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The Planning and Control Model (PCM) of Motorvisual Priming: Reconciling Motorvisual Impairment and Facilitation Effects

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Previous research on dual-tasks has shown that, under some circumstances, actions impair the perception of action-consistent stimuli, whereas, under other conditions, actions facilitate the perception of action-consistent stimuli. We propose a new model to reconcile these contrasting findings. The planning and control model (PCM) of motorvisual priming proposes that action planning binds categorical representations of action features so that their availability for perceptual processing is inhibited. Thus, the perception of categorically action-consistent stimuli is impaired during action planning. Movement control processes, on the other hand, integrate multi-sensory spatial information about the movement and, therefore, facilitate perceptual processing of spatially movement-consistent stimuli. We show that the PCM is consistent with a wider range of empirical data than previous models on motorvisual priming. Furthermore, the model yields previously untested empirical predictions. We also discuss how the PCM relates to motorvisual research paradigms other than dual-tasks.

Keywords: dual-tasks, motorvisual, action planning, movement control

Experimental studies in human information processing have been mostly concerned with the impact of perceptual processes on action. However, for two decades or so, effects in the opposite direction—from action on perception—have also been intensely investigated. Among the most prominent research paradigms in this field are motorvisual dual-tasks (see Schütz-Bosbach & Prinz, 2007, for a review). In a typical motorvisual dual-task, participants respond in one task with one response (R1), according to a fixed stimulus-response mapping to one stimulus (S1), while they detect or identify, in a secondary task, a difficult to discriminate second stimulus event (S2) and report it by a further response (R2). The experimenter varies whether R1 and S2 are consistent (i.e., share a certain feature, such as location or semantic meaning) or inconsistent (i.e., contrast with respect to a certain feature; see Figure 1). An effect of R1–S2 consistency on secondary task performance is commonly interpreted as evidence for a direct impact from motor processing (R1) on perceptual processing (S2; see Schütz-Bosbach & Prinz, 2007). In recent years, a variety of motorvisual effects has

been demonstrated by such dual-task paradigms (e.g., Baldauf & Deubel, 2008; Hommel & Müsseler, 2006; James & Gauthier, 2009; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2011), yet with *contrasting* effect directions.

In one set of studies, R1–S2 consistency *impaired* S2 perception (e.g., Kunde & Wühr, 2004; Müsseler & Hommel, 1997; Nishimura & Yokosawa, 2010; Oriet, Stevanovski, Jolicœur, & Cowan, 2003; Stevanovski, Oriet, & Jolicœur, 2006). In a study by Müsseler and Hommel (1997), for example, participants pressed a left or right key (R1) in response to a left- or right-pointing (respectively) arrowhead (S1) while they had to also identify the direction of a very briefly presented second arrowhead (S2). Incorrect judgments (R2) about S2 direction were more frequent when R1 and S2 were directionally consistent than when they were inconsistent, indicating a detrimental effect of R1 processing on the perception of consistent S2 stimuli. As perceptual performance with neutral R1 (responses that are neither consistent nor inconsistent with S2; e.g., double key presses) was found comparable with performance on *inconsistent* trials, the effect can be regarded as perceptual *impairment* by *consistent* responses (Müsseler & Wühr, 2002; Oriet, Stevanovski, & Jolicœur, 2003).

In a contrasting set of motorvisual dual-task studies, R1 processing *facilitated* S2 perception (e.g., Deubel, Schneider, & Paprotta, 1998; Hommel & Schneider, 2002; Müsseler, Wühr, Danielmeier, & Zysset, 2005; Paprotta, Deubel, & Schneider, 1999). Deubel et al. (1998), for example, had participants point to one of six different locations (R1), indicated by the color and orientation of a centrally presented triangular cue (S1). In one of these six locations, either the symbol “E” or “∃” (S2) was presented very briefly while the other five locations were filled with distractors. S2 discrimination performance was better when the target location

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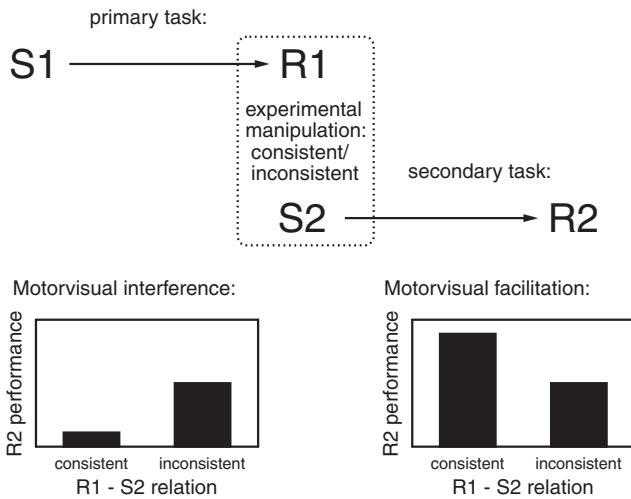


Figure 1. A motorvisual dual-task paradigm. In a primary task, participants respond with one response (R1) to one stimulus (S1). During planning or execution of R1, participants observe a second stimulus (S2). With the second response (R2), participants report their perceptual judgment about S2. The independent variable is typically the categorical or spatial consistency between R1 and S2. The figures on the bottom illustrate exemplary results for a typical motorvisual interference effect (performance in consistent conditions is inferior to performance in inconsistent conditions) and a typical motorvisual facilitation effect (performance in consistent conditions is superior to performance in inconsistent conditions).

of the pointing movement (R1) matched the location of the target stimulus (S2) than when these locations differed. Comparisons with neutral trials (trials without R1) indicated that the effect is due to a perceptual *facilitation* in R1–S2 *consistent* trials instead of an *impairment* of S2 perception by R1 movements to *inconsistent* locations.

Despite a substantial amount of empirical evidence for the *existence* of action influences on perception, it is currently unknown what determines the *direction* of such effects. Accordingly, Schütz-Bosbach and Prinz (2007) noted in their review of research on motorvisual effects “that action production sometimes reduces and at other times increases our perceptual sensitivity to similar events in the environment. Indeed, this issue is so far poorly understood and needs to be investigated further” (p. 351). The lack of an integrative theory poses, for current research into motorvisual effects, the apparent problem that effect direction cannot be properly predicted. As Muthukumaraswamy and Johnson (2007) noted in a related review, “[when] several lines of behavioral evidence of this sort are considered, it can be seen that it is difficult to know *a priori* whether facilitation or interference effects will be observed in any particular paradigm” (p. 52).

Here, we propose a solution to the problem of contradictory effect directions in motorvisual priming. The gist of our argument is that motorvisual *facilitation* is due to movement *control* processes, whereas motorvisual *impairment* is caused by action *planning*. Our suggestion is based on two observations. First, the majority of motorvisual *facilitation* studies reported facilitation for *spatial* R1–S2 consistency (e.g., Fagioli, Hommel, & Schubotz, 2007; Lindemann & Bekkering, 2009; Schiegg, Deubel, & Sch-

neider, 2003), whereas motorvisual *impairment* seems to be confined to cases where R1–S2 consistency is defined on a *categorical*, non-spatial level (e.g., Eder & Klauer, 2007; James & Gauthier, 2009; Kunde & Wühr, 2004). Second, recent findings and theoretical developments in motor cognition research suggest that action planning employs primarily categorical representations, whereas movement control employs exclusively spatial representations (e.g., Glover, 2004b).

