding is preserved what allows to detect new ways of interacting with an object even after its disappearance. Coding an object only with abstract symbols however, would not preserve properties that are relevant for interacting (Glenberg & Kaschak, 2002). For example, encountering a match box and coding it in a way that retains its spatial structure might later allow to use it also for stabilizing a table by putting it under a foot. Having coded it simply as a match box might lead to a loss of the relevant information. Representing perceptual and motor information within the same codes might allow for fast adjustments of motor execution in response to new perceptual inputs because perceptual information is automatically made commensurate. The importance of fast adjustments is stressed by growing evidence that motor and visual areas mutually influence each other in a continuous way (Thelen, Schöner, Scheier, & Smith, 2001).

The involvement of the motor system in action observation has been described as a means to anticipate, to imitate, and to understand other's actions (Rizzolatti, Fogassi, & Gallese, 2001). The latter point is supported by findings that "broadly congruent" mirror neurons (see above), as a plausible basis of motor involvement in perception, respond to action goals independent of the means to achieve them. The advantage of an involvement of the motor system could be that it constrains possible actions and therefore supports their identification. For example, having identified two points along a hand movement trajectory constraints plausible hand positions between or after these two observation points when constraints from the movement systems are applied. The motor system would for instance predict that when the hand travels along one direction it should not end up suddenly in a different region. Thus, motor involvement would put constraints on plausible actions and thereby reduce plausible action candidates (e.g., Shiffrar & Freyd, 1990). An additional advantage of coding observed movements by relying on motor properties could be that it makes it easier to find the matching motor program for imitation (Rizzolatti et al., 2001). Finally, the motor system might help to anticipate the next steps of an observed action (Prinz, 2006; Wilson & Knoblich, 2005). According to Prinz (2006) the motor system is well suited because planning of actions already involves anticipation. One way how these anticipatory mechanisms could be implemented are feedforward models of which the MOSAIC model is one example. This framework will play a role in later parts and is therefore discussed in more detail here.

A specific instance of motor theory is the MOSAIC (MOdular Selection And Identification for Control) model as described by Wolpert, Doya, and Kawato (2003). MOSAIC is composed of modular forward and inverse models (see Basso and Olivetti (2006) for an overview of forward models in cognitive psychology.) The forward model is realized by a structure called "predictor" and the inverse model by a structure called "controller". If a motor command is issued, an efference copy is used as input to the predictor that calculates the state of the motor system which will result from the command. The controller calculates motor commands that would produce a desired state. Each predictor is paired with a controller. These pairs are evaluated on how good they describe a given situation. To this end, the forward models predict in parallel what dynamics will occur next. If the prediction matches the observed data, the predictor captures the true dynamics with a high probability. The associated probabilities are called "responsibilities" and negatively related to the discrepancy between observed and predicted dynamics. Thus predictors can be considered hypothesis testers about the current state of the world. Because predictor-controller pairs differ in their underlying functions each pair covers a given context to a certain extent. For example, one pair might be well suited to describe the dynamics of bicycling to a beer garden, another pair to describe the dynamics of bicycling away from a beer garden. Based on fMRI data, internal models have been attributed to the cerebellum that uses connections to mirror neurons in the ventral premotor cortex for input and output functions (Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003).

Another feature of the MOSAIC model is that sensory data can be linked to action components (modules) of the observer. Central for this task is that the output of the controller can be fed in the predictor instead of producing an overt movement. In this way the motor system can be used to determine what movement is observed by comparing it to dynamics of different movements in the repertoire of the observer. In result observed action components are translated into a private movement lexicon. Because predictors and controllers use different sources of information but still interact, these inputs must be made commensurate by a common code. Wolpert et al. (2003) assumed that this common code reflects properties of the motor system, e.g., joint angles. Putting the interface to the motor side might be advantageous when most tasks rely more on information exchange in motor systems than on exchange in perceptual systems. Thus this account stresses the importance of action-control for the human system.

Motor frameworks in general suggest that properties of the motor system should underly interference effects between action and perception. Finding interactions between features that are hard to code in motor terms, e.g., color, would take credit from motor approaches. Indeed, interactions between the perception of color patches and the production of color words have been reported (Kunde & Wühr, 2004). One solution to this would be to propose the involvement of the perceptual system like perceptual theories do.

#### 1.1.3.2 The Perceptual Approach

Perceptual theories place the interface on another level. They posit that cognition occurs via representations that preserve sensory properties of encoding (Barsalou, 1999). According to Barsalou this view is supported by findings as for example that the speed with which people verify that two views of rotated objects belong to the same object increases with a typical sensory property, i.e., angular difference (Shepard & Metzler, 1971). One way how interactions could arise in this framework is that motor commands are fed via proprioceptive signals into a common sensory area. This would suggest that interactions between action and perception should mainly be based on sensory consequences of motor commands. On the other hand, variables that are hard to assess perceptually, e.g., force, should not interfere. Interactions between response force and stimulus intensity, however, have been shown (Romaiguère, Hasbroucq, Possamaï, & Seal, 1993).

The following Common Coding approach could remedy the struggle of pure perceptual or pure motor theories to explain the variety of features that interfere. The approach proposes a mutual link between perceptual anticipations of motor effects and corresponding motor codes. This mutual link allows for influences between perceptual and motor properties. For example, stimulus intensity might be connected to motor force and in this way stimulus intensity and response force might interfere. A similar argument would work also in pure perceptual or motor theories, if the perceptual and motor properties were bidirectionally connected.

#### 1.1.3.3 The Common Coding Approach

In the Common Coding framework (e.g., Prinz, 1990) actions and perceptions share a common coding system. This avoids the need to evoke a translational mechanism between sensory and motor events. In this the approach is close to the ideomotor theory of Greenwald (1970) or James (1890, 1950) but extents it. While Greenwald (1970) and James (1890, 1950) stressed the importance of anticipated sensory feedback, Prinz (1990) also put emphasis on the meaning or goals of actions. Therefore, in the often-quoted passage of (James, p. 526) "movement" could be replaced by "action" and then be made to:

> [...] every representation of an *action* awakens in some degree the actual *action* which is its object.

By demanding common codes for action and perception the theory can readily account for findings of interactions between action and perception that follow a similarity structure (see Sections 1.5 and 1.4), i.e., interactions that are more probable the more the features of the action matches the features of the perception.

The Theory of Event Coding (TEC) extended this representational framework by adding processing components to it (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). The two determining factors at this level are activation and binding. Binding has been suggested to play a role for sensory features (e.g., Kahneman, Treisman, & Gibbs, 1992) and action features (e.g., Stoet & Hommel, 1999) before, however the new approach of TEC was to demand bindings between sensory and action features as well. Thus, binding occurs across features that belong to the same evoking event independent of their source, e.g., from motor or perceptual processing or their origin, e.g., proximal or distal. When a feature is bound to an event code it is less available for other events. Activation of a feature on the other hand increases when information consistent with it is processed. Therefore the perception or production of events can facilitate single features by activating them and at the same time make them less available for other events by binding. TEC also added representational assumptions to Common Coding. Similar to Common Coding, no qualitative differences between action and perception representations are retained except for different connections to motor or sensory areas. The assumption of a commensurate format was however extended by demanding limited identical features. These limited resources lead to competition between concurrent events for features and thus prepare a place for interactions between action and perception.

Later theoretical developments distinguished bindings within action or perception, and across action and perception (Colzato, Erasmus, & Hommel, 2004; Colzato, Fagioli, Erasmus, & Hommel, 2005; Colzato, Warrens, & Hommel, 2006). This processing difference takes away some of the elegance of demanding indistinguishable codes for action and perception. Also whether the use of common codes for action and perception can be observed empirically in related interaction effects is still an open question. While influences from action on perception and from perception on action have been found in different experiments (Schubö, Aschersleben, & Prinz, 2001; Schubö, Prinz, & Aschersleben, 2004), these effects are seldom found in the same experiment. What is more, it seems that effects on action and on perception exclude each other to a certain extend (e.g., Grosjean, 2001; Müsseler & Hommel, 1997). Müsseler and Hommel (1997) for example, reported 5 different experiments in which an influence of action on perception was found. The only experiment in which also an influence of perception on action was detected led to a smaller influence on perception.

#### 1.1.3.4 The Attentional Approach

Attentional approaches use attention to link action to perception. For example, Allport (1987) proposed that perceptual events that are important for an action are enhanced. Similarly, Schneider and Deubel (2002) described attention as a connecting mechanism for selecting motor programs and visual representations that belong to an attended object. Another approach that stressed the mediating factor of attention is Premotor Theory of Attention (Rizzolatti & Craighero, 1998). According to this theory preparing a movement activates cortical pragmatic maps that correspond to the position towards which the movement is planned. This activation in turn leads to facilitation of stimuli and to higher motor readiness of movements connected with the corresponding region. This facilitation is seen as the mechanism of attention. Eye-movements received a special status in this framework because of their frequency in everyday life. Later extensions of the theory proposed an enhancing effect of prepared grasping movements not only for associated space locations but also for objects corresponding to the prepared grasp (Craighero, Fadiga, Rizzolatti, & Umiltà, 1999).

By demanding that attention results from higher activity in the same circuits that underly motoric and sensoric functioning, the Premotor Theory dismisses the concept of a supramodal attentional system. The key concept was mostly developed from neurophysiological data in monkeys and humans. Thus it is physiologically well founded (e.g., Rizzolatti & Craighero, 1998). Because attention links properties of action and perception, Premotor Theory seems also to suggest that interference arises at a level where motor and perception codes are retained.

As described above, these frameworks differ in what kind of interactions is expected from them. One way to elicit interferences is to overburden the human system. This can be done by dual-task paradigms to which I will turn next. In the following a task is understood as the mapping between a stimulus set and a response set, i.e., the way participants are asked to react to given stimuli.

## 1.2 Temporally Overlapping Tasks

In the research literature the term *dual-task* is used in a generic way to refer to situations in which two tasks are performed concurrently (e.g., Pashler, 1994). However, for theoretical reasons, it might be fruitful to distinguish between continuous dual-task and psychological refractory period (PRP) paradigms (Telford, 1931).

In continuous dual-task situations participants perform two, normally quite complex, tasks at the same time without an ordering of task sequence, even though sometimes different priority is given to the two tasks (e.g., Wickens & Gopher, 1977). One example of a continuous dual-task paradigm is that of Allport, Antonis, and Reynolds (1972), in which participants played piano from score and orally repeated auditory delivered narrative prose.

In PRP paradigms participants perform speeded reactions in response to two stimuli. As a result, both tasks temporally overlap. The extent of the temporal overlap, however, is determined experimentally by varying the onset-time of the two stimuli relative to each other. Additionally, the order of responses is requested by the experimenter. The term PRP stems from the observation that the sooner the second task follows the first task the larger the decrement in second task performance. In other words, resources used in one task seem to need some refractory time before becoming available again for another task. An example of a PRP task is found in the study of Jolicoeur (1999). The first task was to respond to a tone of varying height (stimulus 1) with a keypress (response 1). In the second task, letters (stimulus 2) were presented that should be typed (response 2). In addition the interval between stimulus 1 and 2, the stimulus onset asynchrony (SOA), was varied.

Continuous and PRP dual-task situations differ in their structure and how they can be interpreted. Continuous dual-tasks are highly demanding for scheduling processes and the participant has to decide when to process which task. In PRP paradigms on the other hand, participants are told in which order the tasks should be processed. Furthermore, varying the SOA between the two stimuli allows to manipulate the processing overlap between both tasks. In fact, this is used in the locus-of-slack method (McCann & Johnston, 1992) to determine the processing bottleneck. By manipulating, e.g., encoding difficulty in task 1 and monitoring its influence on performance of task 2 conclusions about whether the bottleneck lies before or after the stage that the manipulated variable affects are reached. If the bottleneck lies before the stage of processing that the manipulated variable affects, the increase in reaction time in task 1 does not transfer to task 2. If the bottleneck follows the stage that is addressed by the manipulation, the increase in reaction time in task 1 transfers to task 2. In contrast to continuous dual-task situations, the unit of analysis is typically a short trial and not the continuous processing of the two tasks for a longer time. Having clearly separated trials, in principle allows participants to prepare before the trial starts without a secondary task while in continuous dual-task situations preparation for the next stimulus is done online. Therefore, while preparatory processes are part of the interpreted data in continuous dual-task situations, their effect falls nearly out of the analysis of PRP paradigms. This is not to deny that preparatory processes also occur in PRP paradigms but at least part of them can occur before each trial starts and are therefore not analyzed. An advantage of PRP paradigms that will be used in this dissertation is that they better allow to control which processes overlap.

In the paradigm used in this dissertation, similar to everyday life, action and perception did not follow each other but occurred at the same time. In other words a dual-task situation was employed. Trials contained judgments about motions that were perceived during movement production. If movement production is seen as a response to an earlier stimulus and the judgment as a response to a stimulus motion the paradigm resembles a PRP paradigm. It differs however from it in that both responses were unspeeded. The present paradigm also includes features of continuous paradigms in that the response and the stimulus lasted for about 1 second. Therefore, the paradigm consists of a mixture of continuous and PRP paradigms. As the recent discussion showed, looking at dual-task situations is not new but the current paradigm differs in its aim of research in that it looked at specific interference, which will be addressed in the next section.

## 1.3 Specific and Unspecific Interference Research

While research has typically focused on limited unspecific resource demands caused by an additional task, the current focus is on specific interference effects (Müsseler, 1999). In the following, the term "interference" is used for a change in performance in one task that is caused by another task, irrespectively of whether this change is facilitatory or inhibitory.

Unspecific interference is typically "attributed to more general demands of action control" (Müsseler, 1999, p. 132) and associated with interactions between neural *processing* mechanisms (Wickens, 1984). The amount of unspecific interference is seen as a result of the similarity of tasks along dimensions like, for example, modalities or stages of processing; content variables on the other hand are normally not varied or of little interest (Wickens, 1980, 1984). In contrast, specific interference is caused by the *content* of processing and attributed to the amount of shared features between two tasks.

In other words, unspecific interference relates to the similarity in operations while specific interference is caused by the features of these operations. For example, when steering a car and talking on the phone, there are at least two main operations going on: One operation would be to encode the visual scene and map this to appropriate steering actions. The other operation would be to encode speech, evaluate it and finally produce a (hopefully) appropriate oral output to it. Unspecific interference would arise between concurrent operations of encoding information or mechanical operations for talking and steering. Specific interference on the other hand would arise between the features. For instance, steering to the right (feature 1) to avoid an obstacle while encoding verbal information to take the next exit to the left (feature 2).

Manipulating content or processing variables addresses different questions. Due to the supposed origin of unspecific interference, limitations and errors in dual-task situations are informative about processing similarities and resource allocations between tasks. A different question is tackled with specific interference paradigms, because here not the processes but the contents of the tasks are manipulated; as a result, the focus is on the overlap of content and hence the underlying coding structures. As will become clear below, in addition to understanding which content combinations lead to increased errors, the direction of the errors can be predicted. As a consequence of focusing on the influence of content, interferences are demonstrated between levels that are commonly seen as separate, relatively independent processing stages, like encoding and acting (Vidulich & Wickens, 1981; Wickens, 1984).

Therefore, notwithstanding that resource demands are high in dual-task situations and of great interest, a fuller picture can be gained by also investigating underlying coding mechanisms to better understand the conflicts and pitfalls of dual-task situations. This was the aim of the present dissertation. Studies that already addressed specific interference experimentally are discussed next.

## 1.4 Specific Influences of Perception on Action

The concept of specific interference is commonly found in stimulus-response (S-R) tasks, where participants respond to a stimulus with an instructed reaction (for overviews see Hommel & Prinz, 1997; Kornblum, Hasbroucq, & Osman, 1990; Proctor & Reeve, 1990). For instance, responding to a stimulus with a right hand keypress is faster and less error-prone when the stimulus is presented to the right side of a fixation mark compared to the same stimulus presented to the left side.

Kornblum and Lee (1995) described such situations in which an irrelevant (in terms of instruction) stimulus dimension overlaps with a response dimension and stimulus and response share a common value on this dimension as *S-R consistent*. In contrast to this definition in the following, the word "compatibility" is used for S-R consistent relationships, irrespective of whether the overlapping dimension is relevant or not.

Assuming that participants comply, stimulus information affects responses according to the task instruction. Given however, that responding and stimulus encoding occur close in time, similar to dual-task situations, processing of stimulus information might influence responses over and above task dependent S-R mappings. To detect this additional influence, instruction irrelevant features of the stimulus can be varied. For example, Simon (1968) asked participants to move a lever either to the right or to the left as instructed by a verbal command. Not surprisingly, the instruction was followed by the participants and the stimulus affected the response. More interestingly, the ear where the command was presented was varied. Despite this manipulation was instruction-irrelevant it influenced movement and reaction times. Both were shorter when the heard direction was compatible to the ear of instruction (e.g., command "right" to the right ear) compared to an incompatible combination. Manipulating instruction irrelevant features of the stimulus thus allowed to detect a specific influence on responding. In studies where instruction irrelevant features of the stimulus are manipulated that are either compatible or incompatible to response features, generally a benefit of overlapping S-R features is observed. This benefit is typically found in decreased reaction times and lower error rates for compatible mappings (e.g., Hommel, 1995). Lower reaction times for compatible situations have also been reported for simple response tasks (e.g., Brass, Bekkering, & Prinz, 2001). In simple response tasks participants react to a stimulus by a single response. Therefore, the response is specified before the stimulus occurs and only when the response should occur is uncertain. For example, Brass et al. (2001) asked participants to respond to the presentation of tapping or lifting movements as a go signal. For half of the experiment the response was tapping, while for the other half a lifting movement was required. Therefore, stimulus and response could be compatible or not. Faster responses were found in compatible conditions. In sum, similar to dual-task situations, specific interferences are also found in simple and choice S-R tasks. However, the sequential nature of single S-R tasks mainly allows to *detect* influences from stimulus properties on responses. This is however an argument about what a paradigm typically allows to measure. There is no principled reason why the influence should not be bidirectional.

Other experiments allowed to test which spatial attributes caused the compatibility effects. For example, in one condition of Nicoletti, Anzola, Luppino, Rizzolatti, and Umiltà's (1982) experiments, participants responded to left and right lights with the button that corresponded in location to the light. By having participants cross their hands in one condition, Nicoletti et al. (1982) could dissociate response side from anatomical hand side. As the results showed, spatial location of the keypress and not anatomical side determined the compatibility effect. Further, Hommel (1993) asked participants to press a right or left button in response to high or low tones that were produced randomly by a right or a left loudspeaker. Pressing the buttons resulted in a light opposite to the button press (e.g., a right press resulted in a light on the left side). By instructing participants, for example, either to "press the right-hand key" or to "produce the right-hand light" in response to the tone, Hommel could show that instructing individuals to produce an action effect could turn the compatibility effect between key and tone location into a compatibility effect between location of the instructed goal and the tone. This stresses that in the definition of compatibility not overlap in physical dimensions of stimulus and response is crucial but overlap in represented dimensions.

In the following section typical examples of specific influences between stimulus and responses are discussed first for single continuous movement and PRP tasks, and finally, similar to the paradigm used in this dissertation, in combination.

### 1.4.1 Specific Influence in Continuous S-R Tasks

Some theorists have argued that continuous S-R tasks should be understood as composed of many intermittent decisions (Pashler, 1994). These intermittent decisions could be conceptualized as frequent S-R subtasks. In this case, specific interference should also be expected. It could, however, be that the frequent S-R mappings lead to a better shielding of the responses from instruction-irrelevant stimulus information. Whether continuous performance diminishes specific interference effects is relevant to this dissertation because in the experiments specific interference from perceptual features on continuous movements was investigated.

When the influence of compatibility in continuous S-R tasks was investigated there was again a bias due to the unidirectional task definition to study the influence of perception on action. For example, Chua and Weeks (1997) have reported that people are better at synchronizing their movements with stimulus motions when the endpoints of the movements and motions are spatially compatible than when they are not. In their study, participants were asked to move a lever in coordination with a periodic visual stimulus. The stimulus moved back and forth along a horizontal straight line. Similarly, the lever was moved to the right and left. The experiment manipulated whether participants should respond in phase with the motion (compatible situation) or in antiphase (e.g., a motion to the left should be responded to by a lever movement to the right). Participants were better able to temporally align their movement oscillations with the oscillations on the screen when movement and motion where compatible than incompatible. Similar results that visuomotor tracking performance is more stable for in-phase than anti-phase movement-motion relationships were reported by Michaels and Stins (1997).

Ehrenstein, Cavonius, and Lewke (1996) additionally varied the amount of compatibility by varying the angle between a straight stimulus motion on a screen and its corresponding tracking movement on a digi-pad. Stimulus motions and tracking movements were varied between 0° and 315° degrees in steps of 45°. Tracking performance was best with 0° disparity (condition of high compatibility) and worsened with higher disparity. These findings were among the first to demonstrate that feature overlap between stimuli and responses affects performance in more dynamic tasks in which movements are generated during the perception of stimuli. Compatibility is also encountered in dual-task situations, which is the focus of the following section.

### 1.4.2 Specific Influence in PRP tasks

Keele (1967) and Greenwald (1972) were one of the first to systematically investigate compatibility, i.e., specific interference, within one task on performance of another task in a PRP paradigm. Greenwald (1972) showed that the unspecific decrement caused by a second task is reduced if the tasks involved ideomotor compatible S-R mappings. According to Greenwald (1972) ideomotor compatibility denotes "the extent to which a stimulus corresponds to sensory feedback from its required response" (Greenwald, 1972, p. 52). Therefore, if the sensory feedback of the response is seen as a response feature, ideomotor compatibility is a special case of high S-R compatibility. In Greenwalds' study stimuli were either arrows pointing to the right or to the left presented to the right or left from screen center (stimulus set 1) or the words "right" or "left" presented via headphones (stimulus set 2). Responses consisted of either moving a switch to the right or to the left (response set 1) or saying the words "right" or "left" (response set 2). Ideomotor compatibility was varied by manipulating the pairing of stimulus and response sets. In the high ideomotor compatible condition, participants responded to the verbal commands orally, or to the arrows with right/left movements of the switch. The other combinations of sets were considered of low ideomotor compatibility but still stimulus-response compatible. When decisions were required for stimuli from set 1 and 2 concurrently, reaction times in high ideomotor compatible conditions were very similar to when only one decision was required. An increase in reaction times compared to the single decision situations, however, was observed for low ideomotor compatibility combinations. This was interpreted as an indication that responses are centrally coded by their sensory feedback, which allowed to bypass the limitations from response selection processes.

The study led to an ongoing debate of whether ideomotor compatible mappings can fully eliminate dual-task decrements (e.g., Lien, McCann, Ruthruff, & Proctor, 2005 and its reply Greenwald, 2005), but at least also to an agreement that compatibility can affect task performance (e.g., Lien, Proctor, & Allen, 2002; Lien & Proctor, 2002). As a result, compatibility is now accepted as a means to manipulate task difficulty in PRP paradigms (e.g., McCann & Johnston, 1992).

Even though the investigation of Greenwald (1972) led to inferences about underlying coding mechanisms, and in this is close to the aim of this dissertation, it differs from the present aims in that the specific interference was manipulated within the two tasks but not across. On the other hand, results of single task experiments already showed that compatibility effects of a certain S-R mapping can be influenced by other S-R mappings of the experiment (Duncan, 1977). In a similar way, S-R mappings of concurrently performed tasks could as well influence each other. In Duncan's experiment, participants mapped 4 numbers to 4 spatial keys. As the reaction times showed, performance of a given S-R mapping depended on the other mappings. For example, the reaction time to a compatible mapping of the number 1 to the leftmost key increased when the numbers 2 and 3 where not mapped in a spatial congruent way. This finding of interactions between temporally separated mappings suggests that single mappings are not perfectly shielded against each other. Therefore, performance of one task might also be affected by another task, especially if the two tasks overlap in time. This suggests that specific interference in dual-tasks could also occur *across* tasks. I turn to compatibility effects across tasks next.

Hommel (1998) investigated the influence of compatibility across tasks in a PRP paradigm. In one experiment, colors were combined with letters in a single stimulus. Participants were presented with either the letters "H" or "S" displayed in red or green. Participants first had to respond to the color of the letter by a right or left keypress and then to the letter identity by either saying "green" or "red". In this way, the color attribute of the first task could be compatible with the response to the identity of the letter of the second task (e.g., a letter presented in green and reporting the word "green" in response to the letter identity). For these stimulus-response compatible trials a decrease in reaction time was observed. This showed that compatibility effects are not confined within tasks but can also occur across tasks. For newer research on these cross-task compatibility effects see, e.g., Müsseler, Koch, and Wühr (2005).

### 1.4.3 Combining PRP and Continuous Paradigms

Cross-task interference was also found when continuous movements were used in PRP paradigms. Schubö et al. (2001) investigated influences that arose between the perception of a continuous visual stimulus motion (S) and the production of a continuous manual response (R) when the concurrent S and R events belonged to two different tasks (see Figure 1.1). In a given trial, participants produced the S of the previous trial while encoding the current S for reproduction in the next trial. The Ss were sinusoidal trajectories produced by a moving dot with kinematics that resembled natural drawing movements. Three different sizes of amplitudes were manipulated within participants (small, medium and large). All S motions had durations of 2 seconds. In consequence, Ss with small amplitudes had a lower velocity than Ss with large amplitudes, with Ss with medium amplitudes laying in between. The interesting question was whether the size of the different amplitudes and velocities of the Ss would influence the amplitudes and velocities of the concurrent medium sized Rs. To asses this specific influence of amplitude size, amplitudes at the first and second extreme values of the Rs were compared across small, medium, and large amplitudes of Ss. Similarly, tangential velocity was compared across S velocities at the second and third inflection point. To counter sequential effects, each amplitude size combination of the concurrent S and R and the previous R occurred with equal frequency in each block. The results showed that the produced amplitudes and velocities veered away from the concurrently perceived Ss. For example, high compared to low amplitudes in S led to smaller R amplitudes; medium sized amplitudes in perception led also to medium amplitude sizes in production. Similarly, slow, medium, and fast S velocities led to faster, middle, and slower R velocities. This pattern was described as a contrast between perception and action.

In the following, I will use the term contrast effect (CE) to describe these kind of interferences when a produced/perceived event (e.g., R) is made less similar to a concurrently produced/perceived event (e.g., S). The opposite finding, when the two events become more similar when performed concurrently compared to independently will be called an assimilation effect (AE). As Section 1.5.3 will show, these CEs and AEs can be related to compatibility effects within the framework of Common Coding (Prinz, 1990).

With further experiments, Schubö et al. (2001) were able to rule out the concern that the effect was caused by online control hand movements. According to this interpretation

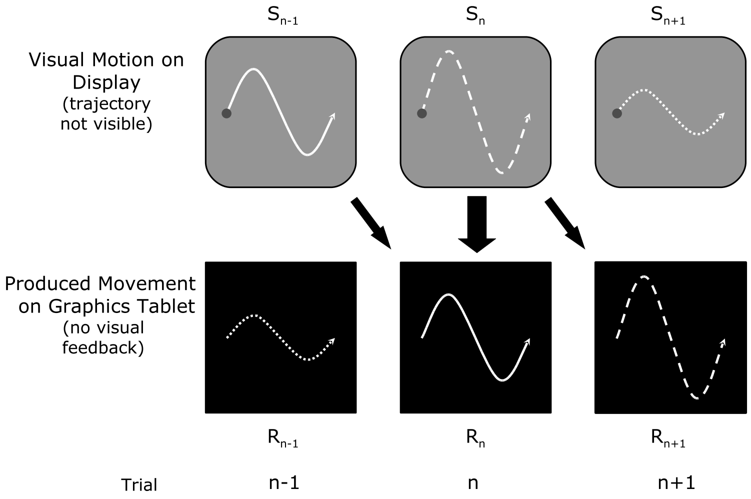

*Figure 1.1: In the paradigm of Schubö et al. (2001), participants in trial n reproduced the stimulus motion of trial n-1 while encoding the concurrent stimulus motion of trial n. The thick arrow shows the investigated influence, thin arrows show the S-R associations across trials, i.e. they denote the tasks.*

participants believed that the motions on the screen would reflect their hand movements and counteract the observed pattern. To rule out this interpretation two experiments were conducted. The first experiment tested whether the amount of visual information that could be interpreted as online feedback influenced the CE. This amount was manipulated by having the dot trajectory remain on the screen for the duration of a stimulus motion. This however did not influence the CE. The second experiment further discouraged an interpretation of the S as feedback of the R by manipulating R onset relative to S onset. To this end a tone was used as a go-signal for the Rs. A CE was found even in conditions where the Ss preceded the Rs by 500 ms and therefore could not be the online feedback of the Rs. Having established an effect of perception on action, the paradigm was also used to detect specific influences of action on perception. Therefore, I come back to this paradigm in Section 1.5. Other specific interference effects on continuous actions can be found in studies of e.g., Keller and Burnham (2005) or Kilner, Paulignan, and Blakemore (2003).

## 1.5 Specific Influence of Action on Perception

Everyday life lacks situations where an action on perception influence (API) is explicitly experienced. As a consequence APIs might seem a strange phenomenon. Therefore, in the following section a distinction between different levels of influences is made to help structure the phenomenon and place the dissertation experiments into a broader context. The considered distinction follows the classification of Viviani and Stucchi (1992) that APIs can be addressed at the *ecological level*, *the level of active exploration*, *the abstract level*, and *the level of the generation of expectations*.

### 1.5.1 Four Levels of APIs

APIs at the *ecological level* describe how perception occurs in natural situations and therefore acknowledge the influence that body displacements have on sensory input. For example, when looking out of a moving car, the sensory inputs change. Yet, an object under focus is perceived as unchanging. This stability, in spite of changing sensory information, is according to Gibson achieved by finding invariant relationships in the sensory data (Bruce, Green, & Georgeson, 1996), e.g., even though the retinal input from two cows changes during a parallel body displacement, the ratio at which their bodies intersect with the horizon stays constant. Because the human system normally compensates for this type of APIs and achieves a stable representation, there might be a tendency to overlook influences at the ecological level.

At the level of *active exploration* the importance of active motor exploration for perception is stressed. Put in a strong version it argues that perception of an object only occurs via active interaction with the object. The importance of action for perception has already been stressed by Gibson (1979). Gibson proposed that objects are understood by their offers to interact with them, i.e., their affordances. For example, waves might be perceived differently by someone who intends to use them for surfing, because they afford different behavior of the surfer than of someone who just enjoys the breaking of the waves at a beach. One intriguing argument for this view is that people who wear prism glasses can adapt better to this distorted sensory input when actively exploring the environment (Held, 1965). Furthermore, acquisition of space knowledge of even simulated environments improves with the possibility to actively explore them, e.g., by means of a joystick instead of passively observing the environments (Peruch, Vercher, & Gauthier, 1995). Even though the importance of active exploration is apparent in early acquisition and a key component of the sensorimotor period in infants as proposed by Piaget (Michel & Moore, 1995), its relevance to *adult* life and *abstract* concepts is less clear.

At the *abstract level* the influence of motor competence (e.g., movement constraints) on perception is considered. This means that the way motor actions are organized influences the organisation of perceptual information. For example, Shiffrar and Freyd (1990) showed that when sensory information about human movements is ambiguous and allows for two perceptual interpretations, the one that is consistent with the properties of the motor system is preferred. In their experiment, the start and endpoints of a movement were alternatively shown. This introduced the perception of apparent motion. However, the trajectory was not specified by the pictures. Nevertheless, at slower speeds of flipping between start and endpoints, participants reported seeing movements that were consistent with motor properties when a human arm was shown but not when clock hand positions or rectangles were used: For the human arm, the perceived apparent motion followed not simply the shortest path as was the case for non human objects but followed a path that was mechanically possible. A similar influence of implicit motor competence on perception was reported by Viviani (2002) based on findings of different experiments. In the experiments, participants either had their arm moved by a robot or watched a light point along an elliptic trajectory. Their task was to indicate at which aspect ratio the trajectories seemed to follow circles. The velocity profile of the movements were manipulated and corresponded in one condition to the typical human velocity profile of an ellipse with a vertical major axis and in another condition to that of a horizontal major axis. Participants were biased to perceive ellipses consistent with the velocity profile as if the velocity information was integrated with aspect information. For example, vertical ellipses were perceived as more circular when the movement followed the biological velocity profile of a horizontal ellipse compared to that of a vertical ellipse. This was true for the visual judgment as well as for the blindfolded kinesthetic condition. That two different sensory channels use information about biological velocity profiles in the same way was taken as an indicator that motor competence information influenced both channels. Similarly, Casile and Giese (2006) showed that motor competence for certain movements influences the perception of these movements. In their study, participants were trained on a certain arm movement pattern. Despite this training was done without visual feedback, participants were better at discriminating visual motions that involved the trained motor pattern after than before training. Further, training proficiency in the study of Casile and Giese correlated with later visual discrimination performance (see also Hecht, Vogt, & Prinz, 2001). These experiments show that motor competence influences how motions are perceived. In addition they suggest a common knowledge of structural properties of action and perception. A possible mechanism that could give rise to these commonalities between action and perception is considered at the next level.

The level of *generation of expectations* addresses how predictions of action consequences can help to maintain a stable representation of the environment. Predictions of action results achieve stability in several ways. First, by taking eye motor commands into account when retinal information changes, the system is able to distinguish between changes in the outer world and eye movement related changes. More generally, comparing predicted with perceived states allows to differentiate between self initiated and environment induced changes (R. Miall & Wolpert, 1996). Second, online movement corrections are facilitated because aimed and actually produced movements can be compared already during the movement (R. Miall & Wolpert, 1996) . Third, attention can be allocated in advance to the movement target position (Schneider & Deubel, 2002), or to action relevant features (Bekkering & Neggers, 2002) guaranteeing a fast processing of relevant information (see also Premotor Theory in Section 1.1.3). The postulated common mechanism behind these motor influences on perception is that motor commands or a copy of them are used for predicting the state of the body and world after the motor act has been performed (see Common Coding and MOSAIC approach in Section 1.1.3). This goes back to the outflow theory of Helmholtz, who postulated that the motor command itself rather than motor *consequences* influences perception (Viviani, 2002). Further, because the predictions have to be comparable to sensory information they have to be commensurable. Given that motor predictions make action and perception commensurate, interactions at this level could explain the common properties of the abstract level, or how specific interference effects arise. As specific APIs are the phenomenon under investigation in this dissertation they will be considered in the next section in more detail.

### 1.5.2 Paradigms Addressing Specific APIs

Müsseler and Hommel (1997) investigated the influence of preparing a right or left keypress on perceiving (in)compatible directions of arrows ("<"/">"). To this end, participants were presented with response cues of arrows either pointing to the right or left ($S_1$) and should prepare a right or left keypress ($R_1$) accordingly (see Figure 1.2). When participants had prepared $R_1$ at a self chosen pace they performed a trigger-keypress and made the prepared $R_1$ as fast as possible to $S_1$. The trigger-keypress started the display of a second arrow ($S_2$) and participants were asked to make a perceptual judgment ($R_2$) about the direction of this arrow by pressing either the right or left key without time pressure. $S_2$ was covered by a random dot mask. The presentation time of $S_2$ was determined individually in a training phase to ensure that participants produced between 60 and 80 percent correct answers to $S_2$. A specific influence in this design would be revealed by a difference in error rate for compatible $R_1$ and $S_2$ conditions when compared to incompatible conditions. This was what they found. Compatible $R_1$-$S_2$ conditions led to *higher* error rates than incompatible conditions. In other words, a CE was obtained because compatibility between action and perception led to a tendency to perceive $S_2$ as being of a different direction than $R_1$.

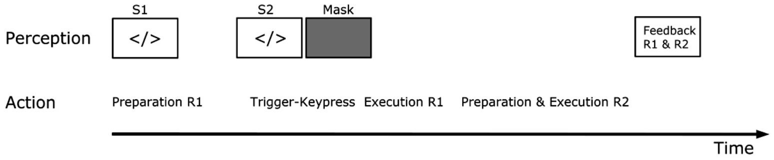

*Figure 1.2: Action effect blindness paradigm. While participants were preparing and executing the response (R1) to the arrow stimulus (S1), another arrow stimulus (S2) was displayed to which participants responded with a second response (R2). While R1 was speeded, R2 was obtained without time pressure. The random dot mask for S2 is shown as a black rectangle.*

This specific interference effect was explained in the framework of Common Coding. According to two explanations offered, preparation of $R_1$ inhibited/occupied codes that were needed for perception of $S_2$. According to the inhibition account (Müsseler & Hommel, 1997), preparing $R_1$ activated the directional code LEFT[2] or RIGHT which then started to self-inhibit. Therefore, when $S_2$ shared features with $R_1$, these features were less activated. According to the occupation account (Wühr & Müsseler, 2001), activating, for example, the LEFT code for $R_1$ binds this code to the response and makes it less available for $S_2$. Inhibition and occupation therefore differ in that the latter describes codes as bound to one event and therefore not available even though they might be active, while the former predicts less activation of the shared codes. Because the CE was attributed to the activation of codes that represented the effects of actions (e.g., right press), the compatibility effect was termed action-effect blindness (AEB).

The interpretation of an action-based CE was supported by Danielmeier, Zysset, Müsseler, and von Cramon (2004). Danielmeier et al. (2004) used fMRI to compare brain activation during encoding of an arrow stimulus in trials where participants performed a concurrent motor response to trials when no concurrent response occurred. For movement trials, a lower activation in V3 and V3A in extrastriate visual cortex was found. Activation of these areas is thought to be contrast and orientation sensitive and mediated by the frontal eye fields, that in turn are affected by visual information and motor planning (Danielmeier et al., 2004). Accordingly, the frontal eye fields could be the route through which action influences perception at early encoding stages in V3 and V3A. The reduction of activation in these areas was hence interpreted as reflecting the interference in perception that was caused by action.

Further studies with slightly different designs to Müsseler and Hommel (1997) allowed to rule out alternative interpretations to an API: One concern was that the CE might actually reflect a response bias, for example, a tendency to change the response direction from $R_1$ to

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[2] "LEFT" and "RIGHT" are set in uppercases to stress that they do not refer to language codes "left" or "right" but to cognitive codes that represent directions.

$R_2$. The response bias explanation could be ruled out with a signal-detection method (Müsseler et al., 2001). When sensitivity and response bias measures were compared between $R_1$ - $S_2$ compatible and incompatible conditions, compatibility led to lower sensitivity but did not affect the response bias. Another possibility was that the interference did not arise during $R_1$ but was caused by a confusion in memory. This possibility was excluded by Wühr and Müsseler (2001) who obtained no AEB when $S_2$ (the stimulus for the perceptual decision) occurred prior to $S_1$. This showed that having $S_2$ in memory is not enough to elicit the compatibility effect. Another confounding factor could have been motor-motor interactions. $R_1$ - $R_2$ carry over effects were investigated by including catch-trials in which, unknown to the participants, no $S_2$ but only the mask was presented. When no physical sensory information constrained $R_2$, $R_2$ should reveal response tendencies (Müsseler & Hommel, 1997). However, no influence of $R_1$ on $R_2$ was found, which provided evidence against motor-motor interactions. $S_1$ - $S_2$ interference effects could also be excluded by asking participants to endogenously prepare a movement. Despite that no $S_1$ was presented, AEB was observed, which ruled out a sensory-sensory influence as a necessary factor (Müsseler, Wühr, & Prinz, 2000).

Having excluded alternative interpretations to an API, later experiments addressed the source of the CE. To investigate the crucial overlapping components, temporal occurrence of $S_2$ was varied relative to $R_1$. As the results showed, AEB could be obtained if $S_2$ was presented between $S_1$ and the keypress of $R_2$ (Wühr & Müsseler, 2001) and was still significant but smaller when presented after $R_2$ (Stevanovski, Oriet, & Jolicoeur, 2002). Therefore, the whole preparation and execution period as well as some time after the execution elicited an AEB. The dependence of the effect on the executed movement was addressed by Kunde and Wühr (2004). In their experiment, half of the participants kept their hands crossed during the experiment, i.e., pressed the right button with the left hand and the left button with their right hand. In this way, anatomical spatial information of the arms could be dissociated from distal spatial information of the buttons. As the results showed, AEB was found relative to the distal position and did not differ between parallel and crossed-hands conditions. Thus, AEB did not depend on motor commands. Similarly, it was shown that AEB does not depend solely on the physical $S_2$ but also on the interpretation of it (Stevanovski et al., 2002). The crucial finding was that AEB could be reversed by instructing participants to interpret $S_2$ as a headlight, i.e., to interpret ">" not as an arrow to the right ($\rightarrow$) but as a headlight to the left ($\triangleright$). Thus, AEB was neither a result of physical perceptual features nor physical motor commands, but depended on the interpretation of $S_2$ and $R_1$. This abstraction from the physical properties as the source of the CE was further strengthened by Stevanovski, Oriet, and Jolicoeur (2003). Their finding that AEB is also present when $S_1$ was merely used as a "get ready" signal without demanding a response, led them to conclude that AEB is caused at least partly by a symbolic congruency component that is independent of motor preparation. In a later experiment, in some trials $S_1$ was again used as a "get ready" signal or required a response. A stronger AEB in trials when participants had to respond was found. This led Stevanovski, Oriet, and Jolicoeur (2006) to conclude that the symbolic and the action (planning) congruency components can behave additively. According to this interpretation, the greater AEB reflected the problem of binding a directional feature that is already bound by an abstract representation of $S_1$ *and* by action planning of $R_1$.

Taken together, these studies suggest that AEB reflects a true action influence despite a potential additional symbolic component. What is, however, less clear is why the decrease in accuracy of $S_2$ for compatible conditions is not paralleled by a decrease in $R_1$ accuracy, which occupation of common codes would suggest, or why, when accuracy effects on $R_1$ are found, compatibility leads to *higher* accuracy (Müsseler & Hommel, 1997, Exp. 4). Finding no effect or the opposite effect on $R_1$ might suggest that losses due to binding are asymmetric. While perceptions might suffer from features bound by action, actions might sometimes even benefit from competing with perceptions. It could be speculated that this asymmetry is not caused by the qualitative differences between action and perception but by the strength of their representations. In this paradigm, the responses were normally planned before the visual event. This could result in a stronger representation for the response than for the stimulus. In this case it could be that the stronger event might not only be unaffected by the co-occurrence of a weaker event but might even benefit from the additional response activation to the already bound features. This explanation assumes that binding does not exclude activation, which is consistent with the literature (e.g., Hommel et al., 2001; Stoet & Hommel, 1999, see also Grosjean, 2001). Nevertheless, AEB clearly demonstrates an influence of movement planning on stimulus perception. I turn next to a study that has been interpreted as showing facilitation between prepared movements and compatible stimuli.

In the experiments of Craighero et al. (1999) participants initiated prepared grasping movements faster when the orientations of a "go"-signal and an aimed object were compatible than when they were not. As illustrated in Figure 1.3, on each trial, the words "left" or "right" were written on the computer display. This instructed participants to prepare their movement to one of two targets that matched in orientation to the word. The grasping movement was executed after the "go" signal as fast as possible and without online visual feedback. Even though the orientation of the "go" signal was uninformative for the task, it could be either compatible with the target (same direction for signal and target), neutral (circle with no direction information) or incompatible (signal and target differed in direction). When the "go" signal and the target were compatible the movement initiation times were significantly reduced.

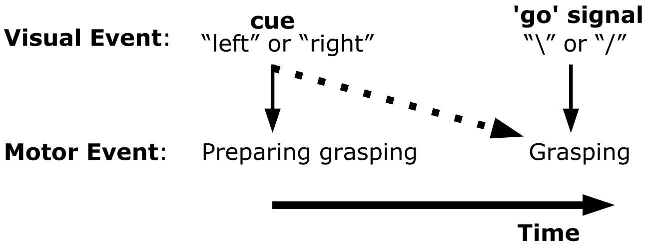

*Figure 1.3: Paradigm of Craighero (1999). Each trial started with the presentation of either the word "left" or "right" written on the screen. This instructed participants to prepare grasping movements to a left or right oriented invisible target bar. The movement was executed at the appearance of a "go" signal. The orientation of the "go" signal could either be compatible or incompatible with the target bar orientation. The meaning of the arrows is described in the main text.*

Two further experiments investigated whether this result was caused by an influence of the "go" signal on the movement or by an influence of the prepared movements on visual processing. The logic of these experiments was that if the faster reaction times for compatible "go" stimuli were also found for movements that had not been prepared this would show that stimulus processing and not the response was affected. To this end, in one experiment the size of the "go" signal indicated whether participants should respond by grasping the object or react with a (unprepared) foot switch press. In the other experiment the alternative response was eye-blinking. The results showed that an influence was obtained even when participants responded with unprepared actions. Finding the same effect even though the action changed was taken as evidence that the processing of the "go" signal and not the action was influenced.

This interpretation of the interference effect as a perceptual effect has been challenged by Grosjean (2001). Grosjean (2001) questioned among other things the use of reaction time measures to assess a perceptual effect. Using reaction times relies heavily on the merit of the motor system and thus might be unsuited to detect the contribution of visual processing. Indeed when an additional discriminative response to the "go" signal was required a decremental effect of compatibility on "go" signal identification was found (Grosjean, 2001). Another challenge for a motor-perceptual interpretation is that the motor preparation manipulation is confounded by the cue presentation. This opens the possibility that not the prepared response but the cue signal influenced the processing of the "go" signal. In this direction points a study of Durso and Johnson (1979) which showed that the concept evoked by a word facilitates processing of a later picture when the picture conveys the same concept. Therefore, it is hard to judge the influence of the cue without further experiments in which no motor preparation occurs.

Similar to AEB, the sources of the facilitative effect seem to be abstracted from the physical properties of the stimuli and motor commands. For example, in later experiments, also a facilitative effect of using pictures of hands as "go" signals that corresponded to the hand end grip posture was found (Craighero, Bello, Fadiga, & Rizzolatti, 2002; see also R. C. Miall et al., 2006; Vogt, Taylor, & Hopkins, 2003). Further support for the involvement of abstract properties activated by actions in interference effects was found in a related paradigm by Lindemann, Stenneken, Schie, and Bekkering (2006). This study pointed to the importance of the semantic level for influences between action and lexical decisions. In the experiments, movement preparation facilitated lexical decisions for words that were semantically connected to prepared actions. In each trial, participants were presented with one of two objects and had to prepare corresponding movements. For example, a cup should be responded to by grasping it and bringing it to the mouth. The action was not to be executed before a "go"/"no-go" signal was shown. Only if this signal was a word should the prepared action be executed. Participants should withhold responding when a pseudoword occurred. Lindemann et al. (2006) found that movement initiation time was reduced when the "go" signal corresponded semantically to the prepared action (e.g., "cup" with "mouth") compared to non-corresponding combinations. This was interpreted as evidence that prepared action goals activated semantic content and thus interfered with the lexical decision. Similarly, the facilitative effect from action on perception in Craighero et al.'s design could be based on semantic features.

At first it might seem surprising to find facilitative effects in compatible situations when Müsseler and Hommel (1997) found a decremental effect. On the other hand, these paradigms differ in some important aspects. While in the AEB paradigm movement preparation overlapped with a visual processing task that was independent from the prepared action, the situation is less clear in the paradigm of Craighero et al. (1999) and Lindemann et al. (2006). One interpretation could be that the prepared action and the "go" signal belonged to the same action (see dotted arrow in Figure 1.3). This means that the "go" signal could be understood as online visual feedback for an ongoing action, i.e., the response, whose preparation has already started, is only temporally modified by the "go" signal. Alternatively, a trial could be conceptualized as being composed of two tasks (see line arrows in Figure 1.3). One task would be to respond to the cue by preparing a movement, the other to respond to the "go" signal by executing the movement. In both cases there would be no situation where two tasks overlapped in time or stimulus information of one task had to be kept in memory during performance of another task. I will return to the difference between these paradigms in Section 5.4 where I discuss what causes CEs or AEs to occur.

More recently, a number of studies have turned to the issue that is at the core of the present study, that is how action influences perception in continuous PRP paradigms. I will now turn to paradigms involving two tasks with continuous movements.

Wohlschläger (2000) investigated the influence of directional hand movements on the perception of an ambiguous motion that could be interpreted as a rotation in a clock or counterclockwise direction. To create the ambiguous motion, white dots were arranged around an imaginary circle with a 60° distance between each adjacent dot on a screen (see Figure 1.4). Apparent motion was then achieved by rotating the dots along the imaginary circle (gray dots in the Figure). Because all dots looked identical the motion direction was ambiguous. As illustrated in the figure, depending on which dots were associated with each other in consecutive frames, either a clockwise (closer gray and white dots are associated) or counterclockwise (more distant gray and white dots are associated) rotation would result. A trial started by displaying the white dots as depicted in Figure 1.4. In the middle of the circle an arrow was placed and indicated to the participants in which direction a knob should be rotated. When participants rotated the knob the cue cleared and the dots started to move along the imaginary circle on the display. Participants were asked to indicate the perceived direction by pressing either a right (clockwise) or left (counterclockwise) button with their left hand while still performing the movement with their right. As the results showed, when participants performed movements around an axis that was perpendicular to the screen, an AE of the produced movements on the perceived motion directions was observed. In contrast, no influence was found when the rotation axis of the observed and performed movements did not correspond.