We assume that planning processes tightly bind representations into stable action plans, preventing them from usage in other concurrent cognitive processes, such as perception of action-consistent stimuli. Thus, planning impairs concurrent perception. Movement control processes, on the contrary, constantly require highly accurate perceptions of *spatial* effector–target relations. Thus, movement programming shifts attention to *spatially* action-consistent areas in perceptual space. Hence, perceptual sensitivity for spatially action consistent stimuli is improved due to movement control demands. As a consequence, motorvisual interference effects can be observed only for categorical R1–S2 consistency, while spatial R1–S2 consistency gives rise to motorvisual facilitation. We refer to this set of assumptions as the planning and control model (PCM) of motorvisual priming. Despite the restriction of impairment to categorical and of facilitation to spatial R–S overlap, the PCM makes further predictions about different characteristics of motorvisual impairment and facilitation. According to the PCM, impairment should be affected by action context and should be sensitive to set-level compatibility between responses and stimuli, whereas facilitation should be unaffected by these factors. Evidence in support of both predictions has been obtained in several empirical studies (Hommel & Müssele, 2006; Thomaschke, Hopkins, & Miall, 2011; Wykowska, Hommel, & Schubö, 2011).

We organize our argument for the PCM as follows. In the subsequent section, we briefly review the previous empirical literature on impairment and facilitation effects in motorvisual dual-tasks. Then we review previous evidence for the processing of different representations in planning and control as well as for the impact of planning and control processes on perception. After specifying the PCM in more detail, we discuss its predictions and show how these predictions have been met in the previous empirical literature on motorvisual priming. Then we analyze the model’s explanatory power in the light of competitor models. We conclude by discussing potential extensions of the model.

Motorvisual Impairment and Facilitation

Motorvisual effects have been shown in a large variety of dual-tasks with different dimensions of overlap between R1 and S2. First, we review studies where the overlap between R1 and S2 had detrimental effects on S2 perception—motorvisual impairment studies. Then we turn to studies in which overlap between R1 and S2 improved S2 perception—motorvisual facilitation studies.

Motorvisual Impairment

Motorvisual impairment has been found in dual-tasks with overlap dimensions such as linguistic similarity, valence congruency, or symbolic meaning. On the linguistic level, Hommel and Müssele (2006, Experiment 3B) have shown a motorvisual impair-

ment effect for verbal R1–S2 consistency. These authors asked participants to speak out the word “left” (R1) in response to a left pointing arrowhead (S1) and the word “right” in response to a right pointing arrowhead. In a secondary task, participants had to identify a difficult to discriminate printed word “LEFT” or “RIGHT” (S2) and to report their perceptual judgment by a later key press (R2). S2 (the printed word) appeared shortly before, after, or during the execution of R1 (speaking a word). S2 identification rate was lower when R1 and S2 were consistent (e.g., speaking the word “left” while observing the word “LEFT”) than when they were inconsistent (e.g., speaking the word “right” while observing the word “LEFT”). These results indicate that primary response execution (R1 = word speaking) selectively impaired the perception of consistent secondary stimuli (S2 = printed words).

Besides word perception, the perception of word-consistent colors can also be impaired by word speaking (Kunde & Wühr, 2004, Experiment 3). In Kunde and Wühr’s (2004) experiment, participants had to read aloud (R1) visually presented color words (S1) while identifying difficult to discriminate color patches (S2), which were either consistent (e.g., reading the word “yellow” and perceiving a yellow color patch) or inconsistent (e.g., reading the word “green” while perceiving a red color patch) with R1. As in Hommel and Müsseler’s (2006, Experiment 3B) experiment, identification rates were higher for inconsistent R1–S2 pairings than for consistent ones. On the single letter level, verbal motorvisual consistency can also produce perceptual impairment. In a recent study by James and Gauthier (2009), participants drew curved or straight letters or shapes (R1) while they had to detect letters or shapes (S2) embedded in noise, as a secondary task. Identification of letters was impaired by concurrent motor performance, and the impairment was particularly pronounced when the category (letter/shape) and the form (straight/curvy) of R1 and S2 were consistent, indicating symbol-specific motorvisual impairment.

Evidence for motorvisual impairment by valence consistency comes from a study by Eder and Klauer (2007, Experiment 1). In a primary task, participants pressed a left or a right button (R1) in response to a visually presented strongly negative or positive word cue (S1). The word cue was assumed to “charge” the responses positively or negatively. In a secondary task, they reported the valence of a difficult to discriminate visually presented adjective (S2). In a further experiment (Eder & Klauer 2007, Experiment 2), the primary task consisted of simultaneously speaking the word “positive” (or “negative”) *and* pressing the left (or right) button (R1) in response to visual letter cues (S1), whereas the secondary task was, again, the discrimination of the valence of visually displayed adjectives. In both experiments, the identification rate for the adjectives’ valence was better when that valence was *inconsistent* with the valence of the primary response (R1), suggesting a detrimental effect from R1 processing on the perception of valence-consistent stimuli (S2).

The majority of motorvisual impairment studies have, however, examined effects from the processing of binary left/right response codes on the perception of symbolically consistent stimuli (symbols representing the binary category left/right). The most frequently applied response–stimulus sets in this line of research are left/right key presses and left/right pointing arrowheads. In a seminal study by Müsseler and Hommel (1997), participants made, in a primary task, a non-speeded left or right key press (R1) signaled by a left or right pointing arrowhead cue (S1). The

secondary task required the identification of a briefly presented and masked arrowhead pointing to the left or to the right (S2). When the categories of the primary response and secondary stimulus were consistent (e.g., a left key press with a left pointing arrowhead), secondary task correctness was lower than when they were inconsistent (e.g., a left key press and a right pointing arrowhead). Thus, execution of a binary choice reaction can impair the perception of a concurrently displayed symbolically consistent stimulus.

A recent study by Cardoso-Leite, Mamassian, Schütz-Bosbach, and Waszak (2010) has shown that R1 can also impair S2 when the categorical associations between response and stimulus have been acquired only within the experiment. In a practice phase, participants generated a random sequence of left and right key presses. The key presses were immediately followed by either a left or right tilted Gabor patch. Left key presses always produced right-tilted Gabor patches, and right key presses always produced left-tilted patches, or the other way around. This association was counter-balanced across participants. In a test phase, participants’ key presses (R1) were followed by difficult to discriminate left-tilted, right-tilted, or non-tilted Gabor patches (S2). In contrast to the practice phase, combinations of R1 and tilt-direction were now randomized. Participants were more accurate in detecting tilted S2 stimuli when the detection target (S2) had, in the practice phase, been deterministically produced by the current R1. Hence, actions specifically impair the perception of previously acquired visual action effects (see also Pfister, Heinemann, et al., 2011).

Motorvisual Facilitation

Motorvisual facilitation effects have been observed when responses and stimuli overlapped with regard to location, size, or orientation. A considerable number of studies have shown that actions can facilitate perceptual processing at action consistent locations. On the level of the left/right visual field, such effects have been shown by three previous motorvisual priming studies (Hommel & Schneider, 2002; Müsseler, Koch, & Wühr, 2005, Experiment 1; Müsseler, Wühr, et al., 2005). For example, Müsseler, Wühr, et al. (2005, Experiment 2) had participants press a left or a right key (R1) in response to a high or a low pitch tone (S1). In a secondary task, participants had to report whether a briefly displayed circle (S2) had horizontal or vertical gaps. The circle was displayed either on the left or right side of the screen. Identification performance in the secondary task was higher when the location of the primary response (R1) and the location of the secondary stimulus (S2) were consistent (e.g., right key press and symbol in the right visual field) than when they were inconsistent (e.g., right key press and symbol in the left visual field). Thus, responses facilitated stimulus processing at response consistent locations.