These findings, together with later experiments, point to the importance of the cue dimension for the AE to occur. In these later experiments, the knob rotation was replaced by right or left button presses. Interestingly, when the cue dimension was orthogonal to the movement dimension (e.g., pressing the upper/lower key in response to a left/right cue) the cue dimension determined whether an AE was observed: Only when the cue dimension was parallel to the perceived motion did an influence occur. This was true whether the movement was executed or only planned during motion perception. Finding such a strong influence of cue-dimension over response dimension makes it difficult to distinguish what interfered with motion perception, that is whether it was the sensory cue or the prepared/executed movement. Wohlschläger (2000) advanced an argument for the importance of the motor involvement. As he noted, no AE was observed when every cue was responded to by the same keypress, which might underline the importance of the movement. On the other hand, in this situation the cue direction was also uninformative and therefore perhaps only superficially processed. If the motor component played a crucial role, experiments which dissociated cue from response dimensions suggest that motor features interfered at a

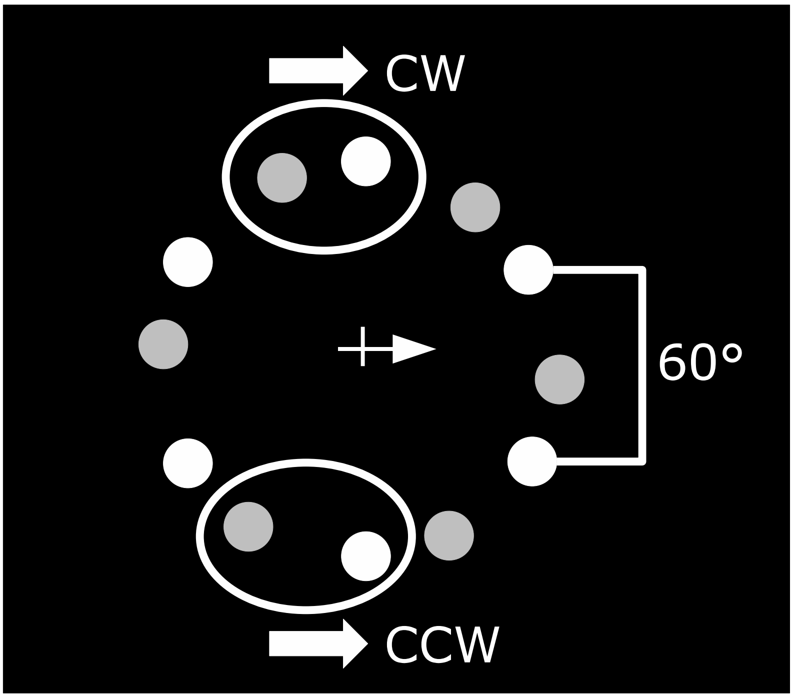

*Figure 1.4: Paradigm of Wohlschläger (2000). On each successive frame, the white dots are rotated along an imaginary circle by a certain angle. The gray (gray is only used for illustration here) dots depict the screen on the next frame. Because all dots look identical, different possibilities to associate white to gray dots arise. Associating closer gray and white dots would result in the experience of a clockwise (CW) apparent motion, associating more distant dots in a counterclockwise (CW). Adapted from Wohlschläger (2000).*

level where direction is not defined by the motor command. Otherwise is hard to see why cue dimension but not response dimension determined the AE.

A similar AE was reported for auditory perception by Repp and Knoblich (in press). In this paradigm, participants listened to two tones in sequence. These tones were selected so that the probabilities of perceiving an up-going or down-going sequence was expected to be equal. When participants performed a left to right movement on a piano or computer keyboard, they were more likely to perceive a rising sequence than when moving from right to left. This was what should be expected because left is associated with low, and right with high tones (e.g., Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Interestingly, the AE was found only in skilled pianists and not in a control group of untrained students, which suggests that learned movement effects might play a role for this effect.

As the following studies show, however, AEs were not found when the perceived stimuli were unambiguous. Instead CEs have been reported. As already alluded to in section 1.4, the paradigm of Schubö et al. (2001) was also used to detect specific APIs. Movement responses were used to measure this influence. In terms of Figure 1.1 the influence of R on S in trial n was measured by the produced R in trial n+1. The underlying logic was that the influence on perception in trial n should be reflected in the reproduction in trial n+1 of the perceived S. The results were consistent with a CE interpretation. Small R amplitudes in trial n led to larger amplitudes in trial n+1, thus presumably reflecting larger perceived S amplitudes in trial n. Conversely, large amplitudes in trial n led to small amplitudes in trial n+1 and medium sized amplitudes resulted in amplitudes in between. A similar CE was found for velocity.

The role of memory processes for the CE was investigated in a further experiment. To do so, the time between encoding and reproducing the S, i.e., the intertrial interval (ITI) was manipulated (Schubö et al., 2004). Instead of the 1.5 seconds ITIs used in the earlier study, the next trial started after 2, 4, 6 or 8 seconds. A CE for amplitudes and velocities was obtained for the 2 seconds ITI condition. For the 4 and 6 seconds ITIs, no effect was found, and finally an AE was obtained for the 8 seconds ITI. This pattern of results was interpreted as evidence for two separate processes: Under concurrent situations, a code modification mechanism is invoked to keep the two events (R and S) separate. This code modification mechanism results in a CE. The second mechanism comes into play after the concurrent events have occurred and when only the Ss have to be kept in memory. This memory process was assumed to lead to assimilation with the prior R. Thus, according to Schubö et al. (2004) CEs arise during concurrent events but turn into AEs in memory (see also Kerzel, 2001).

What makes these experiments difficult to interpret is that there is at least one plausible alternative explanation. Schubö et al. (2004) indeed could rule out that the AE was caused by motor-motor interactions between Rs in trial n+1 and n. To do so, another task was introduced after S motion offset. In the intervening task, participants either had to name the color of a displayed rectangle or to draw a circle for about 1 second. If the assimilation found was due to motor-motor interference, the circle drawing task should cancel the effect of the earlier R and thus diminish the AE. As the results showed, the intervening task had no influence on the AE. Therefore, the motor-motor interference interpretation could be ruled out. The authors also controlled for an equal frequency of S amplitude sizes in trial n+1 when the R was assessed. The design of their study, however, did not allow to exclude another serious problem. Determining the R in trial n by the S in trial n-1 led to a crucial confound: Whenever the influence of R on S in trial n was assumed to occur, amplitudes of the same category as the R were presented as the S in trial n-1. This means that the interference could either be a result of the amplitude of the R in trial n, or of the S in trial n-1. Only in the first case would the CE point to an interference of action on perception. In the other case the CE would be a sensory aftereffect that is known to lead to contrast (e.g., Clifford, 2005).

Another study that looked at the influence of actions on continuous biological motion perception was the study of Hamilton, Wolpert, and Frith (2004). In the experiment, participants watched video clips in which actors lifted identically looking boxes that differed in weight from 50g to 850g. The weights were to be judged by the participants using a rating scale. Crucially, the concurrent task while watching the videos was manipulated and could either involve an active, passive or neutral condition. In the active condition, participants lifted a weight of either 150g or 750g and held it for the duration of the video. Thus, the lifting action preceded the observed movement and the concurrent task was that of holding the weight (see de C. Hamilton, Wolpert, Frith, & Grafton, 2006, p. 526). The passive condition differed from the active one in that the weights were placed on the participants' palm which rested on a desk. In the neutral condition no concurrent task was performed. The question of interest was whether the lifted weights influenced the weight judgments. As the results showed, lifting a heavy weight led to lower weight judgments compared to judgments in the neutral condition. Similarly, lifting a light weight resulted in higher weight judgments. Thus, the lifted weights had a CE on perceived weights. Surprisingly, also the passive condition showed a CE, albeit smaller. This was attributed to proprioceptive information and low level activation of the motor system due to potential interactions with the box.

On the other hand, the similarity between the active and passive condition could point to a problem when considering the CE as resulting from concurrent action and perception. The fact that also in the active condition the weight was simply held static during motion observation blurs the difference to the passive condition what was also reflected in the similar CEs for both conditions. Thus, it is not obvious whether this study can really be considered as a concurrent action and perception study. Non-concurrence on the other hand makes an alternative explanation to the API plausible. It could be that not the action, per se, influenced the judgment, but that having lifted the weight before provided an anchor on one end of an imaginary weight continuum and then pushed judgments away from it (e.g., Brewer & Chapman, 2003). This repulsion from a anchor would then be a general mechanism independent of whether the anchor was set by an action or other events. In addition, the influence would not be caused by a concurrent but a preceding event.

Anchors have indeed already been shown to have a CE on weight judgments. Lollo (1964) asked participants to judge the weights of lifted bottles. Conditions differed in what range of weights had to be judged in the first phase and therefore provided an anchor. When participants first had to judge heavy weights and then shifted to light weights during the experiment, the later were judged lighter than when participants judged light weights in the first part as well. Similarly, when first judging light weights and then judging heavy weights, the heavy weights were judged as heavier compared to a control group that only experienced heavy weights throughout the experiment. This possible anchoring effect in the Hamilton et al. (2004) study could depend on visual information processing or even occur independent of it. The difference would be that in the former no bias would occur when guessing the weights without visual information, while in the latter a response bias would still be observed. Only in the first case would the obtained CE reflect an influence on perception, be it caused by the motor system or not. Relying on a rating scale to assess weight judgments could also have introduced an additional bias caused by the measurement method alone, e.g., responding with higher weights when lifting a light weight, irrespective of sensory information. Using, for example, a same / different judgment would have avoided this problem. Schubö et al. (2001) and Hamilton et al. (2004) each proposed a model to account for the found specific interference effect. I turn to these models next.

### 1.5.3 The Schubö Model

Schubö et al. (2001) advanced a model that was based in the framework of Common Coding. This model is discussed in more detail because it is later evaluated in the experiments. According to the model, common elements for action and perception code for different amplitudes (see Figure 1.5). Further, Rs and Ss of a given trial activate corresponding elements in a graded fashion. Elements that correspond to the produced/observed R and S amplitudes are activated most. The activation levels off for surrounding elements as one moves away from the produced/perceived amplitude (activation curves in Figure 1.5). Because of this graded activation some elements belong both to the R and the S activation curves (gray area). The assumption of the model is that the elements that belong to two different tasks inhibit each other. As a consequence shared features contribute to both tasks to a lesser extent. Accordingly, the means of the activation curves for Rs and Ss shift away from each other and a CE between Rs and Ss is observed. In other words, compatibility between concurrent action and perception makes the two events less similar to each other than when the events occur in isolation. In this way, CEs can be seen as inhibitory and AEs as facilitatory compatibility effects.

### 1.5.4 The Hamilton Model

The CE on weight judgments was explained by a variant (henceforth Hamilton model) from the MOSAIC framework (Haruno, Wolpert, & Kawato, 2001). The model proposes multiple modules, each associated with a different weight (drawn in Figure 1.6 on the left side). During observation of weight lifting each of these modules predicts the kinematics that

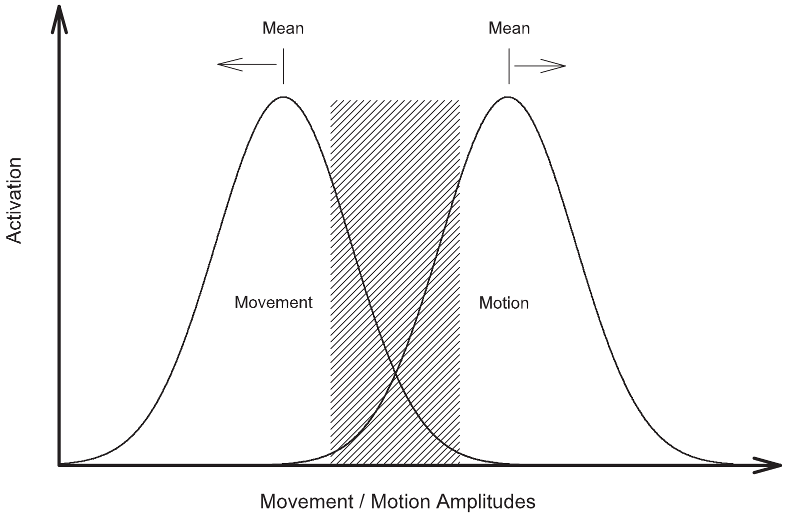

*Figure 1.5: Schubö model. R movement and S motion are represented using the same elements to code the amplitudes. Elements corresponding to the R and S amplitudes are most active and activity decreases with the difference between the R/S amplitudes and the amplitude that is coded by the element. This figure is an adaptation from Schubö et al. (2001).*

would result if its associated weight were lifted (arrows coming from the left side). These kinematic predictions provide the common ground to interact with the visual system. This interaction occurs in the middle of the figure, where the predicted and observed kinematics are compared. As a result of the comparison process different responsibilities (reflected by the thickness of the lines from the middle to the right) are assigned to the respective modules. The value of a module's responsibility corresponds to the similarity between its prediction and the observed movement pattern. Thus, high similarity leads to a high responsibility and low similarity to a low value. These graded responsibilities are thought to reflect noise in the system. To arrive at a weight judgment the responsibilities are normalized, multiplied with the weights associated to the modules, and added.

The crucial assumption to explain the CE is that performing an action with a certain weight occupies the corresponding module[3]. As a consequence the judgment relies more on other modules. Because of this loss of information on one side relative to the observed weight, the judgment is biased to the other side.

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[3] Although Hamilton et al., 2004 did not discuss this assumption, one could be tempted to speculate that gating out motor modules that are currently engaged by action from their contributions to the perceptual judgment might be a means to avoid perceptual illusions that otherwise would arise from the predicted kinematics (for a similar function of inhibition at peripheral muscles see Baldissera et al., 2001 as discussed above.)

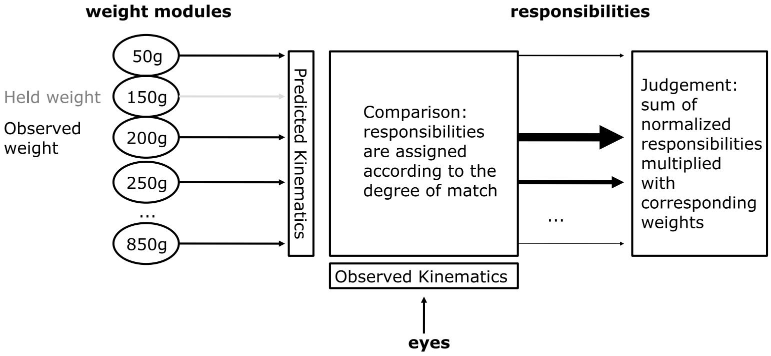

*Figure 1.6: Hamilton model. During motion observation each weight module on the left predicts the kinematics that would result from lifting the module's assigned weight. These predictions are compared to the observed kinematics and responsibilities according to the fit assigned to the modules. The responsibility is higher for close matches and lower when prediction and observation differ to a greater extent. When a module is occupied by lifting a weight, its responsibility does not contribute to the judgment (missing arrow on the right side). Therefore, the judgment is biased away from the held weight.*

Interestingly, there are some issues that question the importance of kinematic data for the CE. For example, given that the weights were held still during movement observation, it is hard to see why kinematic predictions of lifting movements should occur at all. Similarly, findings of de C. Hamilton, Joyce, Flanagan, Frith, and Wolpert (2005) questioned the importance of kinematic details at the level where action and perception interact. de C. Hamilton et al. (2005) manipulated kinematic variables of box lifting in videos and investigated the effect on weight judgments. Participants seemed to rely most heavily on the duration of the lifting movement. In contrast, when (other) participants were asked to lift the weights themselves the most predictive variable of weight was the duration of the grasping phase. Given this discrepancy between motor variables used in box lifting and variables used for perceptual judgments, de C. Hamilton et al. (2005) concluded that "perceptual and motor information may be matched at the level of goals, and that the details of kinematic trajectories are relatively unimportant." (p. 8). This conclusion makes it hard to see how *kinematic* predictions from motor modules, as suggested by the Hamilton model, can produce the observed CE.

On the other hand, a recent fMRI study seems to be consistent with the notion of interaction between kinematic variables. de C. Hamilton et al. (2006) investigated which brain areas are associated with the action bias in weight judgments and found evidence for the involvement of detailed motor activation in the interference effect. In the experiment, participants in one condition performed a weight judgment task similar to the task in Hamilton et al. (2004). The crucial question was whether the biases in the weight judgment task due to hand movements correlated with brain measures. To this end, differences in brain activity during lifting a light and heavy weight were calculated. Significant correlations between the behavioral bias and the differences in brain activity were found for the inferior frontal gyrus (IFG), the central sulcus, close to V5, and the extrastriate body area (EBA). Interestingly, these areas involved motor (IFG and central sulcus) as well as visual (V5 and EBA) areas providing a plausible location for motor-perceptual interference. The involvement of primary motor cortex (central sulcus) was interpreted as suggesting detailed motor simulations of observed actions. One problem when interpreting these correlations is that no significant behavioral API was reported across participants or within participants. Across participants CEs and AEs seemed to occur with nearly equal frequency (Figure 2C of de C. Hamilton et al., 2006). Within participants the respective biases were reported to be "consistent". Thus, it is unclear whether the correlation with brain activity involved any meaningful behavioral measures. In sum, it might therefore be fair to conclude that at least equivocal results were obtained with respect to the issue of which kind of representations underly the interaction between action and perception in the weight judgment paradigm.

An additional problem is that the empirical data of Hamilton et al. (2004) do not fully support the model. Even though the coarse data pattern seems to fit the proposed model, there are some details that are inconsistent with it. For example, the prediction of the judgments for 50g boxes when holding 150g is at discrepancy with the reported data. When participants were lifting the 150g weight and observed the 50g box being lifted, according to the model, the blocked 150g module is one of the heavier modules that contribute to the 50g activation. As a result, the weight judgment should be biased towards lower weights. In contrast, the graphically presented data of Hamilton et al. (2004) show for the 50g box in the light weight condition a bias to judge the box as heavier. Analogously, when lifting the 750g box, the 850g box should be judged heavier instead of lighter when compared to the neutral condition. Again the graphical data do not fit with the predictions of the model. Interestingly, the pattern would be consistent with an influence of the held weight as a function of a category like "light" or "heavy" but not as a function of the weight in grams. I come back to this issue in the General Discussion, when I try to account for the data reported in this thesis.

Another inconsistency between the data and the model is that the model would predict that the more similar lifted and judged weights are, the more the occupied modules should bias the judgment. Hamilton et al. (2004) did not provide statistics on this issue, but graphically the data seem inconsistent with this prediction. I elaborate on this prediction more in the following section. Again, more abstract (in the sense of ignoring details of motor or sensory origin) representations seem to underly the APIs.

Now that the Schubö and Hamilton models have been discussed, the topic of this dissertation can be introduced in more detail: The purpose of this dissertation was to investigate the specific interference that arises in a concurrent movement production and motion perception task. This interference was used as a means to test predictions from the Hamilton and Schubö models and by this gain insight into the underlying coding structure involved in specific interference effects between motor and sensory events. The aim of the dissertation was not so much to distinguish between these two models as to test whether the general assumptions of these current models for APIs can be supported by empirical data. I will discuss the predictions of these models next.

## 1.6 Predictions of the Hamilton and Schubö Models

The Schubö model, due to its symmetric composition, predicts a mutual specific interference on action and on perception, i.e., in cases where action influence perception, an influence of perception on action is also predicted to occur. That is, if action is contrasted by perception because of overlapping features, these features should cause a CE between perception and action as well. The only way how this mutual interference could be avoided in the model is that one event is granted more priority and therefore not affected by the other event. Schubö et al. (2001), however, made no such assumptions but assumed mutual interference. Furthermore, if a mutual interference is detected, the size of these effects should be monotonically related, i.e., they should both increase and decrease together. The relationship however does not have to be linear because the effect size depends on the amount of activation curve overlap. As the the two amounts of overlap depend on the nature of the two activation functions, it is without further specification only possible to predict a monotonic relationship. Therefore, the first prediction was that *the size of the interference effect on action should be monotonically related to the size of the interference effect on perception* (mutual interference prediction).

It is important to note that even though finding a correlation would be consistent with the Schubö model, this finding would be neutral to the question of whether common codes underly these effects. For example, overlap unrelated mechanisms like effort, skill, etc., could lead to a correlation between action and perception measures. Finding on the other hand no relationship would be problematic for the Schubö model.

The Hamilton model, on the other hand, makes no predictions about an influence on action. Therefore, finding a mutual interference effect would not contradict the Hamilton model, but still lend more credit to the Schubö model because it can account for such an empirical observation without further assumptions. This is not to say that the Hamilton

*Table 1.1: Predictions of the Schubö and Hamilton models. Predictions of models are indicated by a "$\surd$". "?" shows that the model is neutral to this prediction.*

| | Mutual Interference | Distance |
|---|---|---|
| Schubö | $\surd$ | $\surd$ |
| Hamilton | ? | $\surd$ |

model could not be modified to account for an effect on action. For example, similar to gating out modules due to a motor event, it could be assumed that perceptual events block via the controller the weight modules. A necessary additional assumption would then be that action also activates weight modules in a graded fashion.

The second prediction is that *the size of the API should increase the more similar action and perception become on the dimension along which the interference occurs* (distance prediction). This can be seen from Figure 1.5 and Figure 1.6. In Figure 1.5, when the amplitudes were more similar to each other, the two curves would be closer to each other and the overlap would increase. This in turn would lead to a higher proportion of elements without a clear assignment and therefore a higher bias. A similar mechanism leads to a distance effect in Figure 1.6: When the held weight is more similar to the observed weight, the occupied weight module is closer to the observed weight module. This means that the occupied module would have gained more activation by the observed weight and therefore its loss biases more strongly the perceived weight. Finding no distance effect would therefore question both models. Table 1.1 summarizes the predictions of the models. I will now turn to an outline of the experiments that were used to evaluate these models.

## 1.7 Outline of the Experiments

The purpose of the following experiments was twofold. First, a new paradigm to measure a specific interference effect should be established. In contrast to the studies on specific interference on motion perception mentioned above, this paradigm did not involve biological motions. There are good reasons to believe that biological and non-biological motions are processed differently or at least in different locations in the brain (e.g., Grossman & Blake, 2002; Puce & Perrett, 2003; Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001). Thus, if specific interference effects are found, it would show that they are not tied to biological motion processing but are a broader phenomenon of concurrent processing. Second, predictions of the Schubö and Hamilton models were put to a first test. By studying where the models succeed and where they fail it was hoped to arrive at a better understanding of the underlying coding and processing mechanisms of two concurrent tasks.

Accordingly, the first five experiments were used to establish a paradigm to measure the API. After finding a CE in Experiment 1, the second experiment excludes a response bias interpretation of the effect. Even though each of these two experiments is subject to alternative interpretations, taken together they make a convincing statement that the observed CE is caused by specific action-perception interference. The third experiment establishes an easier way to assess the size of the CE. Experiment 4 and 5 then exclude alternative explanations to hand movements as the influencing factor on perception: eye-movements and memory processes. Finally, when the ground is set and the effect established, the last experiments test the mutual interference prediction and the distance prediction.

# Chapter 2

# Establishing a Contrast Effect

The aim of the present study was to further our understanding of specific interference by exploring whether assimilation or contrast arises in a concurrent action-perception paradigm involving direction as the overlapping dimension. To this end, participants were asked to move one of their hands in a certain direction while simultaneously trying to identify the direction of an independent stimulus motion. Among the various types of concurrent perception-action interactions that have been examined (e.g., Jacobs & Shiffrar, 2005; Kilner et al., 2003; Müsseler & Hommel, 1997), two effects obtained in paradigms similar to our own have already been reported for the perception of motion amplitude (Schubö et al., 2001, 2004) and the judgment of weights carried by other people (Hamilton et al., 2004). Both of these lines of research have exclusively focused on the perception of biological motion. It is therefore still open whether effects such as these can also be obtained for non-biological motion processing. This question is of interest because it is well known that biological motions are processed differently than non-biological motions (e.g., Viviani, 2002). Moreover, as argued by Hamilton et al. (2004) and others (Jacobs & Shiffrar, 2005; Kilner et al., 2003; Wolpert et al., 2003) perception-action interactions of this type may relate to the involvement of the motor system in the perceptual processing of biological motion. Thus, the degree to which such effects are tied to the concurrent processing of biological motion has yet to be established. We now turn to the paradigm we employed.

## 2.1 Current Paradigm and Predictions

The purpose of the present paradigm was to establish whether and how the direction of a produced movement influences the perceived direction of a concurrently presented stimulus motion. Direction was chosen as the overlapping movement/motion dimension because it is well defined and has already been employed in the study of perception-perception (e.g., Rauber & Treue, 1999; Westheimer, 1990) and action-action interactions (e.g., Heuer & Klein, 2006).