Motorvisual priming studies with pointing and grasping movements as R1 (e.g., Baldauf & Deubel, 2009; Baldauf, Wolf, & Deubel, 2006; Collins, Schicke, & Röder, 2008; Deubel et al., 1998) have shown that more complex movements can focus spatial attention in a more precise way to certain locations, rather than merely favoring one half of the visual field (see also Humphreys et al., 2005). In one of these studies (Deubel et al., 1998), participants had to point (R1) in response to a central visual cue (S1) toward one of 10 horizontally arranged positions. Secondary stimuli were

displayed in positions that spatially corresponded to the pointing targets. On each trial, a target appeared at one of the positions. Participants had to report (R2) which of the targets they had seen. Discrimination performance was higher when the R1 pointing target matched the display location of S2, indicating a motorvisual *facilitation* effect. An analogous facilitation effect has also been observed for cyclically arranged response and stimulus locations (Paprotta et al., 1999) and for grasping movements (Schiegg et al., 2003). Schiegg et al. (2003) have shown that a two finger grasping movement toward an object (R1) directs visual attention toward the two parts of the object that are to be touched by the two fingers (see Baldauf & Deubel, 2008, Experiment 1, for analogous results concerning bimanual pointing).

Whereas the previously reviewed studies applied paradigms in which the spatial consistency-dimension (visual field) was irrelevant to the secondary task (participants had to discriminate symbol-identity, not location), Koch, Metin, and Schuch (2003, Experiment 1) demonstrated that motorvisual location-priming also takes place when location is the task-relevant stimulus dimension. In their study, participants pointed in response to tone pitch (S1) from a home key toward two lateral response keys (R1) and had to report whether a small masked dot moved from the center quickly to the left or to the right side of the screen (S2). Consistency between response target location (R1) and stimulus target location (S2) yielded higher accuracy than R1–S2 location-inconsistency.

Actions can also prime other spatial dimensions besides location. Lindemann and Bekkering (2009, Experiment 3), for example, have shown a motorvisual priming effect for *orientation* consistency between R1 and S2. In a primary task, participants had to manually rotate a cross-like object (R1) either in clockwise or in counterclockwise direction. A secondary task required a speeded foot pedal response (R2) to a visual go signal (S2). The go signal consisted of a sudden tilt of a horizontal or vertical bar in either clockwise or counterclockwise direction. Reaction times for R2 were shorter when the movement direction of R1 and the tilt direction of S2 were consistent than when they were inconsistent, indicating motorvisual facilitation for orientation consistency.

Miall et al. (2006) have shown a case of motorvisual facilitation with a much higher degree of R1–S2 resemblance than the previously reviewed ones. These authors asked participants to execute one of two cyclical hand movements (open/close a fist vs. alternated pronation/supination) while monitoring a movie display of the same or of the other one of the two movements on a computer screen. The visual task was to respond verbally as soon as a deviant orientation of any fingers (e.g., victory sign) was detected within the monitored movement display (also see Stanley & Miall, 2009). When executed and observed movement were consistent (i.e., the same hand movement), verbal RTs were faster than when they were inconsistent—a motorvisual facilitation effect. Thus, motorvisual facilitation effect for spatial orientation can also be observed for complex displays of effector movements.

Some recent motorvisual facilitation studies have compared the spatial attentional effects of different movement types with each other, finding marked differences depending on the type of primary response with regard to the primed stimulus *dimension*. In a study by Fagioli, Hommel, and Schubotz (2007), participants had to either point to a location or to grasp and lift an object (R1) while detecting either location or size deviations in an unrelated regular

visual stimulus movement (S2). Deviations in size (a spatial dimension relevant for grasping control) were better detected during grasping movements, whereas deviations in location (a spatial dimension relevant to pointing movements) were better detected during pointing movements. Using a similar design, Wykowska, Schubö, and Hommel (2009) found facilitation for the search of luminance defined targets (S2) among distractors during *pointing* movements (R1), whereas *grasping* facilitated visual performance in the same task when the targets were defined by size. These results show that actions can facilitate, besides visual processing in certain *areas* on a spatial feature dimension (like left location or small size), processing on an entire spatial stimulus dimension such as location or size, when this dimension is particularly important for the control of the action.

Representations in Sensory-Motor Cognition

A basic assumption of the PCM is that action planning processes primarily categorical representations and movement control processes primarily spatial representations. Before reviewing evidence for this assumption, we specify in more detail how we distinguish between categorical and spatial representations and between action planning and movement control.

Definitional Issues

There is converging evidence from behavioral and neuropsychological research that cognitive processing makes use of two fundamentally different kinds of mental representations (Kosslyn, 2006; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Logan, 1995). One kind of representation is non-metric and relational. It is used to represent stimuli and responses as members of categories. Categories can be linguistic, semantic, symbolic, or spatial relational. We refer to these representations as categorical representations. Typical examples for categorical representations are representations that code whether a certain response falls into a response category in a binary choice task. Representations for word identities, for the meaning of symbols, or for valence categories (positive/negative) are other examples.

The other kind of mental representation has metric properties and codes exact spatial parameters of stimuli and responses. The spatial parameters for which metric representations have been empirically established are location, size, and orientation (Kosslyn, 1994). We refer to this kind of representation with *spatial* representations. Please note that some *categorical* representations have relational content that is sometimes referred to as “spatial” in a non-metric sense. For example, a categorical semantic representation of the word “left” represents a *meaning* that refers to binary categories like relative location or relative direction. However, we would not regard this representation as spatial, as it does not convey any metric information. Our usage of “spatial” is restricted to metric representations of spatial information.

Another crucial distinction in our model is that between action planning and movement control. Many traditional and current theories of motor cognition distinguish between a planning component and a control component of an action that each have neurally and behaviorally distinct characteristics (see Elliott, Helsen, & Chua, 2001, for a review). Action planning usually refers to the process of selecting an appropriate action based on the

current environmental situation and one's motivational state. A typical example of an action planning process is the selection of a response, given a certain imperative stimulus in a choice reaction task. Note that some authors differentiate action planning further into a selection and a programming stage (e.g., Pashler, 1994; Proctor & Dutta, 1995) where selection determines an abstract "non-motoric" representation of an action category, and programming translates this abstract representation into basic executable motor-parameters. Others have argued that motor cognition can better be understood by assuming a unified process encompassing selection and programming (e.g., Hommel, 2009). Our model does not rely on the distinction between selection and programming, and is thus compatible with both views. For our argument, it is only relevant that representations processed in action planning specify the basic parameters for the movement required to achieve the action goal. By basic parameters, we refer to the information necessary to initiate the movement. For a grasping movement, for example, planning would specify which object to grasp, whether a full hand grip or a precision grip is required, and which effector is most appropriate.

Once the basic movement parameters are chosen, movement control sets in. Most current theories of motor cognition assume that movement execution is accompanied by constant online monitoring mechanisms, ensuring that the movement reaches its intended goal (Bubic, von Cramon, & Schubotz, 2010; Wolpert & Ghahramani, 2000; Wolpert, Miall, & Kawato, 1998). Motorvisual feedback cycles are thought to constantly predict sensory consequences of the current state of the motor system and to integrate these predictions with actual sensory feedback and the intended action goal to diminish mismatch between actual movement and action goal. We refer to these monitoring processes with the term *movement control*.