Figure 2.1 illustrates the basic structure of the paradigm. Participants were asked to produce an upward ($M_u$) or downward ($M_d$) movement while simultaneously observing a reference stimulus (RS) motion that either moved upwards, horizontally or downwards. To avoid potential carry-over effects associated with visually cueing the movements, movement directions were blocked. The velocity profile of the stimulus motion was constant and therefore non-biological. (A biological velocity profile would, in the present case, involve a relatively smooth transition between an acceleration phase and a subsequent deceleration phase.) Once participants had finished their movement, they were presented with a test stimulus (TS) motion to asses how they had perceived the RS. The TS was either identical to the RS motion or deviated upwards or downwards from it. The task of the participants was then to judge the relationship between the TS and the RS motions. Since no movement on the part of the participants was allowed during the judgment phase, their judgments of the TS should not be influenced by the recently produced movements and should therefore only reflect how those movements had affected their perception of the RS motion direction.

As will be discussed in more detail below, the nature of the perceptual judgment was also varied between experiments. This was done to provide converging ways of assessing the influence of action on perception and to differentiate between competing interpretations of the effects that were obtained. Importantly, all types of perceptual judgments allowed us to either estimate or directly measure the size of interference effects in the units of the manipulated variables, i.e., degrees. Thus, the dimension that was supposed to be influenced by action (i.e., direction) was also the dimension that had to be judged.

If the CEs obtained in earlier studies (Hamilton et al., 2004; Schubö et al., 2001, 2004) are not tied to biological motion perception, then the perceived direction of the RS should be repulsed by the direction of the produced movement. That is, as shown in Figure 2.2, upward movements should lead to perceived RS motions that are shifted downwards (upper panel of the figure) and downward movements should lead to perceived RS motions that are shifted upwards (lower panel of the figure). In the context of the present task, the RS should therefore be perceived as more similar to a downward deviating test stimulus ($TS_1$) when it was observed during an upward movement and more similar to an upward deviating test stimulus ($TS_5$) when it was observed during a downward movement.

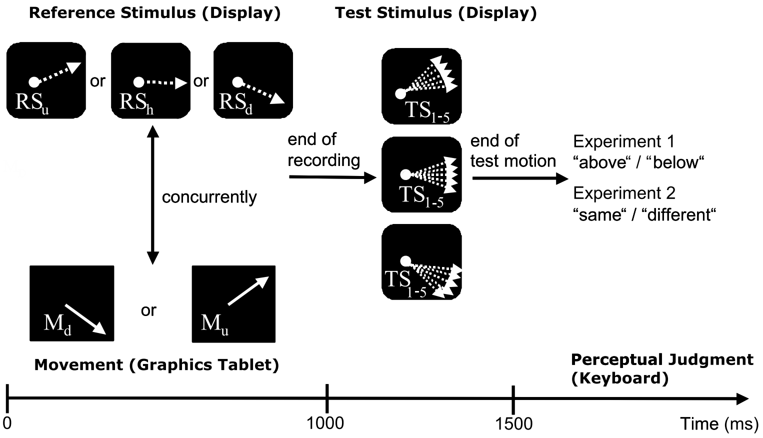

*Figure 2.1: The paradigm employed in Experiments 1 and 2. Upward ($M_u$) and downward ($M_d$) movements deviated from the horizontal axis by +25° and -25°, respectively. The reference stimulus (RS) moved +15° upwards ($RS_u$), 0° horizontally ($RS_h$), or -15° downwards ($RS_d$), and the test stimulus (TS) deviated in direction from the presented RS motion direction by -4°, -2°, 0°, +2° or +4° ($TS_{1-5}$). Movement recording lasted 1000 ms, whereas RS and TS durations were both 500 ms.*

## 2.2 Experiment 1: Obtaining the Effect

To assess how the direction of movement affects the perceived direction of the concurrently presented stimulus motion, a two-alternative forced-choice procedure was employed in which participants had to indicate whether they perceived the TS motion as *above* or *below* the RS motion. Based on the logic outlined above, if a CE occurs, perceived directions should be repulsed by the direction of the produced movements (see Figure 2.2). With the present perceptual measure, this CE should translate into a lower proportion of "above" judgments for downward movements than for upwards movements.

### 2.2.1 Method

#### Participants

Sixteen right-handed individuals (mean age = 24.94 years; age range = 21-35 years; 4 males, 12 females) participated in the experiment. In this, as well as in the subsequent experiments, all participants reported normal or corrected-to-normal vision and no motor impairments, were not aware of the purpose of the study, and were paid for their time.

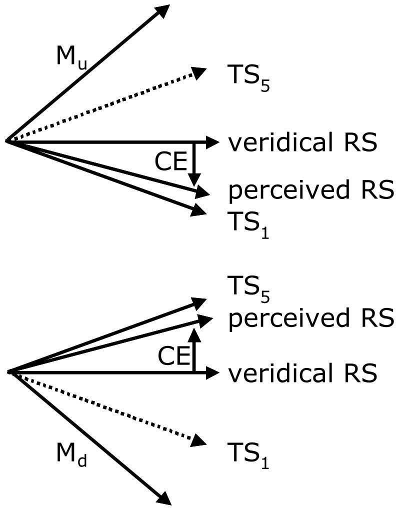

*Figure 2.2: Illustration of how the direction of upward ($M_u$) and downward ($M_d$) movements should affect the perceived direction of a reference stimulus (RS) as assessed by participants' judgment of the test stimulus (TS). Two TS direction deviations are included in each panel of the figure exclusively for illustration purposes, since there was actually only one TS presented on a given trial of the experiments (see text for details). CE = contrast effect*

### Apparatus

The experiment was conducted in a dimly-illuminated and sound-attenuated chamber. Stimulus presentation and data collection were controlled by an IBM-compatible microcomputer connected to a 21" color monitor. Movement data were collected with a Wacom Ultrapad A3E graphics tablet that sampled the $x$ and $y$ positions of a hand-held stylus in synchrony with the monitor's refresh rate, which was set at 70 Hz. The graphics tablet was placed directly below and centered with respect to the monitor, and was covered with a board such that no on-line visual feedback of the stylus/hand was available.

### Stimuli and Movements

A red circle with a diameter of 6 mm was used for the RSs and TSs. The start position of the circle was always vertically centered and shifted 9.5 cm to the left of the vertical midline of the display area (see Figure 2.1). The circle moved to the right along a straight 20 cm line on a black background without leaving a trace on the display. Motion duration was held constant at 500 ms and the circle disappeared at motion offset. For the RS, the direction of the circle motion deviated by either 0 or $\pm 15°$ from a horizontal motion. The subsequently presented TS motion was identical to the RS motion except that it deviated in direction from it by either 0, ±2, or ±4° (the differences between the different TSs is exaggerated in Figure 2.1 for the purpose of illustration). At the approximate viewing distance of 60 cm, the circle subtended 0.57° of visual angle and traversed a path of 18.92° at a constant speed of $37.84\frac{\circ}{s}$.

For the movements, participants were asked to draw with their right hand straight-line trajectories on the graphics tablet. The start position for the hand movements was also held constant and was horizontally aligned with the start position of the stimuli. The required trajectories deviated by 25° upward or downward from the horizontal axis. Given that the stylus was moved within the horizontal plane, "upward" and "downward" trajectories actually involved hand movements that went away from and toward to the participants' body, respectively. The mapping between these latter trajectories and those presented on the display was learned during a training phase in which off-line feedback of the produced movements was provided (see the *Procedure* section for more details).

### Design

Three variables were manipulated within participants: movement direction (upward, downward), RS direction (upward, horizontal, downward), and TS direction deviation (the angular difference between TS and RS directions: -4°, -2°, 0°, +2°, +4°). Movement direction was blocked and counterbalanced across participants, such that half of the participants started with upward/downward movements and switched half-way through the experiment to downward/upward movements. Each movement direction was performed for 9 consecutive blocks. In each block, all 15 RS direction × TS direction deviation combinations appeared once in a new pseudorandom order. This resulted in a total of 270 trials.

### Procedure

To ensure that participants always started their movements from the same position, they began each trial by moving a cursor inside the RS start position. The cursor was a white disk with a diameter of 2 mm (0.19° of visual angle) that represented on-line the movement of the stylus on the graphics tablet. The gain was adjusted such that there was a 1:1 mapping between the movement of the stylus and the corresponding movement of the cursor on the screen. One second after the participants had moved into the start position, a tone (1760 Hz, 15 ms) signaled that they could start drawing whenever they felt ready. As soon as the participants had left the start position, the cursor disappeared and the RS motion started. The end of the RS motion (after 500 ms) was marked by the disappearance of the RS and the onset of a second tone (880 Hz, 15 ms). The recording of the stylus movement lasted for another 500 ms (i.e., for a total of 1000 ms), at which time a third tone was played (440 Hz, 15 ms). As shown in Figure 2.1, as soon as the movement recording had finished, one of the five TSs was displayed. At TS motion offset, the screen went blank and participants were asked to indicate whether the TS motion had been "above" or "below" the RS motion by pressing the *up* or *down* keyboard key, respectively, with their left hand. No time limit was placed on this perceptual judgment. The next trial started after an inter-trial interval of 1000 ms.

Each series of 9 blocks of the experiment was preceded by a training phase in which participants practiced making either a 25° upward or downward movement trajectory. In each training trial, the to-be-produced trajectory was presented as a red line for 2000 ms and then erased. Participants then had to move the cursor into the start position and wait for 1000 ms, after which the first tone indicated that they could start to move whenever they felt ready. The rest of the tone sequence was identical to that used in experimental trials and it was stressed to the participants that the third tone indicated the end of the movement recording and the time by which the movement should be finished. After each movement, the required and the actually produced trajectories were presented for 2000 ms as red and white lines, respectively. This off-line feedback was provided to help participants learn the movements and was not available during the experimental blocks. If participants kept on moving after the third tone, an error message was displayed to that effect. Additionally, throughout the training and experimental phases, participants received an error message whenever they lifted the pen or reversed movement direction during drawing. Error messages were displayed after the off-line feedback in the training phase and after the perceptual judgment in the experimental phase. The training phase came to an end when the participants had produced a sufficient number of acceptable trajectories (as determined by a point system based on the below-mentioned criteria) or when 30 training trials had been completed. On average, participants needed about 17 trials to complete the training. The entire experiment lasted between 45-55 minutes.

### Data Analysis

Each movement trajectory was analyzed by first realigning the $x$ and $y$ stylus values to a common (0,0) coordinate position. Tangential velocity profiles were then obtained through numerical derivation and low-pass filtered at 8 Hz using a fourth-order and zero-lag Butterworth filter. Movement onset was defined as the first moment at which 5% of peak tangential velocity was reached. Similarly, movement offset was defined as the first moment at which tangential velocity subsequently dropped below 5% of peak tangential velocity. Based on these temporal markers, movement end angle (as defined by the angle with respect to the horizontal axis of the line connecting the start position to the position of the stylus at movement offset) and trajectory length (from movement onset to offset) were determined for each condition and participant. In order to only include trials that complied with the movement instructions, trials were excluded when one of the following hierarchical criteria was met: (a) the pen was moved after the tone that signaled the end of the movement and before the perceptual judgment was provided (late movement), (b) the pen was lifted during movement (pen lift), (c) participants reversed the direction of drawing (movement reversal), (d) the movement end angle deviated by more than 20° to the outside, 9° to the inside of the required movement angle, or the produced trajectory was shorter than half of the required trajectory length (trajectory failure). If these exclusion criteria led to zero observations in any of the conditions for a given participant, all of their data were discarded from the analysis.

Perceptual judgments were analyzed by computing the proportion of "above" judgments for each condition and participant. These values were then arcsine transformed to deal with the non-normality of proportions and subsequently averaged across the three RS directions to increase statistical power. To establish the influence of movement production on perceived motion direction, a two-way repeated-measures ANOVA on the arcsined values with movement direction (downward, upwards) and TS direction deviation (-4°, -2°, 0°, +2°, +4°) as within-participant factors was performed. Whenever necessary, violations of sphericity were corrected for using the Greenhouse-Geisser $\varepsilon$ (to facilitate reading, the uncorrected degrees of freedom are provided).

Finally, to determine the size of the CE in perception, psychometric functions were fit to the perceptual judgment data in order to determine the point of subjective equality (PSE) for each movement direction. Figure 2.3A shows the proportion of "above" judgments as function of TS direction deviation and movement direction for one participant. It was assumed that perceptual sensitivity as a whole would not be affected by movement production and therefore the slopes of the psychometric functions should not differ for the two movement directions. In contrast, the effect of movement production should manifest itself as a shift in the PSE for each movement direction, that is the TS direction deviation at which participants provide an equal proportion of "above" and "below" judgments. To determine the PSEs, a separate logistic function was fit for each movement direction and participant using a maximum-likelihood estimation method assuming binomial distributed choices (see Figure 2.3A). The fitted function is given in Equation 2.1:

$$p = \frac{1}{1+e^{\frac{a-x}{b}}}, \tag{2.1}$$

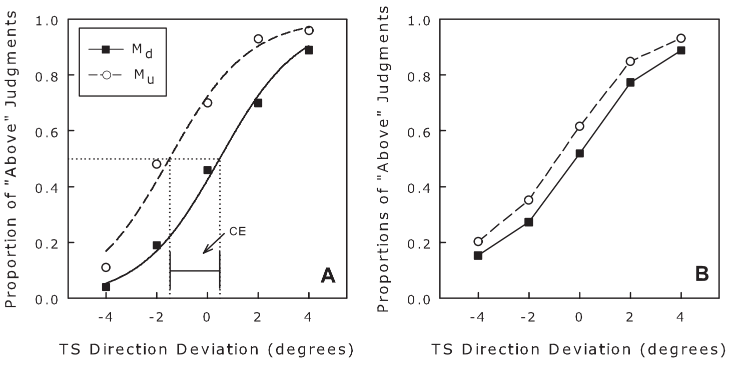

*Figure 2.3: Proportion of "above" judgments as a function of test stimulus (TS) direction deviation (-4°, -2°, 0°, +2°, +4°) and movement direction ($M_u$: upwards, $M_d$: downwards) for Experiment 1. (A) Data from one participant with the best-fitting psychometric functions and a depiction of how the contrast effect (CE) was defined (see text for details). (B) Mean proportion of "above" judgments for all participants.*

where $p$ denotes the probability of responding "above", $x$ is a given TS direction deviation, $b$ is related to the slope of the psychometric function (with higher values indicating a lower slope), and $a$ corresponds to the value on the abscissa which gives a value of 0.5 on the ordinate, i.e., the PSE. The quality of the fits was assessed with the goodness-of-fit $\chi^2$ and the normed-fit index ($NFI$), while the PSEs for the two movement directions were compared using a paired-samples $t$ test.

### 2.2.2 Results

The data of two participants had to be excluded. One participant had at least one condition with zero observations because of more than 38% of excluded trials, with 95% of those involving trajectory failures. The other participant was excluded because of an apparent failure to follow the instructions, as evidenced by exclusively responding "above" or "below", irrespective of the TS direction deviation. For the remaining participants (N = 14), the mean percentages of excluded trials were 1.64%, 1.61%, 0.77%, 6.98%, for late movements, pen lifts, movement reversals, and trajectory failures, respectively, resulting in a total percentage of discarded trials of 11.01%.

The mean proportion of "above" judgments as a function of TS direction deviation and movement direction are presented in Figure 2.3B. Negative values on the abscissa refer to a TS that was below the RS and positive values refer to a TS that was above the RS. As shown in the figure, the proportion of "above" judgments increased with TS direction deviation and was higher for upward than for downward movements by a similar amount across TS direction deviations. In support of this, there were significant main effects of TS direction deviation ($F(4, 52) = 215.14$, $MSE = 0.02$, $p < .001$) and movement direction ($F(1, 13) = 5.30$, $MSE = 0.06$, $p < .05$), but no interaction between these two factors ($F(4, 52) = 0.11$, $MSE = 0.01$, $p > .90$).

In order to determine the size of the CE in perception, we began by fitting a "restricted" model in which the "slopes" (i.e., the $b$ parameter in Equation 2.1) for a given participant were the same for both movement directions while allowing the shift parameters (i.e., the $a$ parameter in Equation 2.1) to vary. This led to acceptable overall fits (mean $\chi^2_{(7)} = 2.46$, $p > .20$, for all participants). To further evaluate these fits, we tested whether the "restricted" model was better than a "guess" model in which "above" and "below" judgments were assumed to occur with equal probability. The difference in the goodness-of-fit $\chi^2$ between these two models was highly significant for all participants (mean $\chi^2_{(2)} = 77.17$, $p < .001$, mean $NFI = 0.95$). Finally, to test the adequacy of our assumption that perceptual sensitivity remained constant across the two movement directions, the fits of the "restricted" model were compared to those of an "unrestricted" model in which the "slopes" were also allowed to vary. The difference in the quality of the fits between the "restricted" and the "unrestricted" models did not reach significance for any participant (mean $\chi^2_{(1)} = 0.72$, $p > .05$, for all participants, mean $NFI = 0.24$), suggesting that perceptual sensitivity did not vary with movement direction.

Using this "restricted" model, the mean PSEs for upward and downward movements were -0.21° and -1.05°, respectively, and the difference between these means (0.84°[4]) was significant ($t(13) = 2.09$, $p < .05$, one-tailed[5]).

### 2.2.3 Discussion

The results of Experiment 1 support the notion that perceived motion directions are repulsed by concurrently produced movement directions. Consistent with a CE interpretation, the proportion of "above" judgments was overall higher for upward than downward movements. Moreover, the TS direction deviation at which people provided an equal proportion of "above" and "below" judgments (i.e., the PSE) was lower for upward than for downward movements, with the estimated size of this CE being 0.84°. It is also worth noting that par-

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[4] Given the RS trajectory length of 20 cm, this corresponds to about 3 mm of arc length on the screen.

[5] The fact that this difference only reached significance with a one-tailed test led us to corroborate this result with a different, non-parametric, estimation method: The Spearman-Kärber method (Miller & Ulrich, 2001, 2004; Ulrich & Miller, 2004), which does not make any assumptions about the underlying psychometric functions. When comparing the PSEs obtained with this method, the $t$ test reached significance two-tailed ($t(13) = 3.02$, $p < .05$).

ticipants were indeed able to perform the judgment task required of them, as evidenced by the increase in the proportion of "above" judgments with increases in TS direction deviation.

Although the present results are consistent with the idea that movement production has a repulsing effect on motion perception, there is an alternative explanation of these results that does not rely on an influence of action on perception. According to this explanation, producing an upward/downward movement makes the perceptual judgment "above" more/less likely because of an abstract feature overlap between the movement directions and the judgment categories. As this response-bias explanation could in principle account for the results, the next experiment was performed.

## 2.3 Experiment 2: Excluding a Bias Interpretation

The goal of Experiment 2 was to replicate the perceptual CE found in Experiment 1 and rule out the response-bias explanation that could have accounted for that effect. To this end, the same experiment was performed, except that the nature of the perceptual judgment was changed such that there was no longer any feature overlap between the judgment categories and the direction of the produced movements. This involved replacing the "above"/"below" judgments with "same"/"different" judgments. If the produced movement directions actually lead to a repulsion of the perceived RS motions directions (as illustrated in Figure 2.2), then TSs that deviate away from the direction of the produced movement should be judged more often as "same" than TSs that deviate toward the direction of the produced movement. This, in turn, should result in an interaction between movement direction and TS direction deviation.

### 2.3.1 Method

#### Participants

Seventeen right-handed individuals (mean age = 24.29 years; age range = 19-32 years; 4 males, 13 females) took part in the experiment. The number of participants was increased with respect to the previous experiment in order to replace the data of one participant that had to be excluded (see *Results* section for details).

#### Apparatus, Stimuli and Movements, Design, and Procedure

Everything remained the same as in Experiment 1, except that participants were asked to judge whether the TS motion was the "same" as or "different" from the RS motion, rather than "above" or "below" it. Moreover, to further prevent any form of feature overlap between the movement directions and the perceptual judgments, participants made these judgments by pressing with their left hand one of two non-vertically arranged keyboard keys. The entire experiment lasted between 45-60 minutes.

#### Data Analysis

The data analysis was identical to that of Experiment 1, except that the proportion of "same" judgments was taken as the perceptual measure and a different form of psychometric function was employed to determine the PSEs and, thereby, the size of the CE. Figure 2.4A shows the data of one participant as a function of TS direction deviation and movement direction. The basic reasoning was the same as in Experiment 1. That is, the psychometric function for downward movements should correspond to that for upward movements, but shifted to the right. It was again assumed that movement direction should not influence perceptual sensitivity and, thus, the width of the psychometric function. Given the change in perceptual measure, the PSE now corresponds to the TS direction deviation at which participants provided the maximum number of "same" judgments (see Figure 2.4A). In order to estimate this value, Equation 2.2 was chosen as the underlying psychometric function. This function is the first derivative of Equation 2.1 with one additional free parameter, $c$, that was included to allow for variations in the height of the function:

$$p = \frac{c}{b} \cdot \frac{e^{\frac{a-x}{b}}}{(1+e^{\frac{a-x}{b}})^2}, \tag{2.2}$$

where $p$ is the probability of responding "same", $x$ denotes a given TS direction deviation, $b$ is related to the width of the psychometric function (with higher values indicating a wider width), and $a$ is the value on the abscissa which leads to the maximum value on the ordinate, i.e., the PSE.

### 2.3.2 Results

The data of one participant had to be discarded because of conditions with zero observations. This resulted from more than 48% of trials being rejected, with nearly 98% thereof being trajectory failures. For the remaining participants (N = 16), the mean percentages of discarded trials were 1.62%, 1.27%, 0.49%, 4.86%, for late movements, pen lifts, movement reversals, and trajectory failures, respectively, leading to a total of 8.24% of excluded trials.

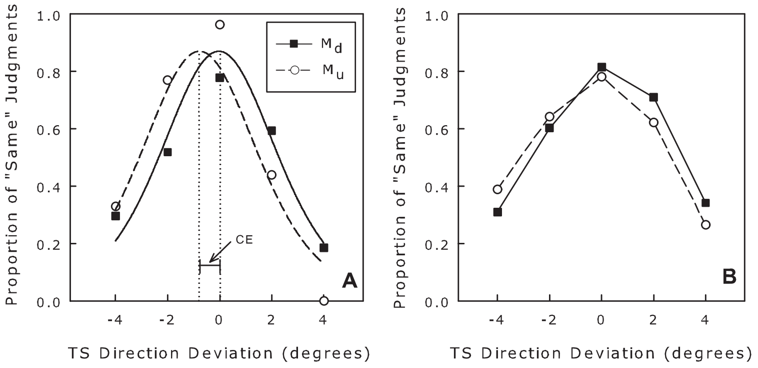

*Figure 2.4: Proportion of "same" judgments as a function of test stimulus (TS) direction deviation (-4°, -2°, 0°, +2°, +4°) and movement direction ($M_u$: upwards, $M_d$: downwards) for Experiment 2. (A) Data from one participant with the best-fitting psychometric functions and a depiction of how the contrast effect (CE) was defined (see text for details). (B) Mean proportion of "same" judgments for all participants.*

The mean proportion of "same" judgments as a function of TS direction deviation and movement direction are shown in Figure 2.4B. The probability of responding "same" decreased with increases in TS direction deviation and, more critically, was slightly higher for TS directions that deviated away from, as opposed to toward, the direction of the produced movement. Movement direction alone had no apparent effect. In accordance with these observations, the ANOVA yielded no effect of movement direction ($F(1, 15) = 2.98$, $MSE = 0.009$, $p > .10$), a significant main effect of TS direction deviation ($F(4, 60) = 65.87$, $MSE = 0.03$, $p < .001$), and a significant interaction between these two factors ($F(4, 60) = 2.95$, $MSE = 0.02$, $p < .05$).

To estimate the size of the CE in perception, we again began by fitting a "restricted" model in which only the shift parameter (i.e., the $a$ parameter in Equation 2.2) was allowed to vary between movement directions for a given participant. In doing so, acceptable fits were achieved for all participants (mean $\chi^2_{(6)} = 3.35$, $p > .20$). When comparing these fits to those obtained with a "guess" model that assumed an equal probability of "same" and "different" judgments, highly significant differences were obtained (mean $\chi^2_{(3)} = 26.85$, $p < .001$, for all participants, mean $NFI = 0.89$). Moreover, applying an "unrestricted" model in which all free parameters of Equation 2.2 were allowed to vary did not significantly improve upon the fit of the "restricted" model (mean $\chi^2_{(2)} = 0.83$, $p > .20$, for all participants, mean $NFI = 0.29$), which suggests that perceptual sensitivity as a whole did not vary with movement direction. The "restricted" model was therefore used to estimate the PSEs and the difference between the mean PSE for upward (-0.36°) and downward (0.33°) movements was significant ($t(15) = 2.52$, $p < .05$, two-tailed). The size of the CE can therefore be estimated at 0.69°.

### 2.3.3 Discussion

Experiment 2 lends further support for the notion that perceived motion directions are repulsed by produced movement directions. The expected interaction between movement direction and TS direction deviation on the proportion of "same" judgments was present, and, as in Experiment 1, the PSE for upward movements was lower than for downward movements. The estimated CE of 0.69° was also similar in size to that found in the previous experiment (0.84°). More generally, the decrease in the proportion of "same" judgments with increasing TS direction deviations indicates once again that participants could perform the judgment task required of them.

As there was no feature overlap between the perceptual judgment categories and the movement directions in this experiment, the response-bias explanation of Experiment 1 can be ruled out. Even if for some reason responding "same" became systematically associated with only upward or only downward movements, the fact that the main effect of movement direction was not significant further excludes this account.

Taken together with the findings of Experiment 1, another alternative interpretation for the CE can be discarded. According to this interpretation, perception should be facilitated or enhanced in the space surrounding the (endpoint of the) hand trajectories (e.g., see Humphreys, Riddoch, Forti, & Ackroyd, 2004; Schneider & Deubel, 2002). Although the movement trajectories were not visible to the participants, they could have nonetheless imagined what their movement trajectories would have looked like on the screen, had they been displayed. If this was case, then RS and, more critically, TS motions that deviated in the direction of the movement trajectories would have been perceived more accurately than motions that deviated away from the movement trajectories. This would lead to a decrease in the probability of judging the TS as "same" when it differed from the RS and deviated in the direction of the movement trajectory. The interaction between TS direction deviation and movement direction that was obtained in Experiment 2 could thereby be explained. However, the absence of such an interaction in Experiment 1 and, as will be seen, the consistency of the estimated CE sizes across experiments suggests that such an action-based enhancement of perception cannot, at least by itself, account for the present effects.

Experiments 1 and 2 assessed the effects of movement production on motion perception by relying on categorical judgments and fitting psychometric functions to estimate the size of the CEs. By employing TS motions that were very similar to the RS motions, the observed effects cannot be attributed to differences in the stimulus material between the reference and test phases, such as the amount of representational momentum the two motions should have induced (Freyd & Finke, 1984). Having consistently found effects under such conditions, Experiment 3 was performed to provide further converging evidence for the size of the effects obtained until now by employing a more "direct" way of measuring the CE.

## 2.4 Experiment 3: Measuring the Effect More Directly

To corroborate the size estimates of the CEs obtained in the first two experiments, a more "direct" way of measuring perceptual performance was introduced in Experiment 3. Instead of employing a TS motion that resembled the RS motion and asking participants to provide categorical judgments, the TS now consisted of a line that rotated around the previously seen RS motion direction. The participants' task was to stop the line when they felt it matched the direction of the RS motion. This measure has the advantage of providing perceptual judgments that are directly in angles. With this measure, the CE should be reflected in higher TS end angles for downward movements than for upward movements.

### 2.4.1 Method

**Participants**

Seventeen right-handed individuals (mean age = 23.06 years; age range = 18-30 years; 3 males, 14 females) participated in the experiment. As in the previous experiment, the number of participants was increased with respect to Experiment 1 in order to compensate for the loss of data from one participant (see *Results* section for details).

**Apparatus, Stimuli and Movements, Design, and Procedure**

The only changes with respect to Experiments 1 and 2 related to the nature of the TS and the associated perceptual judgment. The TS now consisted of a line composed of 5 equally spaced circles, with the first and last circle located at the start and end positions of (potential) motion trajectories. The circles were identical in size and color to the RS circle. At movement recording offset, the line appeared 15° above or below the angle of the previously presented RS motion and immediately started to rotate downwards or upwards, respectively, around the (fixed) circle located at the start position. The line moved by 0.2° every refresh of the monitor (i.e., after about 14 ms). The direction in which the line started to rotate was varied pseudo-randomly and balanced within each block. When the line had rotated 30°

(i.e., 15° beyond the angle of the RS motion), it changed direction of rotation. Participants were asked to press the space bar on the keyboard with their left hand as soon as they felt the line matched the direction of the RS motion. The experiment lasted between 30 and 55 minutes.

#### Data Analysis

The data analysis was identical to that of the previous experiments, except that the size of the CE was determined on the basis of the end angles at which the TS line motions were stopped by the participants. These *perceived* angles were computed separately for each movement direction (and, as before, averaged across RS directions) and submitted to a one-way repeated-measures ANOVA with movement direction (upward, downward) as the within-participant factor.

### 2.4.2 Results

One participant was excluded because of conditions with zero observations due to more than 64% of excluded trials. Nearly 90% thereof were trajectory failures. For the remaining participants (N = 16), the mean percentages of excluded trials were 0.40%, 0.97%, 0.60%, and 16.02%, for late movements, pen lifts, movement reversals, and trajectory failures, respectively, resulting in a total of 17.98% discarded trials.

Downward movements led to higher perceived angles (-0.36°) than upward movements (-0.97°) and the ANOVA revealed that this difference of 0.61° was significant ($F(1, 15) = 5.38$, $MSE = 0.56$, $p < .05$).

### 2.4.3 Discussion

Using a more "direct" perceptual measure, Experiment 3 once again shows that the direction of a produced movement has a repulsing effect on the direction of perceived motions. The perceived motion angles were lower for upward than downward movements and the estimated CE of 0.61° was similar in size to those found in Experiments 1 (0.84°) and 2 (0.69°). This conclusion is supported by the absence of a main of effect of Experiment when the CE estimates were submitted to an additional one-way between-participants ANOVA ($F(2, 43) = 0.13$, $MSE = 1.51$, $p > .80$). The fact that the observed effect sizes did not differ across experiments points to the reliability of the different perceptual measures that were employed.

## 2.5 Discussion of Establishing a Contrast Effect

As others have already shown for the perception of amplitude (Schubö et al., 2001, 2004) and weight (Hamilton et al., 2004), the present experiments demonstrate that perceived motion directions are also subject to specific interference effects from concurrently produced movements. Consistent with those studies, a CE was obtained in that perceived motion directions were repulsed by simultaneously produced movement directions. Moreover, the estimated size of the CEs was similar across experiments, despite the use of different types of perceptual measures. This latter result points to the robustness of the effect and allowed us to exclude various interpretations of the CE. In particular, that it may reflect a judgment bias induced by a categorical overlap between movement and perceptual judgment categories or an action-based enhancement of perceptual processing in the space surrounding the (endpoint of the) movement trajectories.

Unlike previous studies (Hamilton et al., 2004; Schubö et al., 2001, 2004), the current findings also show that such effects are not tied to the perceptual processing of biological motion. It points therefore to the generality of the CE in concurrent action-perception paradigms. This result is noteworthy because biological motions are known to be processed differently than non-biological motions (e.g., Viviani, 2002) and it has been argued that perception-action interactions of this type may relate to the involvement of the motor system in the processing of biological motion (Hamilton et al., 2004; Jacobs & Shiffrar, 2005; Kilner et al., 2003; Wolpert et al., 2003).

For example, in the context of weight perception, Hamilton et al. (2004) accounted for their CE by proposing that there are multiple weight modules (one for each weight) that play a role in the perception and production of actions (see Section 1.5.4). Each of these modules is responsible for generating a prediction of the kinematics associated with lifting/holding a corresponding weight. The predictions of each module are then compared to the kinematics of observed lifting movements and the resultant discrepancies provide the basis for the perceptual judgment. However, to the extent that the comparison process is tied to the prediction of biological motion, it is unclear how this model would deal with visual motions that have non-biological velocity profiles.

As discussed in Section 1.5.3, an alternative account of CEs was proposed by Schubö et al. (2001). Although they also employed biological stimulus motion, their model was not formulated in a way that is specific to biological motion processing. According to their model, movements and motions activate common codes. Overlap of activated codes then leads to the observed CE. Figure 2.5 illustrates an adaptation of their model for the overlapping movement/motion dimension of direction (instead of the original dimension of amplitude). In the model, overlap between common codes that gradually represent the directions

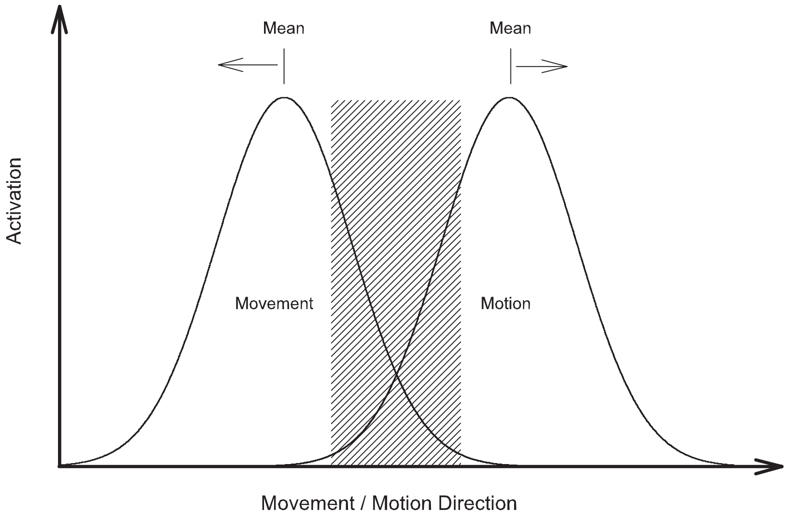

*Figure 2.5: A depiction of the model proposed by Schubö et al. (2001) for the overlapping movement/motion dimension of direction.*

of the movement and motion leads to inhibition of these overlapping codes. Therefore, the activation curves for movement and motion directions are biased away from each other.

The applicability of these two models to the present data may ultimately depend on assumptions related to biological motion processing. However, their merit should also be evaluated on the basis of specific predictions. For example, both models make a strong claim about the CE that has yet to be tested: The size of the CEs should increase monotonically with the amount of similarity (feature overlap) between what is produced and perceived. This "distance prediction" is of interest because it is consistent with a well-studied perception-perception interference effect: The motion repulsion effect (Marshak & Sekuler, 1979). This phenomenon refers to the finding that the directions of two simultaneously presented visual motions have a contrasting effect on each other, i.e., the angle between the two motion directions is perceived as bigger than it actually is. It has also been shown that the size of the motion repulsion effect depends on the angular distance between two motions/lines, with larger distances leading to smaller repulsion effects (Marshak & Sekuler, 1979; Rauber & Treue, 1999; Patterson & Becker, 1996; Westheimer, 1990). Thus, an aim of the later experiments will be to test this prediction for action-perception interactions and, thereby, determine to what degree it relates to its perception-perception interaction counterpart. In this way, it may be possible to integrate models of specific interference in the perceptual domain and across the perceptual and action domains.

# Chapter 3

# Testing for Other Influences than Hand Movements

The next experiment was designed to explore the influence of eye-movements on the CE. One could argue that the CE was a result of eye-movements that co-occurred with the hand movements and not caused by the hand movements themselves. Indeed, eye and hand movements seem to be linked (e.g., Carey, 2000; Gribble, Everling, Ford, & Mattar, 2002). To test whether eye-movements are a prerequisite for the CE to occur, participants in Experiment 4 were asked to always fixate the RS starting position. Their compliance with the instruction was assessed with an eye-tracking system. In particular, we checked that participants did not produce horizontal eye-movements when performing rightward/leftward or upward/downward movements, to exclude that participants' eyes followed their hands or the RS. In addition to earlier experiments, we also wanted to test for an influence of perception on produced end angles. To this end, in half of the trials no RS motion was presented. This allowed to compare produced end angles when a RS motion was present versus when no motion was present.

## 3.1 Experiment 4: Excluding Eye-Movements

### 3.1.1 Method

#### Participants

Twenty-six right-handed individuals (mean age = 26.50 years; age range = 17-34 years; 11 males, 15 females) participated in the experiment.

### Apparatus

In addition to the apparatus employed until now, a Skalar IRIS Eye-Tracker was used to measure horizontal eye-movements. The output of the eye-tracker was monitored online by the experimenter and fixation errors, i.e., eye-movements that corresponded to more than 0.6 cm on the screen, were entered directly into the data file via a keyboard. To avoid interference with participants' response participants reacted by pressing a separate response button in response to the test stimulus. The participants' head position was fixed with a chin-rest that was placed 50 cm in front of the computer screen.

### Stimuli and Movements, Design, and Procedure

The differences between the current experiment and the former were that two additional variables, setup condition (vertical/horizontal) and trial type (motion/no-motion), were varied. For half of the participants the RS motions moved to the right as in earlier experiments (horizontal condition). For the other half, the RS motions were rotated by 90° counterclockwise (vertical condition in Figure 3.1) and therefore moved upwards. For half of the trials (motion trials), the RS motions deviated either by +4°, or -4° from the horizontal/vertical midline. For the other half (no motion trials), no RS motion was present. In no motion trials, no TS was shown and participants started the next trial with a button press. In the horizontal setup condition, the start position of the circle was always vertically centered and shifted 7.5 cm to the left of the vertical midline of the display area. In the vertical setup condition the start position was horizontally centered and shifted by 7.5 cm below the horizontal midline. The required movement angles were either 30° above or below the horizontal midline to the right (horizontal setup condition) or 60° to the right or left of the vertical midline (vertical setup condition). In this way, the required movement direction for rightward movements in the vertical condition corresponded to the required direction for upward movements in the horizontal condition. The required movement length was 15 cm. Three blocks of 24 trials were run for each movement direction. Participants started a trial by moving with their pen the cursor in the RS start position which this time was additionally marked by a fixation cross. This fixation cross remained until the end of the RS motion. Participants were instructed to move their eyes to this cross and stay there as long as the fixation mark was visible. Before each block, the eye-tracker was recalibrated by asking the participant to sequentially fixate three different horizontal locations marked by the fixation cross. The distance between these adjacent fixation marks on the screen was 3.5 cm. Additionally, prior to each block, except for the first block with a new movement direction, 5 practice-trials were run.

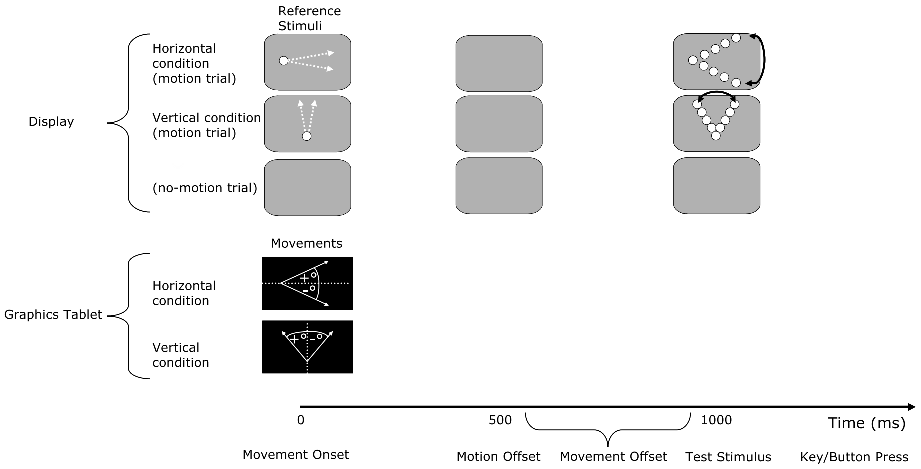

*Figure 3.1: The paradigm employed in Experiment 4. Each trial started with a hand movement on the graphics tablet. The onset of the hand movement triggered the reference stimulus motion on the screen. Motion trials are illustrated by two example motions. In the experiment, however, only one motion was presented at a time. Participants were told to finish their hand movements after reference stimulus motion offset but prior to the test stimulus which occurred at 1000 ms after movement onset. Participants were asked to stop the rotating line by a button press when the rotating line seemed to match the last reference stimulus.*

### Data Analysis

Angles were coded relative to the horizontal midline in the horizontal setup condition and relative to the vertical midline in the vertical condition. The data analysis was the same as for earlier experiments, except that trials were also excluded when eye-movements occurred that corresponded to more than 0.6 cm on the screen (fixation error), or the difference between perceived and RS angle was larger than 5° or the response occurred earlier than 200 ms after the TS started its rotation[6] (concentration failure).

### Influence of Motion Perception on Movement Production

To assess the influence of motion perception on movement production, first, absolute produced end angles were calculated relative to the horizontal midline in the horizontal condition, and relative to the vertical midline in the vertical condition. The mean of these absolute end angles was then computed for each movement direction, trial type, and participant separately. In the horizontal condition, these mean absolute end angles of upward and downward movements were added. The same was done for rightward and leftward movements in the

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[6] The conclusions based on the data reported in the following do not change if the analysis is done without the 5° rejection criterion.

vertical condition. To calculate the CE in production, added values of no-motion trials were subtracted from added values of motion trials. Finally, an ANOVA on the added values with trial type as a within-participant factor and setup condition as a between participant factor was calculated to assess the influence of the RS motion on the produced trajectory direction. Significant interactions were followed up by performing repeated-measures ANOVAs for each setup condition separately.

#### Influence of Movement Production on Motion Perception

The CE in perception was calculated by subtracting the mean perceived angles of upward movements from the mean perceived angles of downward movements in the horizontal condition. Similarly, to obtain the CE in the vertical condition, mean perceived angles of leftward movements were subtracted from mean perceived angles of rightward movements. To detect a change in motion perception as a function of movement direction, an ANOVA on mean perceived angles with movement direction as a within participant factor and setup condition as a between participant factor was computed across participants.

### 3.1.2 Results

The data of two participants had to be excluded because of conditions with zero observations. In one case, this resulted from about 64% excluded trials, with 97% thereof beeing concentration failures. In the other case, there were about 49% excluded trials, with 26% thereof being fixation failures and 68% beeing concentration failures. For the remaining participants (N=24) the following percentages of excluded trials were observed, 4.03%, 0.41%, 0.22%, 6.66%, 7.69%, 6.71% for late movements, pen lifts, movement reversals, trajectory failures, concentration failures, and fixation errors, respectively, resulting in a total percentage of discarded trials of 25.66%.

#### Produced Movements

Figure 3.2 shows the CEs for the produced end angles (empty circles). As can be seen from Figure 3.2, the size of the CEs differed between the horizontal and vertical setup condition. As the positive CE values show, participants' movements veered away from the observed motion in motion trials compared to no-motion trials. This pattern was confirmed by a significant main effect of setup condition ($F(1, 22) = 359.82$, $MSE = 104.33$, $p < .001$) and of trial type ($F(1, 22) = 45.27$, $MSE = 2.23$, $p < .001$) that was modified by an interaction between trial type and setup condition ($F(1, 22) = 5.29$, $MSE = 2.23$, $p < .05$). Two follow-

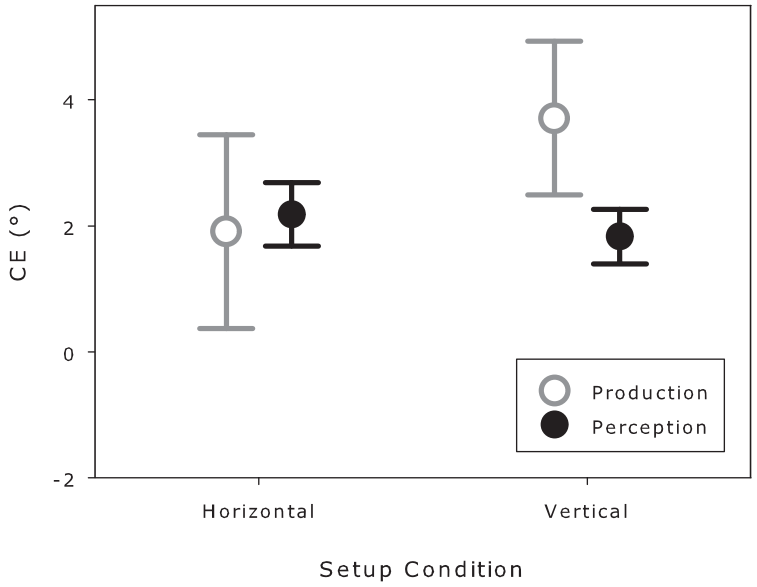

*Figure 3.2: Size of the CEs as a function of setup condition for production and perception. Whiskers indicate 95% confidence intervals.*

up ANOVAs showed that the CEs were significant for the horizontal ($F(1, 11) = 7.43$, $MSE = 2.94$, $p < .05$) and vertical ($F(1, 11) = 59.92$, $MSE = 1.52$, $p < .001$) setup conditions.

**Perceived Motions**

Figure 3.2 also shows the CEs in perception (filled circles). The positive CE values show that perceived angles were higher for downward than upward movements and for rightward than leftward movements. The size of the CEs were similar in both setup conditions. This finding was reflected in a significant main effect of movement direction ($F(1, 22) = 94.15$, $MSE = .60$, $p < .001$), and the absence of a significant effect of setup condition ($F(1, 22) = .74$, $MSE = .81$, $p > .10$), or an interaction between movement direction and setup condition ($F(1, 22) = .01$, $MSE = .60$, $p > .10$).

### 3.1.3 Discussion

For the produced movements, a trivial main effect of setup condition was found, which simply reflected that different end angles had to be produced in the two conditions. Even though the setup condition and trial type variables interacted, follow-up analysis showed that the CE was found for both setup conditions. The variability in CE size could be attributed to differences between upward and downward versus leftward and rightward movements.

By comparing the perceived angles for the two movement conditions, a CE was found in the perceptual measure that was not modulated by setup condition. Importantly, for the first time, it was possible to show an influence of perception on action and of action on perception in the same experiment. Therefore, this paradigm will be used in Experiment 6 to test the mutual interference prediction.

In sum, even though participants were instructed to fixate the RS start position and their compliance was controlled with an eye-tracker, a significant CE in action and in perception was obtained.

## 3.2 Experiment 5: Testing the Influence of Memory Processes

An issue that none of earlier studies on the specific influence of action on perception has fully addressed is the contribution of short-term memory processes. This issue merits further attention because it is known that effects of this type are influenced by such processes. For example, when Schubö et al. (2004) increased the interval between the presentation of the stimulus motions and the assessment of how participants had perceived them, the CE obtained by Schubö et al. (2001) turned into an assimilation effect (i.e., an attraction of produced on perceived amplitudes). It has also been shown that action production can have an assimilatory effect on visual short-term memory. Kerzel (2001) asked participants to first observe stimulus motions that could vary in velocity, then produce a fast or slow movement, and subsequently judge the velocity of the previously seen motion. The results revealed that the remembered velocities were biased in the direction of produced velocities.

Surprisingly, no study has tested whether the CE also arises without a delay between the concurrent events and when the measurement of the CE is obtained. In fact, all paradigms have relied on perceptual judgments that were provided without speed stress and after the movement and motions were completed. It is therefore unclear if and in what way action-based influences on short-term memory, rather than on perception, might have contributed to the observed effects (for a similar argument in context of research on inattentional blindness, see Moore, Grosjean, & Lleras, 2003). In light of this, we sought to minimize the influence of short-term memory processes by investigating the *online* influence of action on perception. The term "online" is used here to refer to the fact that perceptual performance was assessed under speed stress and while the stimulus motion was still in progress.

To address this issue, we changed the way perceptual performance was assessed. We asked participants to perform hand movements either to the left or right while monitoring the motion of a stimulus. In most trials, the stimulus moved vertically before unpredictably deviating to the left or right. The task of the participants was to press a button with their non-moving hand as soon as they detected a deviation in motion direction. The direction of the deviation was either compatible with the hand movement direction (e.g., both went to the right) or incompatible. If action leads to an AE in perception, compatible conditions should lead to a stronger experienced deviation in the direction of the hand movement and reaction times should be shorter compared to incompatible conditions. Conversely, if action leads to a CE in perception, as indicated by the repulsion effects obtained by Hamilton et al. (2004), Schubö et al. (2001) and the experiments reported here, this reaction-time pattern should be reversed.

### 3.2.1 Method

#### Participants

Sixteen right-handed individuals (age range 21-31 years) were paid for their participation.

#### Stimuli, Movements, and Apparatus

The stimulus motions consisted of a red circle (6 mm in diameter) that moved on a black background without leaving a trace. The length and duration of the motions were 20 cm and 1000 ms, respectively. The motions always started from a position that was horizontally centered and shifted 10 cm below the horizontal midline of the monitor. As Figure 3.3 illustrates, the motions followed one of nine trajectories with equal probability: straight upwards without changing direction, straight upwards before deviating 5° to the left or right at 0, 250, 500, or 750 ms after motion onset. The circle subtended 0.57° of visual angle and moved at a constant speed of $18.92\frac{\circ}{s}$, at the approximate viewing distance of 60 cm.

The same setup as in the earlier experiments was used to record the movements of a hand-held stylus. The required movements consisted of 20 cm straight-line trajectories that were directed 45° to left or right of the participants' body midline. Movements were always performed with the right hand. Participants held a response box in their left hand to indicate the moment at which they perceived a change in stimulus motion direction.