Categorical and Spatial Representations in Action Planning and Movement Control

We assume that action planning processes primarily categorical representations and that movement control processes primarily spatial representations. This assumption has been supported by a considerable amount of neuroscientific and behavioral evidence (see Glover, 2004b, for a review).

With regard to action planning, research on stimulus–response compatibility has shown that RTs are faster when stimuli and responses overlap on a categorical dimension than when they do not (see Proctor & Vu, 2006, for a review). When, for example, a left-pointing arrowhead is mapped to a left key press, and a right pointing arrowhead is mapped to a right key press, RTs are faster than when the mapping is reversed (Wang & Proctor, 1996). Thus, the action planning process is affected by categorical information processing. Similar results have been found in studies with other categorical overlap dimensions, such as stimulus intensity/response force (Romaiguère, Hasbroucq, Possamaï, & Seal, 1993) and stimulus duration/response duration (Kunde & Stöcker, 2002).

Spatial representations (in the above defined sense) are not processed in action planning. Although some earlier theories had assumed that the precise spatial course of an action is preselected in advance of its initiation (Keele, 1968), current accounts of action cognition assume that metric spatial parameters are controlled only during the course of the movement (Hommel, 2009;

Schmidt, 1975). The processing of certain features in movement control is mostly studied with perturbation paradigms. In such paradigms, certain features of the movement target are quickly changed at or after movement onset (e.g., Prablanc & Pélissou, 1990). Fast corrections to perturbations of a certain target feature indicate that representations of that feature are processed in movement control (for reviews, see Desmurget, Pélissou, Rossetti, & Prablanc, 1998; Proteau, Boivin, Linossier, & Abahini, 2000). There is extensive evidence for online corrections for perturbed *spatial* features of movement targets, like location, size, and orientation. Paulignan, Mackenzie, Marteniuk, and Jeannerod (1991), for example, demonstrated quick reactions to online *location* perturbations. Others have shown that individuals can also compensate well for online *size* perturbations (Castiello, Bennett, & Chambers, 1998; Castiello, Bennett, & Stelmach, 1993; Glover, Miall, & Rushworth, 2005; Paulignan, Jeannerod, Mackenzie, & Marteniuk, 1991; van de Kamp, Bongers, & Zaal, 2009) until quite late in the course of a movement (Hesse & Franz, 2009). Likewise, an initially inappropriate hand *orientation* can be corrected to match target orientation in late phases of a grasping movement (Gosselin-Kessiby, Messier, & Kalaska, 2008), and perturbations of target orientation are compensated for quickly (Desmurget & Prablanc, 1997; Desmurget et al., 1996, 1995).

Several studies have explicitly investigated the different influence of categorical and spatial factors on action planning and movement control. Glover and Dixon (2002b) have adapted a paradigm by Gentilucci and Gangitano (1998) to investigate the relative timing of categorical and spatial effects on movement. Gentilucci and Gangitano found that the words "short" and "long" printed on objects primed the initial movement kinematics of grasping these objects in a direction as if the objects would have really been placed at the distance indicated by the respective word (for similar effects, see Bonfiglioli, Finocchiaro, Gesierich, Rositani, & Vescovi, 2009; Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Scorolli, Borghi, & Glenberg, 2009). Importantly, in the present context, Glover and Dixon have shown that the effects of categorical spatial priming on reaching in Gentilucci and Gangitano's paradigm are present at the beginning of the reaching movement but constantly decline over the course of the movement. This suggests that categorical representations of binary spatial relations are *not* processed in movement control. Instead, control processes compensated, during the course of the movement, for the wrongly planned initial kinematics during the course of the movement by processing metric spatial representations of the true spatial object properties. Another line of research has shown that categorical variables affect RT (a measure of action planning) rather than spatial movement accuracy (a measure of movement control). For example, influences from subsequent action requirements seem to be restricted to action planning but not affecting movement control. Fleming, Klatzky, and Behrmann (2002) had participants first reach to—and then either grasp, post, or lift—an object. Different overarching action goals affected the RT of initial reaches but not the reaching movements themselves. Moreover, Liu, Chua, and Enns (2008) have shown that control seems to be unaffected by verbal processing. Dual-task interference from a secondary unrelated letter identification task on a pointing movement was observed for RT but not for movement accuracy.

The involvement of different representations in planning and control is also a basic assumption of a sensory-motor processing

model by Glover (2002). In a review (Glover, 2004b), he marshaled a substantial amount of evidence for the processing of categorical representation in action planning and for the processing of spatial representations in movement control. One of Glover's central concerns in developing his models was, however, to explain earlier empirical findings (Haffenden & Goodale, 1998; Jackson & Shaw, 2000; van Donkelaar, 1999; van Doorn, van der Kamp, & Savelsbergh, 2007; Westwood, Chapman, & Roy, 2000) showing that the visual illusory context of movement targets has seemingly no effect on movement control (see, e.g., Glover & Dixon, 2001a, 2001b, 2002a). These older empirical studies have, since then, been heavily criticized (Danckert, Sharif, Haffenden, Schiff, & Goodale, 2002; Franz, Scharnowski, & Gegenfurtner, 2005; Grierson & Elliott, 2009; Handlovsky, Hansen, Lee, & Elliott, 2004; Meegan et al., 2004; Mendoza, Elliott, Meegan, Lyons, & Welsh, 2006). Consequently, it is commonly assumed now that movement control is not immune against visual illusions (see Franz & Gegenfurtner, 2008, for a review). Thus, one of the main explanatory targets for Glover's models needs no explanation anymore, as it has been rejected by empirical means with further developed experimental designs and measurements. This does, however, not devalue his model as such, because there is solid empirical evidence for different representations in planning and control that has nothing to do with visual illusions (see Glover, 2004a, and above). Thus, we retain the basic assumption of Glover's model, namely that action planning processes categorical representations, and movement control processes spatial representations.

The PCM of Motorvisual Priming

In the preceding subsections, we have argued that motor planning employs primarily categorical representations, whereas motor control employs primarily spatial representations. Here, we propose that these assumptions, together with the different *functions* that mental representations have in action planning and movement control, explain why actions, on the one hand, impair the perception of categorical stimulus features but, on the other hand, facilitate the perception of spatial stimulus features.

Binding and Motorvisual Impairment

The function of action planning is to integrate information about action goals, situational factors, and knowledge about one's own motor system into a consistent action plan. This integration can be considered as binding representations of all relevant aspects of the action together and stabilizing this binding so that other cognitive processes cannot interfere with it before or during action initiation. To achieve this stabilization, the binding of representations inhibits their manipulation by other cognitive processes. Consequently, representations that are bound in action plans are less accessible for other cognitive processes such as visual perception. We do not make any assumption about the specific physical realization of the binding process for action plans. Several different neural binding models could account for the binding of intermodal representations in action plans (Hommel, 2004). Important for our model is only that binding representations in an action plan implies limiting the accessibility of these bound representations for other cognitive processes. Others have described this phenomenon as "occupa-

tion" (e.g., Schubö, Aschersleben, & Prinz, 2001) or "encapsulation" (Müsseler, 1999) of representations by action plans. It follows that when a particular non-spatial representation is currently involved in an action planning process, concurrent visual perceptual processes have only limited access to this representation. Consequently, perception of stimuli that possess the represented feature is impaired. This assumption serves to explain the previously found motorvisual interference effects with categorical response and stimulus features.