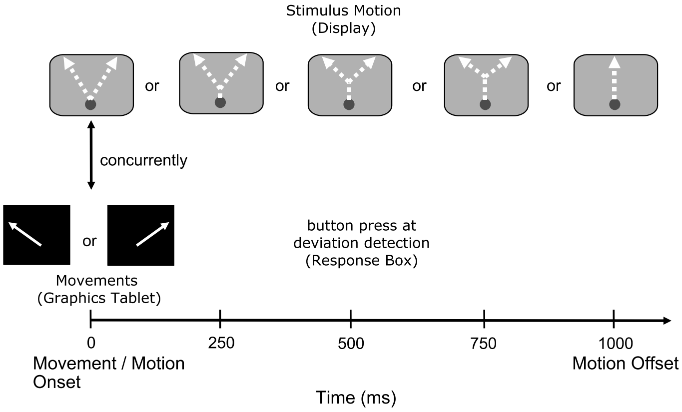

*Figure 3.3: The paradigm employed in Experiment 5. While participants performed straight-line hand movements that deviated 45° to the left or right, they were asked to observe a stimulus motion and make a speeded response as soon as the motion deviated from its initial direction. The deviation occurred with equal probability 5° to the left or right of vertical after 0, 250, 500, 750 ms, or not at all (the angles are exaggerated in the figure for the purpose of illustration.)*

### Design

Movement direction (left, right), deviation direction (DD; left, right) and direction deviation time (DDT; 0, 250, 500, 750 ms) were manipulated within participants. Movement direction was blocked and counterbalanced across participants, with each movement direction being performed for eight consecutive blocks. In each block, all eight DD x DDT combinations + one catch trial (in which no motion deviation occurred) appeared twice in a pseudorandom order. This amounted to a total of 288 trials.

### Procedure

Prior to every block, participants practiced the leftward or rightward hand movements with the help of a display that depicted the required and actually produced trajectories. This feedback display was only provided between practice trials.

In the experimental blocks, the task of the participants was to press a button on the response box as soon as they detected a change in stimulus motion direction while concurrently performing the required movement with their other hand. The trial structure was the same as in earlier experiments except that the stimulus motions lasted for 1000 ms and the movements phase ended after 2000 ms. Accordingly, the motion and recording offset tones were played after 1000 ms and 2000 ms. If participants lifted the pen, reversed movement direction, or pressed the button less than 150 ms or more than 1000 ms after the DDT, an error message to that effect was shown. The next trial started after a 1000 ms interval.

#### Data Analysis

Reaction Time (RT) was measured relative to DDT. In addition to the exclusion criteria of Experiment 1-3, trials were also discarded when RTs were shorter than 150 ms (anticipation) or longer than 1500 ms (miss). Catch trials were not analyzed. Movement analysis was the same as in Experiments 1-3. To establish the influence of produced movement direction on perceived motion direction, trials were classified as *compatible* when movement and deviation directions corresponded (e.g., both were leftward) or as *incompatible* when they did not. Mean RTs were then submitted to a two-way repeated-measures ANOVA with Compatibility (compatible, incompatible) and DDT (0, 250, 500, 750 ms) as within-participant factors.

### 3.2.2 Results

The mean percentages of excluded trials were 0.27%, 1.49%, 0.95%, 0.59%, 3.49%, 3.98% for late movements, lifts, reversals, trajectory failures, anticipations, and misses, respectively, resulting in a total of 13.72% discarded trials.

#### Reaction Times

Table 3.1 presents mean RT as a function of DDT and compatibility. As can be seen, RTs decreased with DDT. More importantly, RTs were higher for compatible than incompatible conditions and the size of this compatibility effect decreased with DDT (see Figure 3.4). In support of these observations, there was a significant main effect of DDT ($F(3, 45) = 234.74$, $MSE = 7019.88$, $p < .001$), Compatibility ($F(1, 15) = 17.79$, $MSE = 1346.41$, $p = .001$), and a significant interaction between these two factors ($F(3, 45) = 9.29$, $MSE = 1133.15$, $p = .001$). The 95% confidence intervals in Figure 3.4 reveal that the compatibility effect was significant at DDTs of 0 and 250 ms, but not thereafter.

#### Anticipations and Misses

Table 3.1 also contains the percentage of anticipations and misses. When the same ANOVA as above was performed on these measures, no evidence of any speed-accuracy tradeoffs involving the factor Compatibility was obtained.

*Table 3.1: Mean Reaction Time (in ms), Anticipations (in %), and Misses (in %) as a Function of Direction Deviation Time (0, 250, 500, 750 ms) and Compatibility (Compatible [C], Incompatible [I]).*

| | Direction Deviation Time | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | | 250 | | 500 | | 750 | |
| | C | I | C | I | C | I | C | I |
| Reaction Time | 912 | 848 | 717 | 682 | 578 | 569 | 523 | 521 |
| Anticipations | 2.34 | 2.34 | 1.56 | 2.93 | 1.95 | 2.73 | 7.23 | 6.84 |
| Misses | 7.03 | 1.17 | 2.93 | 1.56 | 1.17 | 0.78 | 10.16 | 7.03 |

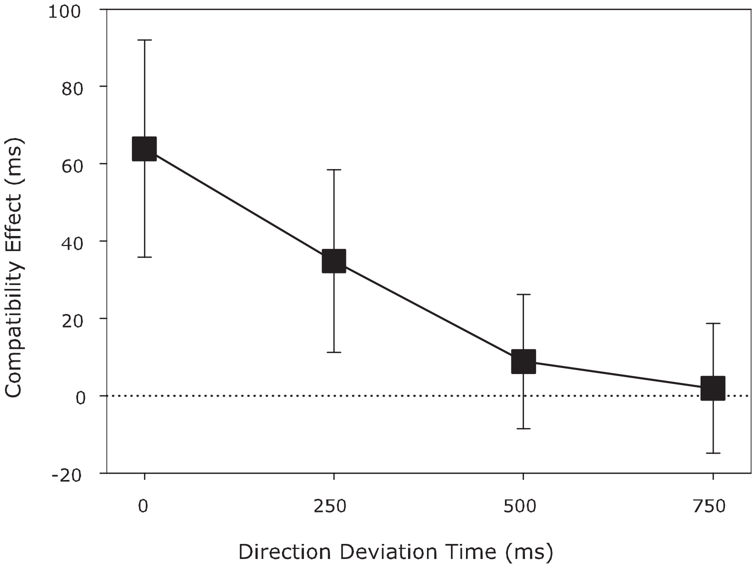

*Figure 3.4: The size of the compatibility effect (= compatible minus incompatible mean reaction times) as a function of direction deviation time. Whiskers correspond to 95% confidence intervals.*

### 3.2.3 Discussion

The present findings demonstrate that produced movement directions interfere with concurrently perceived motion directions. Motion deviations were detected later when they deviated in a direction that was compatible with that of the movements. This reversed compatibility effect suggests that perceived directions were repulsed by produced directions, which led to a delay in detecting the moment at which the motions diverged from their original (i.e., vertical) direction. As proposed by Schubö et al. (2001) and Hamilton et al.

(2004), this repulsion (contrast) effect could reflect the inhibition or occupation of common codes/modules employed by perception and action.

By employing an online measure, the current results go beyond existing ones (e.g., Hamilton et al., 2004; Müsseler & Hommel, 1997; Schubö et al., 2001) by showing that interference of this type occurs during perceptual processing, as opposed to in short-term memory. Mean RT in the 0 ms DDT condition was 880 ms, which indicates that most responses in this condition were provided prior to motion offset (i.e., at 1000 ms). Thus, the contribution of action-based influences on short-term memory processes were at a minimum. Moreover, the observation that the compatibility effect decreased with DDT further supports the notion that movement production had an online influence on perceptual processing. Indeed, the later the motion deviation occurred, the higher the probability that it was detected following motion offset. This points to the importance of ongoing visual processing for the occurrence of the reversed compatibility effect.

A result that was not considered until now was that overall mean RTs decreased with DDT. There are at least three possible explanations for this effect. First, as is typically observed in paradigms with variable foreperiods between warning and imperative stimuli (in our case, motion onset and deviation, respectively), RTs decrease with the amount of unspecific preparation (e.g., Niemi & Näätänen, 1981). However, foreperiod effects are typically smaller than the RT decrease observed here. According to the second explanation, the amount of dual-task-like interference (e.g., Pashler, 1994) was reduced for longer DDTs because motions and/or movements were already completed at the time of responding. Third, it is likely that more attention was required for initiating the hand movement and therefore less attention was available for the detection task (e.g., Posner & Keele, 1969). Importantly, none of these explanations are mutually exclusive.

# Chapter 4

# Testing the Model Predictions

Having established the CE and excluded alternative interpretations to an interaction between hand movements and visual motion perception, the following experiments tested the predictions derived from the Schubö and Hamilton models in Sections 1.5.3 and 1.5.4. One prediction was that, according to the Schubö model, mutual interferences exist between action and perception. Furthermore, a monotonic relationship should hold between the CEs found in action and perception. The following experiment was designed to address this question.

## 4.1 Experiment 6: Testing the Mutual Interference Prediction

One problem of the study of Schubö et al. (2001) was that in a given experiment either a measure for the influence on perception or a measure for the influence on action was available but not for both at the same time. This was due to the use of an action to measure the influence on perception. To avoid this problem, the paradigm employed in Experiment 4 was chosen because it allowed to obtain a measure of the CEs in action and perception within the same experiment. That is, the difference in added mean produced absolute end angles for motion and no-motion trials was chosen to measure the CE in movement production; the difference in perceived angles between the two movement directions provided a measure of the CE in perception. By obtaining both measures in the same experiment, it was possible to establish the sizes of these effects and to evaluate whether a relationship existed between the influences on action and on perception.

The question of how this relationship should be statistically assessed depends on what causes the variability in the CE measures for perception and action. The Schubö model is neutral to the question as to whether the amount of code overlap differs from trial to trial or between participants. In the first case, different amounts of overlap would be reflected in different sizes of interference in each trial. In the second case, different amounts of overlap would be reflected in different sizes of interference across participants. Accordingly, within or across participants correlations should be used.

In the case that the amount of code overlap does not vary from trial to trial, the interference effect for a given stimulus configuration can be assumed to stay constant within a participant. Inter-trial variability should then only be caused by noise. Therefore, in a given trial i, the produced movement direction ($R_{A_i}$) is a function of the instructed direction of the hand trajectories ($I_A$), interference from perception ($\alpha_A$), and noise ($\varepsilon_i$). Similarly, the perceived direction ($R_{P_i}$) is given by the veridical RS direction ($I_P$), interference from action ($\alpha_P$), and noise ($\varepsilon_i$). Formally, $R_{A_i} = I_A + \alpha_A + \varepsilon_i$ for the produced direction and $R_{P_i} = I_P + \alpha_P + \varepsilon_i$ for the perceived direction in trial i. As mentioned above, $I_A$ and $I_P$ are assumed to be constant for a given participant within a condition. Furthermore, the way the CEs are calculated would cancel an influence of $I_A$ and $I_P$. $\varepsilon_i$ on the other hand varies from trial to trial and produces the inter-trial variability. Under the assumption that $\varepsilon$ follows a random normal distribution, its influence should cancel out across trials. Hence, differences in the interference terms *between* participants would cause differences in participants' mean $R_{A_i}$ and $R_{P_i}$. Therefore, to assess whether a monotonic relationship between the interference terms in action and perception $\alpha_A$ and $\alpha_P$ holds, the CEs in action and perception should be correlated across participants.

In the case that the amount of overlapping codes varies randomly from trial-to-trial, the inter-trial variability in the perceptual and motor measures is at least partly caused by it. To indicate this variability in interference sizes across trials, $\alpha_A$ is additionally indexed by i: $R_{A_i} = I_A + \alpha_{A_i} + \varepsilon_i$ for the produced direction, $R_{P_i} = I_P + \alpha_{P_i} + \varepsilon_i$ for the perceived direction in trial i. Under the assumption that the size of $\varepsilon$ is rather small compared to the size of the $\alpha$s, a monotonic relationship between $\alpha_P$ and $\alpha_A$ should be detectable by a within-participant correlation across trials.

As mentioned above, the Schubö model does not specify whether the amount of code overlap changes from trial to trial or not. Furthermore, these two possibilities are not mutually exclusive. To increase the chance of detecting a relationship in the following experiments, both correlation measures, across and within-participants, were calculated.

### 4.1.1 Method

#### Participants

Twenty-four right-handed individuals (mean age = 24.88 years; age range = 20-35 years; 3 males, 21 females) participated in the experiment.

#### Apparatus, Stimuli and Movements

The same apparatus as in earlier experiments was used. The required trajectories were straight lines that deviated, depending on the condition, either by 25° upward or downward from the horizontal midline (see lower left part of Figure 3.1). The required trajectory and RS motion lengths were set at 20 cm. At the approximate viewing distance of 60 cm the trajectory length corresponded to 18.92° of visual angle. The RS motion started its trajectory vertically centered and 10 cm to the left of the vertical midline of the display area. The circle moved at a constant speed of $37.84\frac{\circ}{s}$. RS direction was manipulated between participants and was 4° above, 4° below, or along the the horizontal midline for the same number of participants. TSs were the same as in Experiments 3 and 4.

#### Design

Movement direction (upward, downward) and trial type (motion, no-motion) were manipulated within participants. Between participants, the RS motion angle (+4°, 0, -4°) was varied. Participants either performed downward movements for the first 6 blocks and then switched to upward movements for the last 6 blocks or followed the reverse sequence. The order of the movement direction was balanced across participants. Each block consisted of 20 pseudo-randomly arranged trials. Within a block, trial type × TS starting direction was balanced across trials. Each participant performed a total of 240 trials.

#### Procedure

The procedure was the same as in Experiment 4 except for the absence of eye-tracking related fixation marks and calibrations. The entire experiment lasted between 55-90 minutes.

#### Data Analysis

Data analysis resembled that of Experiment 4. In particular, mean produced absolute end angles were calculated for each movement direction, trial type, and participant separately.

These mean absolute end angles of downward and upward movements were subsequently added. The difference in these added values between motion and no-motion trials was then used as a measure for the CE in production. Finally, a paired-t-test on the added values between motion and no-motion trials was calculated to assess the influence of trial type on the produced trajectory direction. To obtain a measure of the CE in perception, mean perceived end angles of upward movements were subtracted from mean perceived end angles of downward movements. In order to detect a change in motion perception as a function of movement direction, a paired-t-test on mean perceived angles between upward and downward movements was computed across participants.

#### Relationship between Interference on Production and Perception

Because the Schubö model predicts a monotonic relationship between the CE sizes in action and perception, Spearman's rank correlation coefficient was used. This coefficient involves the conversion of values into a rank order and therefore tests for a monotonic relationship.

To obtain a measure of the relationship across participants, mean CEs in produced and perceived angles were correlated across participants. In addition, to obtain the statistics for within-participant correlations, the produced and perceived angles were correlated across motion trials for each movement direction separately. Downward movements were coded with negative angles and upward movements with positive angles. In this way, for upward and for downward movements, a negative correlation would indicate that high CEs in production co-occurred with high CEs in perception and low CEs in production co-occurred with low CEs in perception. For each condition of movement direction and participant, the Spearman's rank correlation coefficient $\rho$ was t-value transformed ( $t = \frac{\rho}{\sqrt{(1-\rho^2)/(n-2)}}$). Then, one-sample student's t-tests on these values were calculated for the two movement setup conditions separately.

### 4.1.2 Results

The mean percentages of excluded trials were 3.44%, 0.28%, 0.19%, 1.60%, and 3.21% for late movements, pen lifts, movement reversals, trajectory failures, and concentration failures, respectively, resulting in a total percentage of discarded trials of 8.72%.

#### Produced Movements

Table 4.1 shows the mean produced absolute end angles for each movement condition. As can be seen, participants were indeed able to produce the required trajectory, albeit not

*Table 4.1: Mean produced absolute end angles and perceived angles for Experiment 6. Produced end angles are displayed as a function of required movement direction (d/u). The produced end angles are collapsed across motion and no-motion trials. Perceived angles are shown as a function of RS angles (-4, 0 , 4). Angles are coded relative to the horizontal midline (see lower-right part of Figure 3.1). d = downward, u = upward.*

| | Prod. End Angles | | Perceived Angles | | |
|---|---|---|---|---|---|
| Trajectory | d | u | -4 | 0 | 4 |
| | 27.84 | 29.10 | -4.27 | -.33 | 3.61 |

perfectly. Figure 4.1 shows the CE, for upward and downward movements (empty circles for the 25° required movements). As can be seen from the positive CE value of Figure 4.1 in the 25° condition, participants' movements veered away from the seen motion in motion trials compared to no-motion trials. This pattern was confirmed by a significant paired t test ($t(23) = 3.98$, $p < .01$).

### Perceived Motions

Table 4.1 shows the mean perceived angles for each RS condition. In Figure 4.1 the difference in mean perceived angles between downward and upward movements, i.e., the CE is drawn (filled circles for the 25° condition). As the positive CE value shows, the perceived angles were higher for downward than upward movements. This finding was reflected in a significant effect of movement direction ($t(23) = 3.46$, $p < .01$).

### Relationship between Interference on Production and Perception

Figure 4.2 shows the correlation across participants between the CEs in production and perception. As can be seen from the figure, no systematic relationship held between the size of the interference effect on action and on perception across participants. This was statistically confirmed by a non-significant correlation value of 0.16 ($p = .45$).

The mean within-participant $\rho$ across all participants and both movement conditions was -0.01. The t-transformed $\rho$ coefficients did not differ from zero when one-sampled t-tests against zero were performed for downwards and upwards movements, respectively ($t(23) = -.15$, $p = .88$; $t(23) = -.62$, $p = .54$).

## 4.1.3 Discussion

With this experiment it was possible to obtain a CE in both action and in perception, i.e., hand movements veered away from displayed motion directions and perceived directions

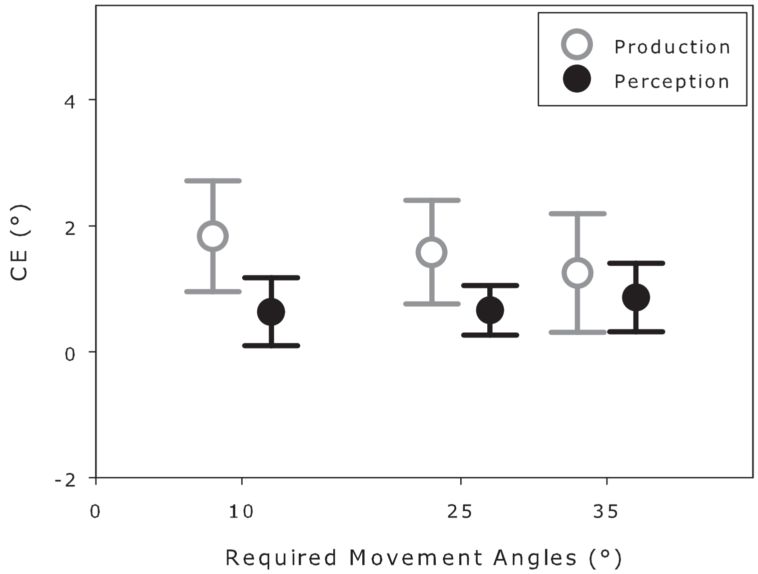

*Figure 4.1: Size of the CEs in perception and production as a function of required movement angles for Experiments 6 (25° required movements) and 7 (10° and 35° required movements), measured relative to the horizontal midline. Whiskers indicate 95% confidence intervals.*

were repulsed by concurrent movements. This mutual interference was predicted by the Schubö model. In contrast to the mutual interference prediction of the Schubö model however, no systematic relationship between the sizes of the CEs in action and perception was found. This indicates that the interference effects were either not caused by the same underlying codes or that the variability in CE size is mostly determined by variables unrelated to the representation that underlies the interference, like for example, encoding, motor, or motivational variables. These unrelated variables could either vary within participants or could be constant for a participant but vary across participants. The former case could explain the variance in the size of the CEs within participants, the latter case could explain the variance across participants.

## 4.2 Experiment 7: Testing the Distance Prediction

Experiment 7 tested the distance prediction of the Schubö and the Hamilton model. Both models predict that with increasing distance between action and perception on the dimension along which the interference occurs, the size of the interference effect should decrease.

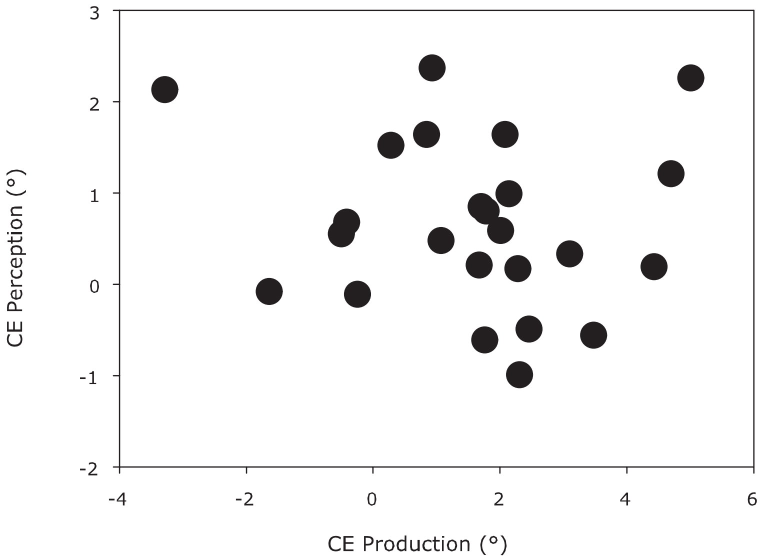

*Figure 4.2: Size of the CE in perception plotted as a function of the size of the CE on production for Experiment 6.*

Accordingly, the angular distance between produced movements and perceived motions was varied and it was determined whether the size of the CE changes as a function of distance.

### 4.2.1 Method

**Participants**

Twenty-seven right-handed individuals (mean age = 24.50 years; age range = 18-34 years; 7 males, 21 females) participated in the experiment.

**Apparatus, Stimuli and Movements, Design, and Procedure**

The experimental setup was the same as for Experiment 6 except that only two RS motion directions (+4°, -4°) were used and participants performed 4 different hand trajectories. In the small distance condition, participants performed movements deviating by 10° above or below the horizontal midline. The large distance condition consisted of movements deviating by 35°. The two distances were blocked and balanced across participants. Each of the 4 directions were performed for 3 consecutive blocks, giving again a total of 240 trials. On average 20 trials were needed to complete training and the experiment lasted between 60 and 95 minutes.

#### Data Analysis

The data was subjected to the same procedure as in the last experiment except that trajectory failures were defined as movements that deviated by more than 5° from the required angles towards the horizontal midline or more than 20° away from it.

#### Influence of Motion Perception on Movement Production

To assess the influence of motion perception on movement production, again added mean absolute end angles of downward and upward movements were calculated. Then, a two-way repeated-measures ANOVA on these values with the within participant factors distance (small, large) and trial type (motion, no-motion) was calculated.

#### Influence of Movement Production on Motion Perception

To detect a change in motion perception as a function of movement production, a two-way repeated-measures ANOVA on mean perceived angles was computed with the within participant factors distance (small, large) and movement direction (upwards, downwards).

#### Relationship between CEs in Perception and Production

To test whether a systematic relationship between CEs in perception and production existed, the same correlations as in the last experiment were calculated for each distance condition separately.

### 4.2.2 Results

The data of three participants had to be excluded. One participant was excluded because of a technical problem. The other two were excluded because, after applying the exclusion criteria, some conditions had zero observations. These zero observation conditions resulted in both cases from about 48% excluded trials that were mainly due to concentration failures (88%). For the remaining participants (N=24), the mean percentages of excluded trials were: 3.39%, 1.94%, 1.60%, 4.93%, and 4.79% for late movements, pen lifts, movement reversals, trajectory failures, and concentration failures, respectively, resulting in a total percentage of discarded trials of 16.65%.

### Produced Movements

Table 4.2 shows the mean produced absolute end angles for each movement direction and distance condition for this and the following Experiments. Figure 4.1 shows the difference in added mean end angles for motion and no-motion trials. As can be seen from Figure 4.1, a CE was obtained for the 10° and 35° required movement conditions. As the similar CE values show, this influence of trial type was not modulated by the distance between the movements and motions. These observations were confirmed by a significant main effect of trial type on mean movement end angle ($F(1, 23) = 18.70$, $MSE = 1.52$, $p < .001$), and an insignificant interaction of trial type with distance ($F(1, 23) = 1.28$, $MSE = 0.80$, $p = .27$). The remaining significant main effect of distance ($F(1, 23) = 1270.53$, $MSE = 21.50$, $p < .001$) showed that participants indeed produced the required trajectories.

### Perceived Motions

Table 4.2 shows the mean perceived angles for each RS condition for this and the following Experiments. In Figure 4.1 the difference in mean perceived angles between downward and upward movements is drawn as a function of required movement angles. Perceived angles were higher for downward than upward movements. The similar sizes of CEs for 10° and 35° required movement angles indicate that distance, however, had no influence on the size of the shift in motion perception. This finding was reflected in a significant main effect of movement direction ($F(1, 23) = 12.12$, $MSE = 1.11$, $p < .01$) but no significant effect including distance (both $F$s < 1).