Attentional Focus and Motorvisual Facilitation

Spatial features are, however, not affected by this planning-based motorvisual impairment phenomenon. This is due to their function in movement *control* processes. Movement control constantly processes representations of the spatial characteristics of the action goal, the effector, and their spatial relation to each other to reduce any potential mismatch between the predicted course of the movement and momentary spatial target characteristics (Diedrichsen, Shadmehr, & Ivry, 2010; Miall, 1998, 2003; Wolpert et al., 1998). Whereas motor planning selects rather gross motor parameters by relatively slow integration of a large variety of contextual information, motor control consists in rapid fine tuning of just the spatial properties of the action and target. This tuning function requires a fast, precise, and fine-grained visual analysis of the course of the movement and its target. Such an analysis greatly benefits from an attentional focus on the action relevant regions in representational space while ignoring others. Consequently, planning an action automatically shifts spatial attention to aspects that are relevant to the planned action to facilitate consecutive control processes. This shift of spatial attention takes place on two different levels, on the feature level and on the dimension level. Planning, for example, to grasp a small object facilitates the processing of size information in general (the dimension level), because it is relevant for online adjustment of grip aperture. However, it also facilitates visual processing of small objects in particular (the feature level), because the quick perception of any changes in the target object is essential for online control of the grasping movement.

With regard to feature dimensions, planning a particular action facilitates visual attention selectively for the spatial feature *dimension* that is relevant for controlling the resulting movement. Planning a grasping movement would, for example, facilitate information processing on the spatial feature dimension "size" as well as on the spatial feature dimension "orientation." The control of other actions, like pointing, does not require the prioritized processing of size and orientation information. Consequently, processing of representations on the feature dimensions "size" and "orientation" are not facilitated by planning of a pointing action. The spatial feature dimension "location" is required by the control of any hand movement as long as it has a spatially defined goal, even if it is only pressing down a certain key. Thus, hand movements in general—key presses, pointing, or grasping—facilitate processing on the spatial feature dimension "location," whereas verbal articulatory movements, on the other hand, do not facilitate visual location processing.

We also propose that planning of different types of movement facilitate processing on a particular feature dimension to different degrees. Although planning of any hand movement facilitates

processing of metric location representations, some movements with a particularly high demand of location control (e.g., precise pointing) facilitate location processing to a higher degree than others do (e.g., a key press).

With regard to features—as opposed to feature dimensions—we propose that planning a movement also shifts visual attention to the relevant areas in representational space *within* a feature dimension. Planning a pointing movement, for example, facilitates not only location processing in general but it also shifts visual attention to the region where the pointing movement is initially aiming at. Control of pointing movements benefits not only from facilitated processing of location in general but also from facilitated visual processing at *particular* locations. Likewise, planning a grasp of a horizontally oriented bar facilitates the processing of horizontally oriented objects. Planning to grasp a large object facilitates the visual processing of objects that are large.

In summary, we propose that perception of categorically action-consistent stimuli is impaired by binding of representations required in action plans, whereas perception of spatially action-consistent stimuli is facilitated by an attentional focus on spatially control-relevant stimuli and stimulus dimensions (for a schematic of illustration of the model, see Figure 2).

Explanatory Power of the PCM

The main purpose of the PCM is to explain why some motorvisual dual-tasks show impairment and others show facilitation effects. In the subsequent subsections, we show that the PCM would correctly predict the observed effect direction for each reviewed motorvisual study. Moreover, the PCM gains further plausibility from more specific predictions about motorvisual impairment and facilitation, which have been confirmed by recent empirical studies. The association of motorvisual impairment with planning and of motorvisual facilitation with control implies that some of the major differences between planning and control should also be observable in motorvisual impairment and facilitation. In particular, the PCM predicts that impairment should be affected by set level compatibility between R1 and S2, and by action context, whereas facilitation should not. The time window of both effects should, however, be comparable. In the following subsections, we discuss the individual predictions of the PCM, and show how these predictions have been investigated empirically.

Categorical and Spatial Overlap

The PCM predicts that categorical overlap between R1 and S2 leads to motorvisual impairment. This prediction is, to our knowledge, met by all previous dual-task studies that have shown motorvisual impairment effects. The motorvisual impairment studies, reviewed above, applied R1–S2 overlap with regard to words (Hommel & Müsseler, 2006), the valence of words (Eder & Klauer, 2007, 2009), letters (James & Gauthier, 2009), colors (Kunde & Wühr, 2004), categorical action effects (Cardoso-Leite et al., 2010), and binary left/right categories (Müsseler & Hommel, 1997). These dimensions of overlap are all commonly regarded as non-metric categorical.

For metric spatial overlap between R1 and S2, the PCM predicts a motorvisual facilitation effect. In particular, we predict dimension-wise facilitation effects when the congruency between R1 and S2 is manipulated on the dimension level, and we predict facilitation effects on the feature dimension when R1–S2 congruency is manipulated on the feature level. To our knowledge, this prediction is also met by all previous dual-task studies that have reported a motorvisual facilitation effect either on the dimension or on the feature level.

With regard to the dimension level, the planning of pointing actions facilitates the visual processing of location information, whereas planning a grasping action facilitates visual processing of size information (Fagioli, Hommel, & Schubotz, 2007; Wykowska et al., 2009). With regard to the feature level, lateral hand or finger movements have been shown to facilitate visual processing in the ipsilateral visual field (Hommel & Schneider, 2002; Müsseler, Koch, & Wühr, 2005, Experiment 1; Müsseler, Wühr, et al., 2005), whereas pointing or grasping movements facilitate visual processing in target compatible locations (Deubel et al., 1998; Linnell, Humphreys, McIntyre, Laitinen, & Wing, 2005). The same has been shown for the metric spatial dimensions “size” and “orientation.” Planning a grasping movement to a small or a large object automatically shifts attention toward size consistent objects (e.g., grasping a small object facilitates perceptual processing of any small objects; see Symes, Ottoboni, Tucker, Ellis, & Tessari, 2010; Symes, Tucker, Ellis, Vainio, & Ottoboni, 2008). Likewise, grasp-

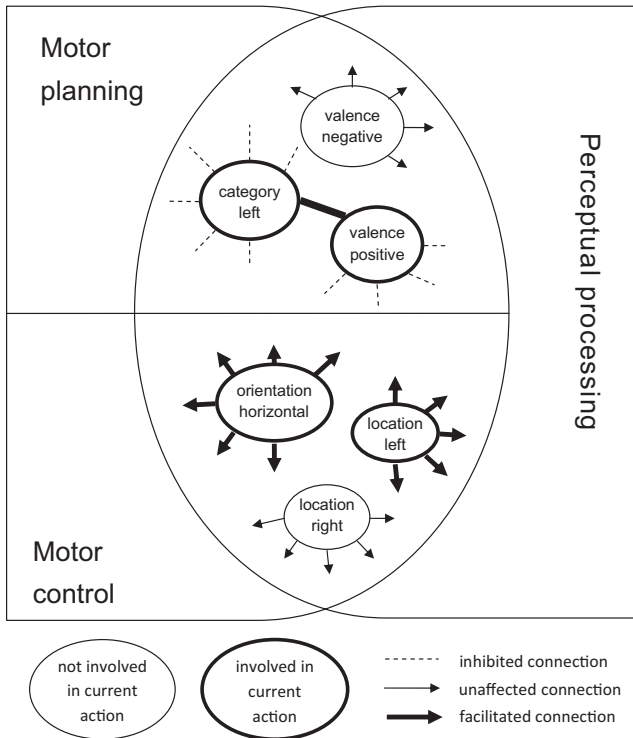


Figure 2. Schematic illustration of the planning and control model (PCM). Motor planning binds categorical representations of the action features (solid line between “category left” and “valence positive”) so that potential connections to other cognitive processes, such as perception, are inhibited. Motor control activates spatial representations of the action so that their potential connections to other cognitive processes, such as perception, are facilitated in general. This has the effect that, during motor processing, the perceptual processing of categorically action consistent stimuli is impaired, whereas the perceptual processing of spatially action consistent stimuli is facilitated.

ing movements facilitate the processing of orientation consistent objects (Lindemann & Bekkering, 2009).

Note, however, that in the majority of interference studies, R1–S2 overlap was manipulated on a S2 dimension that was task relevant, whereas in the majority of facilitation studies, overlap was manipulated on a task irrelevant S2 dimension. One might argue against the PCM, that it is rather the relevance of S2 features that is crucial in determining whether S2 perception is facilitated or impaired by compatible R1. Task relevance of stimuli has been shown to strongly affect the coding of stimulus features in spatial or in a verbal mode (Miles & Proctor, 2011). This alternative to the PCM could, however, be rejected on two counts. First, Pfister, Heinemann, et al. (2011) showed that S2 detection can be impaired by compatible R1 when R1–S2 overlap is irrelevant to the detection task. Participants were better in detecting S2 that have been R1 effects in a previous training phase, although S2 identity was irrelevant to S2 detection in the test phase (see also Cardoso-Leite et al., 2010). Second, for motorvisual facilitation, a study by Koch et al. (2003) revealed that R1 can facilitate S2 perception for S2 features that are task relevant. Location identification of a laterally presented dot was improved when R1 key presses were ipsilateral relative to when they were contralateral.

Moreover, the predictions of the PCM concerning facilitation and interference have also been confirmed by a recent comparative EEG study (Press, Gherri, Heyes, & Eimer, 2010), where responses were compatible to stimuli on a categorial and on a spatial dimension, and where *both* dimensions were task *irrelevant*. Participants observed displays of finger movements while executing their own finger movements. Visual event-related brain potentials were decreased when movement *categories* were compatible (e.g., both finger taps) relative to when they were incompatible (e.g., a finger tap and a finger lift). When observed and executed movements were compatible on a *spatial* dimension (i.e., at corresponding locations), visual brain potentials were increased relative to when they were incompatible (i.e., at different locations; also see Gherri & Eimer, 2010).

Thus, the PCM model can reconcile the frequently recognized (e.g., Müsseler, 1999; Muthukumaraswamy & Johnson, 2007), but previously unresolved (Schütz-Bosbach & Prinz, 2007), contrast concerning effect directions in previous motorvisual priming research.

Categorical Representations of Spatial Relations

Among the most puzzling findings in previous motorvisual priming research were some sets of studies with R1–S2 overlap on, seemingly, the same dimension but with opposing effects directions. For example, lateral key presses *impaired* compatible arrowheads in one set of studies (e.g., a left key press impaired a left pointing arrowhead; Müsseler & Hommel, 1997; Oriet, Stevanovski, & Jolicœur, 2007). However, in another set of studies, with nearly identical experimental designs, lateral key presses *facilitated* perception of stimuli in the compatible visual field (e.g., a left key press facilitated stimuli on the left; Hommel & Schneider, 2002; Koch et al., 2003, Experiment 1; Müsseler, Koch, & Wühr, 2005, Experiment 1; Müsseler, Wühr, et al., 2005, Experiment 2). On first sight, both types of studies applied a R1–S2 overlap that is in the widest sense “locational.” However, a closer

look at the involved representations shows that there is a crucial difference between both types of experiments.

In the one type of studies, the overlap is with regard to *categorical* representations of “location.” The categorical representation of a left key press (representing it as an element of a binary response class) overlaps with the categorical representation of an arrowhead symbolizing left location or direction. According to the PCM, the category for “left” is bound into an action plan and is, thus, less available for the perception of a categorically compatible stimulus. Consequently, an impairment effect is observed from lateral key presses on the perception of compatible arrowheads (Müsseler & Hommel, 1997; Müsseler, Wühr, & Prinz, 2000; Stevanovski, Oriet, & Jolicœur, 2002).

In the other type of studies, the overlap is, however, on a *metric* dimension. A key press has, as a hand movement, also a metric representation of its spatial location. When this location is to the left of the body midline, visual processing in locationally overlapping visual areas (i.e., the left visual field) should, according to the PCM, be facilitated. Consequently, motorvisual facilitation is observed when R1 and S2 overlap in location in a metric spatial sense, as is the case with lateral key presses and lateral stimulus presentations (Hommel & Schneider, 2002; Koch et al., 2003, Experiment 1; Müsseler, Koch, & Wühr, 2005, Experiment 1; Müsseler, Wühr, et al., 2005, Experiment 2).

An analogous contrast between opposing effect directions with seemingly the same overlap dimension has been found for the spatial overlap dimension “orientation.” In a study by Cardoso-Leite et al. (2010), participants learned that one of two key presses was deterministically followed by a Gabor patch tilted in clockwise direction and that the other key press was deterministically followed by a Gabor patch in counterclockwise direction. In a consecutive test phase, they had to detect whether patches were tilted in a certain direction while again executing the two key presses. Orientations were now randomly paired with key presses. In the test phase, key presses selectively *impaired* the perception of patches with the orientation that the key press had deterministically produced in the learning phase. Thus, key presses impaired orientation compatible stimuli. However, in a study by Lindemann and Bekkering (2009, Experiment 3), grasping movements *facilitated* the perception of bars in grasping-compatible orientations relative to bars with grasping incompatible orientations.

Again, differentiation between the different types of “orientation” representations resolves the contrast in effect direction. In the study by Cardoso-Leite et al. (2010), the overlap between R1 and S2 was on a categorial representational dimension. During the acquisition phase, key presses affected the tilt of the patches in a binary categorical fashion. Response category determined which of two alternative tilts was observed. Any potential metric properties of the key presses were unrelated to the orientation of the patches. Thus, binary orientation categories were associated with the key presses. Action planning also involves the processing of learned action effects (Elsner & Hommel, 2001; Kiesel & Hoffmann, 2004; Kunde, 2001; Pfister, Kiesel, & Hoffmann, 2011; Pfister, Kiesel, & Melcher, 2010; see Shin, Proctor, & Capaldi, 2010, for a review). Thus, in the test phase of Cardoso-Leite et al.’s study, categorical representations of the patches’ orientations were bound into the action plans for the key press. This impaired, according to the PCM, processing of stimuli with compatible

orientation categories, leading to the observed motorvisual impairment effect.

In the study by Lindemann and Bekkering (2009), R1–S2 overlap was with regard to metric representations of orientation. R1 were grasping movements. The control of grasping movements, in contrast to the control of key presses, requires the processing of metric orientation information. Thus, according to the PCM, planning a grasping movement facilitates visual processing of metric representations of orientation in general and, in addition, visual processing of metric representations of grasp-compatible orientations in particular. Consequently, the perception of grasping compatible stimuli was facilitated in Lindemann and Bekkering's study.