### Relationship between Interference on Production and Perception

Figure 4.3 shows the correlation across participants between the CEs in production and perception for the two distance conditions (small, large). As can be seen from the figure, no relationship held between the sizes of the interference effects in action and perception. This is shown by a non-significant correlation value of 0.19 ($p = .37$) for small distance movements and of 0.19 ($p = .37$) for large distance movements.

The t-transformed within-participant ρ coefficients did not differ from zero (mean $\rho = -.04$) when a one-sampled t-test against zero was performed ($t(23) = -.78$, $p = .45$; $t(23) = -.004$, $p = 1.00$; $t(23) = -1.34$, $p = .19$; $t(23) = -.89$, $p = .38$) for 10° downwards, 10° upwards, 35° downwards, and 35° upwards movements, respectively.

*Table 4.2: Mean produced absolute end angles and perceived angles as a function of distance (small/large) between required movement directions and RS angles for Experiment 7 - 8. Produced end angles are shown as a function of required movement direction and collapsed across motion and no-motion trials. Upward/downward movement angles are coded relative to the horizontal midline (see lower-right part of Figure 3.1). Rightward/leftward movements have the vertical midline as their reference point. Perceived angles are displayed as a function of RS angles. d = downward, u = upward, r = rightward, l = leftward.*

| | Prod. End Angles | | | | Perceived Angles | | | |
|---|---|---|---|---|---|---|---|---|
| Distance | small | | large | | small | | large | |
| Trajectory | d/r | u/l | d/r | u/l | -4 | 4 | -4 | 4 |
| Exp. 7 | 15.39 | 14.10 | 38.60 | 38.60 | -4.53 | 3.62 | -4.82 | 3.89 |
| Exp. 8a | 35.18 | 37.43 | 78.73 | 79.12 | -3.82 | 4.04 | -3.49 | 4.15 |
| Exp. 8b | 16.33 | 17.61 | 12.97 | 11.20 | -4.28 | 4.13 | -4.86 | 4.20 |

### 4.2.3 Discussion

In line with Experiment 6, no systematic relationship between the CE sizes in action and in perception were found. Importantly, even though CEs were obtained for both distance conditions in action and perception, no difference in the size of the CE as a function of distance could be found for either the action or perception. This is in opposition to the distance prediction of the Schubö and Hamilton models. To avoid a premature conclusion about the distance prediction, we increased the distance between the produced and perceived directions in the next two experiments.

## 4.3 Experiment 8: Testing the Distance Prediction Again

The aim of this experiment was to increase the distance between the direction of the produced movement and the concurrently perceived motion direction to verify that we did not simply miss an influence of distance in Experiment 7 because the distances were too small. Consequently, we increased the distance between the movements in the two distance conditions to 50°.

### 4.3.1 Experiment 8a

#### 4.3.1.1 Method

**Participants**

Twenty-five right-handed individuals (mean age = 25.96 years; age range = 18-35 years; 3 males, 22 females) participated in the experiment.

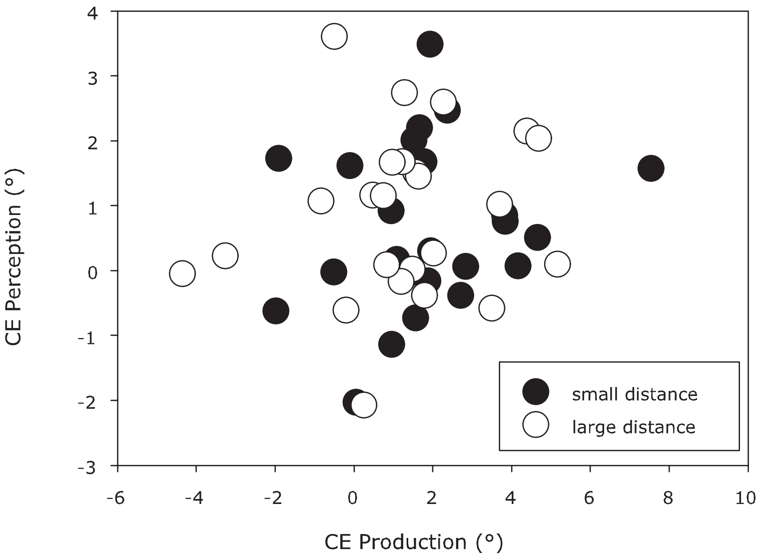

*Figure 4.3: Size of the CE on perception as a function of the size of the CE on production for movements in the small (10 ° required movements) and large (35° required movements) distance conditions for Experiment 7.*

### Apparatus, Stimuli and Movements, Design, and Procedure

The setup of this experiment resembled that of Experiment 7, but rotated by 90 degree to the left. Therefore, the reference point for coding angles was switched to the vertical midline (see lower-left part of Figure 3.1). Coded in this way, the movement trajectories for the small distance condition deviated from the vertical midline by 30° either to the right or to the left; for the large distance condition by 80°. Accordingly, the RS start position was moved to a horizontally centered position, 7.5 cm below the horizontal midline. RS trajectory length was set at 12 cm (11.42° of visual angle) and there were no no-motion trials. Two blocks of 20 trials were run for each movement direction, resulting in a total of 160 trials. The mean number of needed practice trials in the training phase was about 23 trials and experimental time was between 45 and 65 minutes.

### Data Analysis

Data analysis did not differ from earlier experiments except that no effect on production was calculated, and in consequence, no correlation values could be determined. This was owned to that to reduce the experimental time and thereby avoid fatigue of the participants, no-motion trials were omitted. Movements were considered as trajectory failures when produced end angles were closer than 5° to the horizontal midline or deviated by more than 20° from the required angles.

#### 4.3.1.2 Results

The data of one participant had to be excluded because of conditions with zero observations resulting from about 65% excluded trials, 39% thereof being trajectory failures and 56% beeing concentration failures. For the remaining participants (N=24), the mean percentages of excluded trials were: 1.07%, 1.22%, 2.40%, 10.73%, and 7.81% for late movements, pen lifts, movement reversals, trajectory failures, and concentration failures, respectively, resulting in a total percentage of discarded trials of 23.23%.

**Perceived Motions**

In Figure 4.4 the difference in mean perceived angles between rightward and leftward movements, i.e., the CE, is drawn as a function of required movement angles. As the positive CE values for the required movement angles of 30° and 80° show, perceived angles were more to the left for rightward movements than for leftward movements. Distance, however, had no influence on the size of the shift in motion perception, reflected by the similar sizes of CEs for the 30° and 80° conditions. This finding was reflected in a significant main effect of movement direction ($F(1, 23) = 34.30$, $MSE = 1.5$, $p < .001$), but no significant effect including distance (main effect: $F(1, 23) = 1.62$, $MSE = .72$, $p = .22$; interaction: $F(1, 23) = 1.69$, $MSE = .54$, $p = .21$).

#### 4.3.1.3 Discussion

Even with an increased distance between the produced movement directions in the two distance conditions, no difference in the size of the CEs was found. In the next experiment we varied the distance closer to its 180° limit by increasing the distance to 160°.

### 4.3.2 Experiment 8b

In a final experiment the distance between the movements in the two distance conditions was increased to 160°.

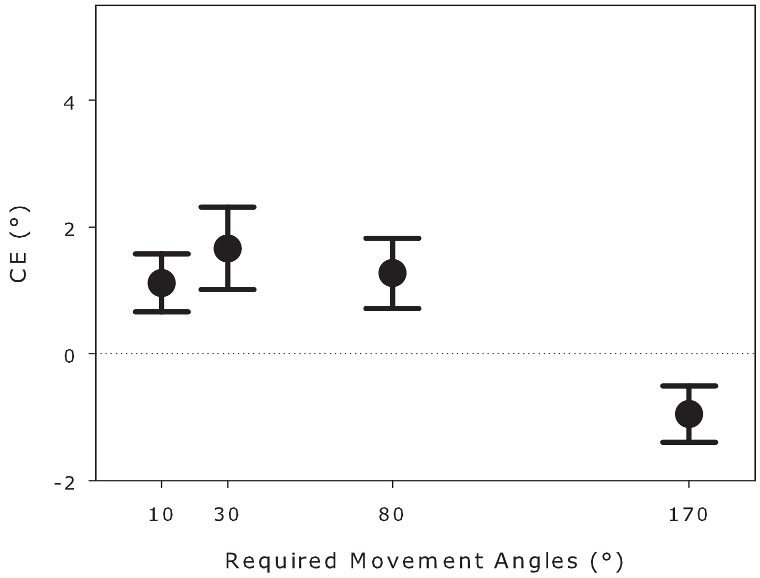

*Figure 4.4: Size of the CE in perception as a function of required movement angles for Experiments 8a (30° and 80° required movement angles) and 8b (10° and 170° required movement angles). Whiskers indicate 95% confidence intervals.*

#### 4.3.2.1 Method

**Participants**

Twenty-five right-handed individuals (mean age = 25.76 years; age range = 17-35 years; 5 males, 20 females) participated in the experiment.

**Apparatus, Stimuli and Movements, Design, and Procedure**

The small distance condition required the participants to draw 10° movements to the right or left of the vertical midline. In the large distance conditions, downward movements either 170° to the right or left of the vertical midline had to be produced. On average, participants needed about 21 trials to learn to perform these movements and experimental time varied between 55 and 75 minutes. Everything else was the same as in Experiment 8a.

### Data Analysis

Data analysis was the same as for Experiment 8a, except that movements that came closer than 5° to the vertical midline or deviated by more than 20° from the required angles were considered trajectory failures.

### 4.3.2.2 Results

The data of one participant had to be excluded because of conditions with zero observations resulting from about 94% excluded trials, with 39% thereof being trajectory failures and 56% beeing concentration failures. For the remaining participants (N=24), the mean percentages of excluded trials were: 1.43%, 1.72%, .70%, 12.14%, and 7.37% for late movements, pen lifts, movement reversals, trajectory failures, and concentration failures, respectively, resulting in a total percentage of discarded trials of 23.36%.

### Perceived Motions

In Figure 4.4 the difference in mean perceived angles between rightward and leftward movements, i.e., the CE is drawn as a function of the required movement angles. As the positive CE of movements above the horizontal (10° required movement angle) shows, perceived angles were more to the left for rightward movements than for leftward movements. For downward movements (170° required movement angle), however, the opposite pattern was found. Movements that were performed downwards to the right shifted the perceived angles to the right compared to downward movements to the left. Distance, i.e., the difference between the 10° and 170° required movement conditions, however, had no influence on the size of the shift in motion perception in absolute values. These findings were reflected in a non-significant main effect of movement direction ($F(1, 23) = .47$, $MSE = .36$, $p = .50$) and distance ($F(1, 23) = 1.53$, $MSE = 1.04$, $p = .23$) that were modulated by a significant interaction between movement direction and distance ($F(1, 23) = 32.05$, $MSE = .80$, $p < .001$). A follow-up ANOVA for the upward (10°) and downward (170°) movement directions showed that for upward movements a significant CE was present, but for downward movements a significant AE was found ($F(1, 23) = 25.17$, $MSE = .60$, $p < .001$; $F(1, 23) = 19.36$, $MSE = .56$, $p < .001$). A paired t test between both distance conditions on the absolute interference effect, i.e., the absolute values of the differences in perceived angles for right- and leftward movements, showed no influence of distance on the size of the effect ($t(23) = 0.68$, $p = .50$). Furthermore, there was a significant positive correlation between the sizes of the CEs and AEs across participants (Spearman's $\rho = .42$, $p < .05$).

#### 4.3.2.3 Discussion

For the first time, the distance manipulation had an influence on the CE. In contrast to the predictions of the Schubö or Hamilton model, this effect was not simply diminished for larger distances, but actually changed its sign. Measured in absolute terms, however, the same size of the effect was obtained for movements below and above the horizontal midline. The similarity between both effects was further stressed by the significant correlation between the CE and AE sizes.

## 4.4 Discussion of Testing the Model Predictions

Experiments 6 and 7 revealed CEs between concurrent action and perception processing in the same experiment. To obtain a measure of the CE in action, produced end angles in trials with motions on the screen were compared to trials without motions. The results showed that the movements veered away from concurrent motions, i.e., a CE was obtained.

Obtaining CEs in action and perception within the same experiment allowed us to evaluate their relationship. No correlation between the size of CEs in action and perception was obtained. This was true for within-participants and across-participants correlations.

Obtaining CEs in both action and perception seemed at first to support the Schubö model, which predicted similar effects in action and perception. Closer inspection however showed that only the coarse pattern confirmed the Schubö model. When the relationship between the sizes of the CEs was assessed, the results were in contrast to the predictions derived from the Schubö model. While the Schubö model predicted a monotonic relationship between the sizes of CEs in action and perception, no correlation was found.

The next prediction that was tested was the distance prediction. When the angular distance between movements and motions was varied above the horizontal midline, the size of the CEs did not change. However, when the movements were below the horizontal midline, the CEs turned into AEs. This was in clear contrast to the predictions of the Hamilton and Schubö models.

Finding no effect of distance for movements above the horizontal midline suggests that exact directional information is lost and movements/motions are activated categorically at the level at which the interference occurs. Assuming that the interfering codes are activated categorical, the exact direction should not influence the size of the effect. Why then should the effect reverse for very large distances? One way to explain this is to invoke control processes that first determine whether two events are likely to be confused. If they can be easily confused due to their similarity and the system is determined to keep the two events apart, it has to solve a discrimination task. This could be achieved by diminishing the contribution of codes shared by both events, which would lead to a CE. A different situation arises, however, when the difference between the events is large enough to avoid any confusion. Then, without a control process that diminishes the contribution of shared codes at work the two events might become more similar to each other. When similarity is linked to comparability, this model is related to the explanations for contrast and assimilation advanced by Aarts and Dijksterhuis (2002). Aarts and Dijksterhuis (2002) found that whether priming of a certain speed had a contrasting or assimilative effect on later speed judgments depended on whether prime and test stimuli were perceived as comparable or not. For example, whether being primed by a turtle led to higher speed estimates of a human depended on whether participants believed that animals and humans are comparable or not. When participants were prepared to believe in a high comparability by reading a text, a contrasting effect was observed. However, reading about the differences between humans and animals led to assimilative effects. In Section 5.3, I will further disentangle the role of control processes and event similarity for CEs and AEs.

Interestingly, contrasting effects have also been obtained for two concurrent visual motions, but in this case an influence of distance was found (Rauber & Treue, 1999). Larger angles between two concurrent motions led to smaller CEs. This latter result indicates that the underlying representations that lead to CEs differ for perception-perception and action-perception interactions. While perception-perception tasks seem to interfere at a level where fine grained directional information is still preserved, the influence of action on perception seems to arise at a more abstract level of representation where specific directional information is lost.

# Chapter 5

# General Discussion

In the general discussion, I first review the experimental findings of this thesis, discuss how other approaches than the Schubö or Hamilton model (see Sections 1.5.3 and 1.5.4) could deal with the experimental results, and then develop a categorical model. Finally, I discuss what factors might influence whether a CE or AE occurs, and relate the experimental findings to observations in perceptual-perceptual and action-action paradigms.

## 5.1 Summary of Experimental Findings

The experiments of this dissertation investigated how concurrent action and perception processing of continuous tasks influence each other. The starting point for these experiments were findings of specific influences as discussed in Sections 1.4 and 1.5. In the paradigm, participants produced a hand trajectory while they observed a continuous dot motion on the screen. By varying the directions of the hand movements it was possible to detect an influence of movement direction on perception of the direction of the concurrent motion. Movements and motions were made less similar to each other when performed concurrently. This was referred to as a CE. The movement directions in this paradigm were blocked, which avoided the use of a visual cue to signal the movement direction. Therefore, interference with a visual cue, which was a potential confound of earlier studies (e.g., Craighero et al., 1999; Hamilton et al., 2004; Schubö et al., 2001, 2004; Wohlschläger, 2000) could be avoided. Manipulating the direction of movements and motions allowed to reduce the impact of timing on the observed interactions. For example, when using sinusoidal motions, as was the case in Schubö et al. (2001, 2004), the direction of the motion changes over time. Upward motions change to downward motions after some time and vice versa. Angular relationships, on the other hand, stay constant independent of whether the produced movement occurs at the same speed as the observed motion. Similarly, using directional motions with a clear defined physical metric allowed to assess easily the perception thereof by way of a same / different judgment (Section 2.3), by a perceptual adjustment procedure (Section 2.4), or even online (Section 3.2) and by this excluded various alternative explanations.

Based on this paradigm, it was possible to obtain a *CE in action and in perception*. Importantly, these *CEs were obtained with non-biological stimulus motions* which showed that specific interference effects are not tied to biological motions. Experiment 1 showed that the CE was not caused by a better discrimination around regions on the screen that corresponded to the final hand position. A response bias explanation was excluded in Experiment 2. A more "direct" measure of the CE was established in Experiment 3. Experiment 4 showed that the CE depended not on eye-movements. Employing an online measure in Experiment 5 excluded the dependence of the CE on memory processes. Further investigations by correlation methods of the CEs in action and in perception revealed the *independence of the CEs in action and perception* (Experiment 6 and Experiment 7). Experiment 7 and 8a further showed that the *CE was not affected by the distance* between movement and motion directions when the movements were performed in the upper half of the graphics tablet. The CE switched to an AE however when the movement was produced in the lower half of the graphics tablet while the motion still occurred in the upper half (Experiment 8b).

Finding a mutual interference between action and perception supported the Schubö model at first. Closer inspection of the relationship between the sizes of the CEs, however, showed that the Schubö model could not fully account for the data because its prediction of a monotonic relationship between the CEs in action and perception was contradicted by the empirical data. Therefore, the Hamilton model, which is neutral to the question of influences on actions seemed to be the better candidate to explain CEs in perception. However, the lack of a distance effect for movements in the upper half and the reversal to an AE contradicted the distance prediction of both the Schubö and the Hamilton model.

Taken together, these experiments suggested that *neither the Hamilton nor the Schubö model could fully account for the experimental results*. The *pattern of findings are consistent with a categorical version of the models*. Before I consider this issue in more detail I discuss other approaches that could be used to explain the empirical findings.

## 5.2 Explaining the Results in Other Approaches

The Premotor Theory of Attention attributes interactions between action and perception to the involvement of common pragmatic maps. Mutual interferences seem to be a natural consequence of this. Whether this interference would be assimilative or contrastive would depend on a more detailed formulation. According to the Premotor Theory of Attention, hand movements facilitate perception of compatible objects. This suggests that shared directional components are facilitated and an AE would be observed. A CE, however, could be obtained by postulating an additional mechanism as, for example, attentional repulsion (Suzuki & Cavanagh, 1997). According to this account, perception of visual stimuli is repulsed from the focus of attention. If attention is enhanced around the end region of the hand movements as the Premotor Theory of Attention would predict, and this end region is mapped onto the screen's coordinates then attentional repulsion could explain the repulsion of the perceived stimulus from the produced direction. The attentional repulsion model in its current formulation, however, would predict an influence of distance (Suzuki & Cavanagh, 1997). Therefore, Premotor Theory of Attention together with the attentional repulsion model could not account for the results of Experiments 7 and 8.

The mutual interference findings between action and perception could also be attributed to the involvement of different reference frames. As Colby (1998) discussed, the human system uses different reference frames to code locations in the world. Two broad classes of reference frames can be distinguished: Egocentric and allocentric reference frames. Egocentric reference frames code objects relative to the observer, for example, relative to the arm, head or eye. Allocentric reference frames, on the other hand, code spatial locations relative to objects of interest, for example, relative to a car or a mountain. The use of the arm as a reference frame to code visual objects was shown by Graziano, Yap, and Gross (1994). Graziano et al. (1994) described bimodal neurons in premotor cortex of monkeys that respond to visual stimuli in a certain portion of the visual field and to tactile stimuli to one arm. Interestingly, the region of visual field that led to a response in these neurons changed with movements of the arm. For example, leftward movements lead to a shift of the receptive visual fields to the left. Therefore, a given visual location excites some neurons before but not after a movement. This could lead to a shift in perception away from the produced movement direction and therefore a CE. For this explanation to work with the current experiments, one has to assume that the reference frame shifted back after the movement and before the test stimulus was judged. What is however harder to explain in this approach is why no effect of distance was found or why CEs change to AEs when downward movements are combined with upward motions. Therefore, I will discuss next which coding assumptions would allow to explain the absence of a distance effect. These coding assumptions are not tied to a specific approach. However, I will illustrate the underlying idea within a common coding approach.

## 5.3 A Categorical Model

The prediction of an influence of distance in the Schubö and Hamilton models was derived from the assumption that the interfering codes contain exact directional information and therefore even similar directions involve different codes. By abandoning this assumption, the absence of a distance effect could be explained. To this end, it is necessary to assume that representations are activated in a categorical manner at the level where interferences occur and exact directional information is lost at this level, i.e., as long as movements of different directions belong to the same category, they activate the same representations at the level where the interference occurs. If these representations then interact with the perceptual representations, their exact direction and therefore distance between the produced and perceived motion directions should play no role. Assuming such abstract coding at the interference level seems to be consistent with other findings discussed in the introduction:

Two studies are especially informative in this regard because they showed that the interference of spatial information depended not on physical properties of the stimuli but on how they were interpreted by the participants. Hommel (1993) showed that instructing participants on an action or on an effect of the action changed whether representations of the action or of the effect interfered with simultaneously presented tones (see Section 1.4). When participants focused on turning on a light, the position of the light was what interfered with the tone location. Instructing the participants, however, to press a button made the button location interfere with the tone location. Similarly, Stevanovski et al. (2002) showed that AEB changes as a function of whether a stimulus is interpreted as a headlight or an arrow. Analogously, in the experiments presented in this thesis, the interference might have occurred at a level where physical properties of the stimuli and actions played a minor role.

Further support for interference of abstract codes has been discussed in Section 1.5: Stevanovski et al. (2006) found an influence of a mere "get ready" signal on later stimulus identification. Craighero et al. (2002) showed that pictures of hand grip end postures facilitated movements that had these postures as goals. Lindemann et al. (2006) reported that movement preparation activated associated semantic content that led to interference with a lexical decision. Further, the empirical data of Hamilton et al. (2004) could be made consistent with their proposed model, if the interference did not occur between exact weight representations of a lifted box and an observed box, but between a categorical representation of the lifted box as for example, "light" or "heavy" and the observed box. Therefore, proposing interference between abstract representations seems well founded in experimental findings. Given these experimental findings, it is not surprising that other researchers have already suggested that abstract codes underly interference effects (e.g., Hommel, 1998; Kunde & Wühr, 2004; Lindemann et al., 2006).

If this assumption of a categorical interference is taken seriously, it implies that trial-to-trial variability in the interference effect was not caused by differing amounts of overlapping codes because the amount should stay the same between categories of a given participant. Inter-trial variability would then be attributed to sources independent of the amount of overlap. This, however, would mean that there is no reason to expect a correlation between the interference effect sizes between action and perception within participants.

On the other hand, which directions belong to a given category could well differ between participants and thus give rise to variability in CE sizes across participants. The fact that no correlation between action and perception CE sizes was observed across participants suggests that participants indeed had a similar category structure. Similar to within-participant variability, variability across participants would then also not be caused by different amounts of representational overlap.

The following model is intended to illustrate how such categorical coding could lead to interference effects that are independent of distance. The model assumes that nodes at the motor and perceptual levels activate corresponding directional exemplars at the interference level (thick arrows in Figure 5.1 and 5.2). In addition to this activation, the motor and perceptual levels also activate the exemplars at the interference level in a categorical way (thin arrows in Figure 5.1 and 5.2). Exemplars of this categorical activation (shown by arrows with different orientations at the interference level) overlap at the interference level. Importantly, the amount of overlap depends on the categories involved and not on the exact directional information from the action or perception level. This exemplar-based coding of categories means that a movement to the right and upwards would activate all directional exemplars that are assumed to belong to this "right-up" category. For an overview of exemplar based category models see e.g., Shanks (1995).

Figure 5.1A illustrates how this model could account for CEs that are not influenced by the exact distance between the stimulus and motor movements. In the figure, activation of an element that comes from the motor level is illustrated by a circle surrounding that element. Similarly, activation from the perceptual level is indicated by a surrounding diamond. In the model, a movement of a certain direction at the motor level activates the exemplars at the interference level that correspond to its category, for example, the category "right-up". Analogously, a visual upward motion activates its category "up"[7]. The exemplar based representation then leads to overlap between exemplars that are activated from the perceptual and motor levels. In line with the assumptions of the Schubö model,

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[7] It is assumed that most participants coded a motion deviating by ±4° from the vertical as "up".