These examples demonstrate the importance of precisely distinguishing between categorical and metric representation to explain motorvisual priming phenomena. This distinction is one of the key features of the PCM. As previous models of motorvisual priming did not make this distinction, they were not able to explain contrasting effect directions between sets of studies that differ only in the type of representational overlap (binary categorical vs. metric spatial) on seemingly the same feature dimension.

Set Level Compatibility in Impairment and Facilitation

Set level compatibility is the degree to which a stimulus set and a response set are physically or conceptually similar (Fitts & Deininger, 1954; Kornblum, Hasbroucq, & Osman, 1990; Proctor & Vu, 2006). For example, responding with the words "left" or "right" to a left or to a right arrowhead has a relatively lower set level compatibility than responding with the words "left" or "right" to the written words "left" and "right." Set level compatibility is to be distinguished from element level compatibility, which refers to the compatibility of the mapping between elements of a stimulus and a response set. Mapping the response-word "left" to the stimulus-word "left" and the response word "right" to the stimulus word "right" is compatible on the element level, whereas the reverse mapping is incompatible. Note that at least some set level compatibility is a precondition for element-level compatibility. An increase of set level compatibility typically leads to better response performance (Fitts & Deininger, 1954; Kornblum et al., 1990). The effect of set level compatibility on performance is commonly thought to be located at the response selection stage (see, e.g., Lien & Proctor, 2002; Wang & Proctor, 1996).

Response selection is part of what we refer to with "action planning" in our model. Consequently, the PCM would predict that motorvisual impairment is affected by set level compatibility. When feature dimensions overlap to a higher degree between R1 and S2, a stronger motorvisual impairment effect should be observed. With higher set level compatibility, more features would overlap in the case of element compatible R1–S2 pairing. Consequently, more features needed to form a S2 percept would be bound in the concurrent action plan, and the perceptual impairment would be more severe.

The motorvisual facilitation effect should not, according to the PCM, be affected by set level compatibility. The facilitation effect is not dependent on mechanisms of response selection or feature binding. Its function is movement control, and shifting attention to spatially movement compatible regions in perceptual space sup-

ports control, independent of how exact is the match between stimulus and response. A hand movement, for example, should always facilitate location processing, no matter which other dimensions overlap between action and stimulus (e.g., orientation or categorical dimensions, such as color). Likewise, grasping movements should facilitate size processing to the same degree for stimuli that match with the grasping movement with regard to color or orientation. This is because variation of the color or orientation does not diminish the facilitation's functional relevance for movement control. Size processing is always important for grasping (to adjust grip aperture), independent of whether the orientation (which is also automatically facilitated) requires more or less online correction.

The PCM's prediction that set level compatibility affects motorvisual impairment, but not control, has been explicitly tested in several studies. In different experiments, Hommel and Müsseler (2006) tested combinations of two response sets and two stimulus sets with different degrees of set level compatibility. R1 sets were speaking the words "left" or "right" and pressing a left or a right key. S2 sets were the written words "left" or "right" and a left or a right pointing arrowhead. The combination between spoken and written words, as well as the combination between arrowheads and key presses, has relatively high set level compatibility, whereas the other combinations have relatively low set level compatibility (Proctor & Wang, 1997). Within each experiment, element-compatibility between R1 and S2 was manipulated trial-wise. In experiments with high set level compatibility, the expected motorvisual impairment effect for element-level compatible trials was found, whereas no such effect was observed in experiments with relatively low set level compatibility (Hommel & Müsseler, 2006). These results show that set level compatibility affects motorvisual impairment, as predicted by the PCM. Note, however, that element level compatibility effects are usually also present in single tasks with low set level compatibility, only with a smaller magnitude relative to high set level compatibility (Proctor & Wang, 1997). The reason for the absence of significant impairment effects for R1–S2 pairing with low set level compatibility (Hommel & Müsseler, 2006) is probably the generally lower effect size of motorvisual dual-task effects compared to visuomotor single task effects and, consequently, a lower statistical power in the former type of studies (Ward, 2002). A high degree of set level compatibility might be a precondition for motorvisual impairment effects to occur. Note, however, that R1–R2 impairment in dual-tasks has also been observed for low set level compatibility (i.e., different modalities; Fournier et al., 2010).

Wykowska, Hommel, and Schubö (2011) have investigated the effects of set level compatibility on motorvisual facilitation. Participants had to plan either a pointing or a grasping movement while detecting a size-oddball target. According to the predictions of the PCM, perceptual performance during planning a grasping movement was superior to performance during planning a pointing movement, because planning a grasping movement automatically facilitates visual processing of size information (see above; also see Fagioli, Hommel, & Schubotz, 2007; Wykowska et al., 2009). Set level compatibility has also been manipulated between experiments. In one experiment, the grasping targets (paper cups on boards) were cyclically arranged, as the visual targets were. This yielded a high set level compatibility between R1 (grasp) and S2 (size defined visual target). In another experiment, grasping targets

were arranged in a horizontal line, whereas visual detection targets were still arranged cyclically, yielding a relatively low set level compatibility between R1 and S2. No effect of the set level compatibility on the motorvisual facilitation effect was observed, confirming the PCM's prediction that the motorvisual facilitation effect is independent of set level compatibility.

Action Context in Motorvisual Impairment and Facilitation

An obvious difference between action planning and movement control is the role of context in both processes, which should according to the PCM be reflected in an analogous difference between motorvisual impairment and facilitation. Context is essentially involved in action planning, whereas movement control is relatively independent from context. The function of action planning is to initiate the most appropriate movement pattern for reaching a given action goal. *Which* action is most appropriate to achieve a certain goal in a particular situation is highly dependent on context. Thus, the processing of contextual information plays a major role in action planning. Accordingly, substantial numbers of studies have shown direct influences of contextual aspects on action planning processes. For example, the already discussed effects from verbal semantic processing on movement RTs (e.g., Bartolo, Weisbecker, & Coello, 2007; Lindemann, Stenneken, van Schie, & Bekkering, 2006) and initial movement parameters (Gentilucci et al., 2000; Glover & Dixon, 2002b; Scorolli et al., 2009) can be seen as evidence for the effects of actually task-irrelevant verbal context on action planning.

Control processes are, on the contrary, relatively immune to contextual influences. The context-independence of control is due to its strong attentional focus on spatially movement consistent stimuli. The function of control is to quickly process motorvisual feedback signals to launch rapid online corrections for potential spatial movement–goal mismatches. Thus, processing speed is an important aspect of control (see, e.g., van de Kamp et al., 2009) that demands attentional focus but practically precludes the integration of any substantial amount of non-essential contextual information (except focused and spatial information).

The PCM's prediction—that motorvisual impairment is susceptible to contextual factors, whereas motorvisual facilitation is not—is in accordance with the previous literature and has directly been tested in a recent comparative study (Thomaschke et al., 2011; also see below). Previous motorvisual priming studies have clearly shown that motorvisual impairment can indeed be modulated by contextual influences. In a motorvisual impairment experiment by Eder and Klauer (2009), for example, ventral or dorsal manual lever-movements (R1) were, for one participant group, instructed as “away” (negative valence) from the body or “toward” (positive valence) the body. For the other group of participants, the same movements were described as “up” (positive valence) or “down” (negative valence). The secondary task required the identification of adjectives (S2) with positive or negative valence. Eder and Klauer found a motorvisual impairment effect from R1 processing on S2 perception. This effect was, however, strongly modulated by the different R1 instructions for both participant groups. When the dorsal lever movement was described as “toward” the body, it impaired selectively the perception of adjectives with *positive* valence. When the same movement was described as

“down,” it selectively impaired adjectives with *negative* valence. The same contrast was observed for ventral movements, suggesting that response context strongly influences the motorvisual impairment effect. For the motorvisual facilitation effect, such contextual modulations by instruction manipulation have not been investigated.