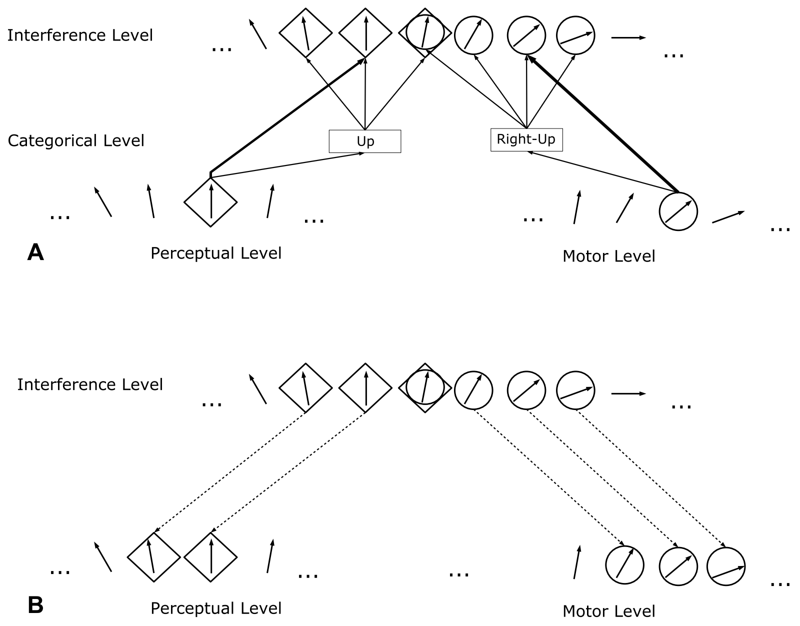

*Figure 5.1: A categorical model. (A) Activation of a certain direction at the motor or perceptual level activates the corresponding exemplar at the interference level (thick arrows). In addition, exemplars at the interference level that belong to the category of the activating event are activated (thin arrows). Activation coming from the motor level is shown by surrounding circles, activation from the perceptual level by diamonds. Overlap in exemplars reduces their contribution to the representation at the interference level. (B) Exemplars at the interference level are bound to the level that caused their activation and feed back to it (dotted lines).*

these common exemplars contribute less than non-overlapping exemplars to the representations at the interference level. However, these exemplars are still bound to the level that caused their activation. Therefore, the exemplars feed back to the perceptual/motor level in a non-categorical way (Figure 5.1B). In this way the feedback from the interference level causes the change in action and perception. If an overlap at the interference level is present then these overlapping exemplars do not feed back to the motor and perceptual levels. This means that when the directions of the nodes at the motor or perceptual level are weighted by their activity and averaged, a bias away from the directions of the overlapping exemplars occurs. Because the overlapping exemplars at the interference level do not differ for similar directional movements as long as these movements belong to the same category, no distance effect would be obtained for this bias. The influence from the interference level, however, has to be small. Otherwise the earlier activation at the motor and perceptual levels would be lost and mainly categorical information from the interference level would be present.

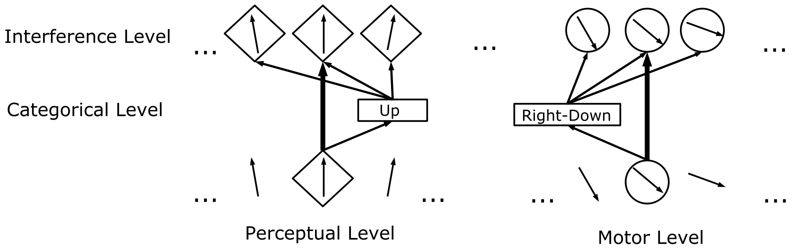

*Figure 5.2: An example of a situation for which activation from the motor and perceptual levels does not lead to an overlap in activated exemplars at the interference level.*

Figure 5.2 shows how the model could also account for the AEs that were observed. When participants, for example, performed downward movements to the right, this could have activated a categorical representation that did not overlap with the motion category. As a consequence, the exemplars at the interference level do not overlap anymore. Therefore, every exemplar at the interference level is uniquely associated to one level only. In this case it could be assumed that noise in the system leads to some erroneous bindings and features between the two tasks are exchanged at the interference level (see for an example of feature exchange between briefly presented stimuli, e.g., Treisman, 1988). Exchange of features would then lead to a higher similarity between the two tasks. While this assimilative influence is masked by a contrastive influence in situations like Figure 5.1, it can be observed when no overlap is present. As mentioned in Section 4.4, this model would be consistent with the presence of CEs for comparable and AEs for non-comparable (less similar) events by Aarts and Dijksterhuis (2002).

This model makes an interesting prediction. Because the feedback from the interference level occurs from exemplars that belong to an activated category, a general bias in action and perception to the central tendency of this category should be observed. For example, right-upward movements should be biased to 45°. Movement end angles of Table 4.1 and 4.2 support this prediction. Similarly, upward motions should be biased to 0°. The support for this prediction is less strong from Table 4.1 and 4.2. However, a different effect might have overlaid the central tendency effect. For example, motion direction judgments are found to be repulsed from reference directions, e.g., the vertical direction (Rauber & Treue, 1999).

According to this model, assimilation and contrast are determined by the similarity between movements and motions. It assumes that feature overlap leads to less availability of these features for both tasks, which seems to preclude facilitative effects of feature overlap as reported, for example, in Section 1.4. This problem can be dealt with by invoking a second mechanism that was only hinted at in Section 4.4: A control process that determines what effect overlap has on the overlapping features (see code modification mechanism of Schubö et al., 2004). Depending on the situation this control process determines whether overlap has a facilitative or inhibitory effect on these features. The control process could be influenced by the probability that two tasks could be confused and whether the situation demands to keep the tasks separate. This explanation attributes an active role to the control process: if two tasks are conceptualized as independent from each other by the participant but the similarity of the tasks could lead to confusion, the control process attempts to distinguish between the two tasks. As a consequence, common features are ignored to make the two tasks less similar to each other. When the tasks are conceptualized as functionally related or the tasks are very different, the system does not try to actively keep the two tasks apart and common features might have a facilitative influence on the task representations. This kind of control process could eliminate the misattributions of elements to the wrong event as demanded to explain the AE for downward movements. Whether control processes for overlapping features play a role could be experimentally tested. For the same two tasks, CEs should turn into AEs if the instruction to keep the two tasks separate changes to one in which the two tasks are functionally related. In the next section, I discuss how these mechanisms could account for the AEs and CEs reported in Sections 1.4 and 1.5.

## 5.4 What Leads to Assimilation or Contrast?

According to the mechanism proposed above, CEs arise between concurrent perceptual and motor processing if the action and perceptual processes are interpreted as conceptually independent but are feature overlapping, while AEs arise when the processing is seen as belonging to conceptually dependent tasks or action and perception processing does not feature overlap. "Conceptually independent" in this context means that motor or perceptual processing seems not to improved by integrating information from the concurrent second task. Importantly, whether a given task is conceptually independent depends on how the participants interpret the situation.

Single tasks, like standard S-R tasks or even continuous S-R tasks, do not induce overlap of two concurrent events that belong to independent tasks. Therefore, facilitative interference should be expected. To the extent that AEs can be related to facilitation, these studies confirm the prediction. Similarly, Craighero et al. (1999)'s task of responding with a prepared movement to a "go"-signal (see Section 1.5) did not involve overlapping tasks and the expected faster processing of overlapping features was found.

On the other hand, the concurrent tasks of Schubö et al. (2001, 2004), Hamilton et al. (2004), and this thesis led to an feature overlap of conceptually independent tasks. This is the situation that is suggested to lead to inhibitory interference and therefore CEs. This was confirmed by their data as well as by those of this thesis.

What might be problematic for this account are findings of Wohlschläger (2000) and Repp and Knoblich (in press). Both found AEs between concurrent processing two conceptually independent tasks (see Section 1.5). A major difference to the other reported studies was, however, that one concurrent event involved an ambiguous stimulus. This ambiguity, by definition, leads to uncertainty about the stimulus. Two different reasons could therefore be advanced to explain the AEs. First, the ambiguous stimulus might have led to such a weak representation that binding of the features of the stimulus did not work properly and included features of the other task to a high degree. This reason seems unlikely on introspective grounds. Even though the perceived direction is uncertain at the beginning, once a directional interpretation is achieved, there should be no ambiguity present. Thus it seems unlikely that the ambiguous motion was represented in a weaker fashion than non-ambiguous motions. Therefore, a second reason seems more viable. While in the experiments of, for example, Hamilton et al. (2004), Schubö et al. (2001), and of this dissertation, further perceptual processing of a stimulus could improve decisions about the stimulus, ambiguous situations need non-perceptual information in addition to the perceptual information to disambiguate them. For example, when Wohlschläger (2000) asked individuals to judge the direction of a rotation of a stimulus, even having exact knowledge of the dot locations would not resolve the ambiguity. Only by applying additional non-visual information, for example, preferring shorter paths between the dots could lead to a directional judgment. The situation is different, for example, in the study of Schubö et al. (2001). In this experiment, having detailed visual location information would allow to give a veridical judgment of the amplitude. Therefore, it might make sense for the human system to integrate information also from other sources in the former case when the stimulus does not provide sufficient information but not in the latter case. While in the former case, additional non-perceptual information is needed to disambiguate the situation, in the latter case adding information of another task would distort the veridical perception. Therefore, the control processes of Section 5.3 seem to take not only into account whether two tasks are conceptually independent but also whether one stimulus is ambiguous and therefore needs information in addition to the sensory information. In this case, the sensory processing seems not to be protected against other concurrent tasks and AEs arise. Figure 5.3 summarizes concurrent action perception conditions in which AEs or CEs are predicted to arise.

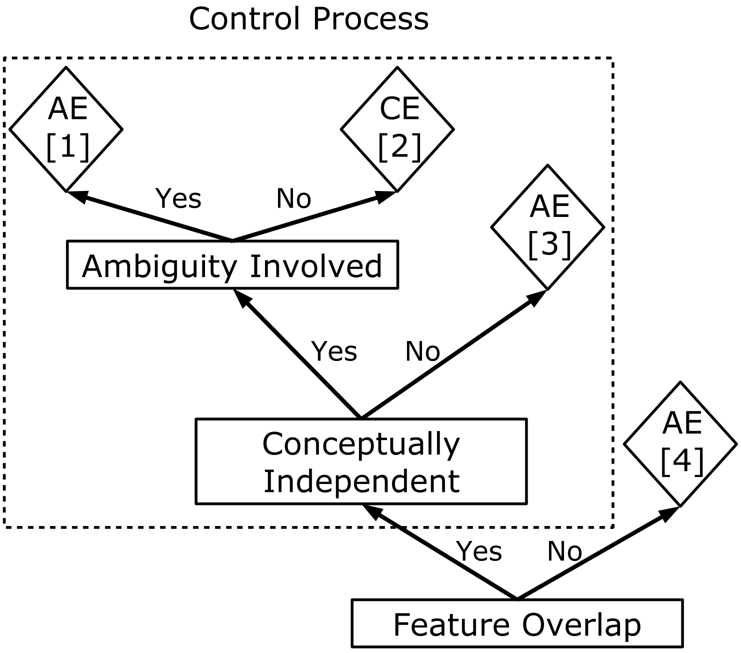

*Figure 5.3: Concurrent action and perception conditions that lead to AEs and CEs. Number in brackets refer to exemplar studies, discussed in the introduction, or to experiments of this dissertation. [1]: Repp and Knoblich (in press); Wohlschläger (2000), [2]: Hamilton et al. (2004); Schubö et al. (2001); Schubö et al. (2004); Experiments 1-8a of this dissertation, [3]: Brass et al. (2001); Chua and Weeks (1997); Ehrenstein et al. (1996); Michaels and Stins (1997), [4]: Experiment 8b.*

## 5.5 Other Interferences in Action and Perception

Similar to the findings of contrast between movements in action and perception, interference effects have also been found within action-action and perception-perception paradigms.

CEs between directions have been reported using perception-perception paradigms. However, in these paradigms, influences of the distance between two motions have been found. For example, in Marshak and Sekuler (1979)'s experiment, participants watched random dots that moved in two different directions in a coherent fashion. One of these directions was always horizontal. Participants' task was to judge the direction of the other motion. The results showed that this motion was perceived as being repulsed from the horizontal direction. Additionally, the size of the repulsion decreased with larger angles between the two motions. These findings have been refined by Rauber and Treue (1999) who argued that this measurement also included a reference repulsion from the horizontal. Rauber and Treue (1999) estimated this contribution by having participants judge a single motion. The results showed that even though half of the measured motion repulsion of

Marshak and Sekuler (1979) might be attributed to reference repulsion, the other half still seemed to be a true motion repulsion effect. Motion repulsion has been attributed to inhibition between the concurrent motions by Marshak and Sekuler (1979) and Rauber and Treue (1999). Another explanation for visual motion repulsions, related to the binding problem of distributed features, has been advanced by Mahani, Carlsson, and Wessel (2005). According to this model, motion repulsion is a side-effect of clustering algorithms. The underlying idea is that when the human system tries to assign features to two different tasks, features of the two tasks might become mixed. According to Mahani et al. (2005) the probability of misclassifications of features of a given motion is higher for features that are less typical for the given motion but more typical for the other motion. This loss of "untypical" and the gain of more "typical" features leads to a CE. However, this mechanism would also predict a distance effect.

In action-action paradigms, interference effects that are influenced by distance have been reported as well. Here however, AEs were found. For example, Swinnen, Dounskaia, Levin, and Duysens (2001) asked participants to produce a vertical line with their left hand while concurrently performing rapid movements in different directions with the right hand. The results showed that the left hand was biased in the direction of the concurrent right hand movement. This assimilation was largest for orthogonal directions and smallest for vertical movements with the right hand. Intermediate distances lay in-between.

These findings of distance effects is in contrast to the findings of Experiments 7 and 8. This seems to imply that representations at the level at which action and perception interact differ from those involved in interactions within action or perception. While interactions within action or perception seem to occur at a level containing detailed representations, interactions between action and perception involve more categorical representations. This would be consistent with an argument by Tipper, Lortie, and Baylis (1992) that the representations at which inhibition is directed flexibly depends on the task requirements. Further support for this dependence of the kind of interfering representations on the nature of the involved events can be found in the study of Suzuki and Cavanagh (1997). In their paradigm, participants reported the location of lines. Attracting participants' attention to a certain position by a cue led to a repulsion in perceived line position away from the attended region. This effect was explained by changes in sensitivity around the location of attention. The distance between the attentional locus and the line location, however, had no influence on the size of the effect. Importantly, finding distance effects only for interactions within perception but not when attention mediates the interference, underlines that the nature of involved events determines the kind of representations that are involved in the interference.

## 5.6 Possible Origins of the Interference Effects in the Brain

Although the experiments of this dissertation did not address where in the brain specific interference occurs, it is worth speculating on its neural basis.

Danielmeier et al. (2004) used a visual identification task to investigate the influence that movement preparation had on visual processing. FMRI was used to establish the corresponding brain regions of the influence. For half of the trials participants prepared a movement during the stimulus presentation; in the other half, no movement preparation was required. Comparing brain activity for preparation and no-preparation trials, Danielmeier et al. (2004) found activation differences in early visual brain regions that are associated with the relevant stimulus features: A modulated activity was found in V3A if the visual stimuli had to be discriminated based on their shape. For color discriminations V4 was affected. Similarly, de C. Hamilton et al. (2006) found activation in areas that were associated with their visual task. As mentioned in Section 1.5, de C. Hamilton et al. (2006) investigated the influence of lifted weights on the judgment of weight lifting movements using fMRI. The activation differences they observed seemed to suggest that the influence occurred in areas that are involved in action observation (IFG, V5, EBA).

Importantly, neither study found a single region where the influence occurred, but showed that the location of the influence depended on the stimuli. This suggests that the CE investigated in this dissertation also occurred in regions that are involved in perceiving the particular visual stimuli that were employed. Because the crucial stimulus dimension was motion direction, the influence was probably located in direction sensitive area V3A and the visual motion sensitive area V5.

Involvement of a further region is suggested by findings with single-cell electrode methods in monkeys. Colby (1998) reviews areas that are involved in the mapping between different reference frames. Neurons in the medial intraparietal area (MIP) are reported as a location where information from visual motion and hand movement directions are mapped to a common reference frame. For example, bimodal neurons in MIP respond to the location of a reaching arm *and* its target. Thus MIP might be involved in the mapping of visual motions to the reference frame of a moving hand.

## 5.7 Conclusions

The starting point of this dissertation was the growing body of evidence for the interwoven nature of action and perception. What is new in this dissertation is that it was possible, within a single experiment, to show mutual interferences between spatial features of action and perception. This allowed to investigate in more detail the representations underlying these interaction effects. It was argued that these interactions do not rely on the representation of physical properties of action and perception, but on how they are categorized. This points to the importance of understanding how physical properties are represented by humans in order to better understand how interactions between action and perception arise. The caveat is that the more abstract the representations involved are the higher is the probability that humans differ in their coding of the physical properties, which would result in different kind of interactions. If this is true, then obtaining similar interference effects across participants was only possible because the stimuli and the actions were constrained enough to lead to similar representations. Which paradigms would allow us to investigate the coding of less constraint and more realistic action and perception situations awaits further research.

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## Dissertationsbezogene bibliographische Daten

Zwickel, Jan

Specific Interference Effects Between Temporally Overlapping
Action and Perception

Universität Leipzig, Dissertation

123 Seiten, 155 Literaturangaben, 22 Abbildungen, 4 Tabellen

### Referat

Die vorliegende Dissertation beschäftigt sich mit dem wechselseitigen Einfluss zwischen gleichzeitigen Handlungen und Wahrnehmungen. In der Einleitung werden zuerst neuropsychologische Studien diskutiert, die eine enge Verknüpfung zwischen Wahrnehmungs- und Handlungsarealen im Gehirn zeigen. Verhaltensexperimente schließlich offenbaren einen wechselseitigen Zusammenhang zwischen Leistungen in gleichzeitigen Wahrnehmungs- und Handlungsaufgaben. Dieser Zusammenhang besteht dabei nicht nur in einer generellen Leistungseinbuße durch die gleichzeitige Ausführung zweier Aufgaben, sondern hängt auch von den spezifischen Inhalten der beiden Aufgaben ab. Zum Beispiel verändert sich die Leistung, Rechts- oder Linkspfeile zu entdecken, durch Handbewegungen nach rechts oder links unterschiedlich: Visuelle Pfeile, die in die Richtung der ausgeführten Handbewegungen zeigen, werden schlechter entdeckt als visuelle Pfeile, deren Richtung sich von den Handbewegungsrichtungen unterscheiden. Dieser spezifische Zusammenhang zwischen der Richtung der Handbewegungen und der Richtung der gesehenen Pfeile zeigt, dass Veränderungen der Wahrnehmung nicht nur durch die höheren Anforderungen einer zweiten Aufgabe entstehen, sondern auch inhaltsspezifisch sind. Dieser Einfluss auf die Wahrnehmung, der von der Merkmalsrelation zwischen Handlungs- und Wahrnehmungsinhalten abhängt, wird "‘spezifische Interferenz"’ genannt. In den folgenden Abschnitten der Dissertation wird zwischen spezifischen Interferenzeffekten von Handlungen auf Wahrnehmungen und von Wahrnehmungen auf Handlungen aufgegliedert. Anschließend werden zwei Modelle aus der Literatur vorgestellt, welche diese spezifischen Einflüsse erklären sollen. Als Abschluss der Einleitung werden zwei aus den Modellen abgeleitete Vorhersagen diskutiert. Diese Vorhersagen betreffen den Zusammenhang der gefundenen Größen des spezifischen Interferenzeffektes in der Handlung und der Wahrnehmung und die Metrik der Interferenzeffekte, d.h. der Einfluss der Ähnlichkeit des

Handlungs- und Wahrnehmungsinhaltes auf die Größe des Effektes. Diese Vorhersagen werden im experimentellen Teil getestet. Zu diesem Zweck wurde ein Paradigma etabliert, welches erlaubt spezifische Einflüsse sowohl auf die Wahrnehmung als auf die Handlung zu erfassen.

In dem verwendeten Paradigma führten die Probanden eine Handbewegung auf einem Grafik-Tablett aus während gleichzeitig die Bewegungen eines Punktes entlang einer graden Trajektorie am Monitor dargeboten wurde. Nach dem Ende ihrer Handbewegung sollten die Probanden die Richtung der gesehenen Punktbewegung beurteilen. Diese Beurteilung diente als perzeptuelles Maß für die wahrgenommene Richtung während ihrer Handbewegung. Indem das perzeptuelle Maß für Handbewegungen nach rechts und links verglichen wurde, war es möglich den spezifischen Einfluss der Handbewegungsrichtung auf die wahrgenommene Bewegung zu untersuchen. Um den spezifischen Interferenzeffekt zu bestimmen, wurden drei verschiedenen Messverfahren verwendet. Das Schätzen von psychometrischen Funktionen ermöglichte dann, die Größe des Effektes für alle drei Messverfahren zu vergleichen. Die gemessene Größe des Effektes unterschied sich nicht zwischen den Messverfahren. In allen drei Fällen kam es zu einer Abstoßung der gesehenen Richtung von der Handtrajektorie. Zum Beispiel führten Handbewegungen nach rechts zu einer Verschiebung der wahrgenommenen Punktbewegungsrichtung nach links. Da alle drei Messverfahren unterschiedliche Konfundierungen ausschlossen, konnte ein Paradigma etabliert werden, das die zuverlässige Erfassung von spezifischer Interferenz zwischen Handlung und Wahrnehmung erlaubt. Weitere Experimente untersuchten den Einfluss von Faktoren, die zwischen ausgeführte Handbewegungen und wahrgenommene Punktbewegungen zwischengeschaltet sind: Der Einfluss von Augenbewegungen wurde dadurch minimiert, dass die Probanden ihre Augen während der Aufgabe auf ein Fixationskreuz richteten. Dies wurde mittels eines Eye-Tracking Verfahrens kontrolliert. Der Einfluss von Gedächtnisprozessen wurde durch ein Online-Maß der Bewegungswahrnehmung minimiert. Dadurch, dass dennoch in beiden Experimenten der spezifischer Interferenzeffekt auftrat, konnte die Interferenz auf den Einfluss von *Hand*bewegungen auf die Wahrnehmung einer Stimulusrichtung zurückgeführt werden. Dies erlaubte dann die oben erwähnten Modellvorhersagen zu testen.

Die Erfassung der Handbewegungen mittels eines Grafik-Tabletts ermöglichte zusätzlich den Einfluss der Punktbewegungen auf die Handtrajektorie zu untersuchen. Auch hier kam es zu einer Abstoßung der ausgeführten Trajektorie von der gesehenen Punktbewegung. Wahrnehmungen und Handlungen wurden somit zueinander unähnlicher, d.h. ein Kontrasteffekt zwischen den wahrgenommenen und produzierten Richtungen trat auf. Um die oben erwähnte Zusammenhangsvorhersage zu testen wurden diese beiden Kontrasteffekte in der Wahrnehmung und der Handlung durch korrelative Verfahren in Beziehung gesetzt. Es stellte sich heraus, dass die Größen des Handlungs- und des Wahrnehmungskontrasteffektes unabhängig voneinander sind. Als nächstes wurde die zweite Vorhersage, der Einfluss den die Ähnlichkeit zwischen Merkmalen der Wahrnehmung und der Handlung auf den Interferenzeffekt hat untersucht. Dazu wurde die Winkeldistanz zwischen produzierter und gesehener Bewegung variiert. Es zeigte sich kein Einfluss der Winkeldistanz auf die Größe des Interferenzeffektes: Für alle Handbewegungen nach rechts oder links oben wurde die gleiche Abstoßung einer vertikalen Bewegungsrichtung gemessen. Allerdings wechselte die Abstoßung zu einer Anziehung wenn die Handbewegungen nach rechts oder links unten ausgeführt wurden während die Punkte sich weiterhin von unten nach oben bewegten.

Im Diskussionsteil wird ein neues kategorielles Modell vorgeschlagen, das die gefundenen Ergebnisse erklären kann. Es wird angenommen, dass die Interferenz zwischen Repräsentationen zustande kommt, die keine genauen Richtungsinformationen mehr kodieren. Die Vereinbarkeit des Modells mit im Einleitungsteil beschriebenen Studienergebnissen zu spezifischer Interferenz wird dargelegt. Anschließend wird die Möglichkeit diskutiert, die Befunde in verschiedenen Modellansätzen zu erklären und der gefundene Interferenzeffekt wird mit Interferenzeffekten in reinen Wahrnehmungs- und reinen Handlungsparadigmen verglichen.

# Curriculum Vitae

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# Selbständigkeitserklärung

Hiermit erkläre ich, dass die vorliegende Arbeit ohne unzulässige Hilfe und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt wurde und dass die aus fremden Quellen direkt oder indirekt übernommenen Gedanken in der Arbeit als solche kenntlich gemacht worden sind.

Jan Zwickel
Leipzig, 20. Oktober 2006

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