Another important aspect of action context, despite action valence, is the action trigger (S1) and its congruence to R1. Whether an action is cued by a congruent stimulus or by an incongruent one has major effects on the processing of that action, as evidenced by slower and more error prone reactions for incongruent S–R mappings compared to congruent ones (Donders, 1868; Fitts & Deininger, 1954; Proctor & Vu, 2006). These effects are commonly thought to be due to action planning instead of movement control (see above; also see Proctor & Vu, 2006). Thus, the PCM would predict that S1–R1 congruency should affect the motorvisual impairment effect but not the motorvisual facilitation effect. This prediction has previously been confirmed for motorvisual impairment by Wühr and Müsseler (2002). In a primary task, participants had to react with left or right button presses (R1) to high or low tones (S1). One group of participants had to respond with a left key press to the low tone and with a right key press to the high tone, whereas the mapping was reversed for the other group. Low tones correspond to the spatial category “left,” whereas the higher of two tones corresponds with the category “right” (see Deutsch, Hamaoui, & Henthorn, 2007; Lidji, Kolinsky, Lochy, & Morais, 2007; Nishimura & Yokosawa, 2009; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006; Wühr & Müsseler, 2002, Experiment 3). Thus, the low-left/high-right mapping can be regarded as congruent on a categorical level, and the low-right/high-left mapping can be regarded as incongruent. In a secondary task, participants had to report the direction of R1-consistent or R1-inconsistent arrowhead stimuli (S2). However, as cue-context affects response planning and, according to the PCM, planning processes underlie the motorvisual impairment of action-consistent perceptions, one should expect that congruence versus incongruence of S1–R1 mapping would strongly modulate the motorvisual impairment effect for R1–S2 consistency. That is indeed what Wühr and Müsseler (2002) observed. For participants with *congruent* S1–R1 mapping, a substantial motorvisual impairment effect from R1 processing on consistent S2 stimuli was found. The group of participants with incongruent S1–R1 mapping did not, on the contrary, show any effects from R1 processing on S2 identification. These results confirm the PCM's prediction that contextual modulations affect the motorvisual impairment effect.

In a recent extension of Wühr and Müsseler's (2002) study, we directly compared the modulation from S1–R1 congruency on motorvisual impairment with categorical R1–S2 consistency, and on motorvisual facilitation for spatial R1–S2 consistency (Thomaschke et al., 2011). With regard to motorvisual impairment, we replicated Wühr and Müsseler's findings: motorvisual impairment with congruent S1–R1 mapping, and no impairment effect with incongruent S1–R1 mapping. With regard to motorvisual facilitation, we substituted horizontal or vertical symbols in left or right locations for the left or right pointing arrowheads as S2 stimulus set. Thus, the R1–S2 compatibility was on a spatial (location) dimension now, suggesting a motorvisual facilitation effect (see Müsseler, Wühr, et al., 2005). Indeed, we found a facilitation effect, and, importantly for the present argument, the facilitation

effect was not modulated by S1–R1 mapping context. We observed a substantial motorvisual facilitation effect with congruent S1–R1 mapping as well as with incongruent S1–R1 mapping. These findings confirmed the PCM’s prediction that action context affects motorvisual impairment but not motorvisual facilitation.

The Time Course of Motorvisual Interference and Facilitation

The PCM claims that the cognitive *functions* of the motorvisual impairment and the motorvisual facilitation effect are quite different. The function of the impairment effect is to stabilize action plans by preventing cognitive interference with features bound into the action plan. The function of motorvisual facilitation is to support movement control by attentional focus. Despite their different functions, both effects are, according to the PCM, caused by the same process: action planning. Action planning binds categorical representations, causing the impairment effect, but also shifts attention to movement relevant areas in representational space. Consequently, the PCM predicts that motorvisual impairment and facilitation can be observed on about the same time scale. Both effects should emerge during the planning process of an action, irrespective of when the action is initiated.

Action plans are stabilized throughout the course of an action to prevent interference from other cognitive processes—unless the action goal changes and the action plan needs to be updated. Thus, representations bound in an action plan should be unavailable for perception during the whole course of the action, producing a motorvisual interference effect from the beginning of the planning process until the action has been executed and the representations are unbound again.

Likewise, motorvisual facilitation should start with the action planning process, because an action plan is usually followed by a movement and, hence, by control demands. Movement control lasts until the action goal is reached. Thus, motorvisual facilitation should also be present throughout the entire movement.

These predictions are in line with previous evidence. Motorvisual interference has been observed from 2,000 ms before a Go-signal for R1 (Hommel & Müsseler, 2006; Wühr & Müsseler, 2001) until 1,000 ms after a R1 Go-signal (Cardoso-Leite et al., 2010; Oriet, Stevanovski, & Jolicœur, 2003; Oriet et al., 2007; Oriet, Stevanovski, Jolicœur, & Cowan, 2003). Motorvisual facilitation has also been shown to be present long before action initiation (see Fagioli, Hommel, & Schubotz, 2007; Wykowska et al., 2009). In the previously discussed study by Fagioli, Hommel, and Schubotz (2007), for example, the detection of size-deviation was already facilitated by *planning* a grasping and lifting action, whereas the detection of location-deviation was already facilitated by *planning* a pointing movement. Fagioli, Ferlazzo, and Hommel (2007) have shown that it is not necessary that an action plan is executed at all for the motorvisual facilitation effect to occur. Even passively watching a pointing or lifting action from videotape facilitates the corresponding perceptual dimension. Thus, processing of very abstract representations of an action plan seems to be sufficient to trigger dimension specific perceptual facilitation. Furthermore, a recent comparative study has shown that within the same paradigm, motorvisual impairment for categorically action-compatible stimuli and motorvisual facilitation for spatially action-

compatible stimuli occur during nearly the same time window (Thomaschke et al., 2011).

The PCM and Other Models of Motorvisual Priming

Several models have previously been put forward to explain motorvisual priming effects (see Müsseler, 1999; Schneider, 1995). Most of them differ from the PCM in that they do not attempt to explain the contrast of effect directions found in motorvisual priming, but rather they focus on either motorvisual impairment (Hamilton, Wolpert, & Frith, 2004) or on facilitation (Baldauf & Deubel, 2010; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Schneider, 1995). Other models attempted to reconcile different kinds of effects from action on perceptual processes; however, these effects were not qualitative perceptual impairment or qualitative perceptual facilitation but were other motor-induced changes in vision. Zwickel and Prinz’s (2011) model, for example, reconciles assimilation bias and contrast bias from actions on perceptual judgments of illusory motion, whereas a model by Christensen, Ilg, and Giese (2011) explains different interactions between actions and concurrent biological motion perception (also see Grosjean, Zwickel, & Prinz, 2009; Stanley, Gowen, & Miall, 2007; and the later subsection on motorvisual bias). A related model by Press et al. (2010) explains different effects from action on perceptual EEG signals. Still others explain motorvisual impairment and facilitation in an integrative manner (e.g., Hommel, 2009; Müsseler, 1999; Muthukumaraswamy & Johnson, 2007), but they cannot explain the full range of motorvisual priming effects covered by the PCM. Thus, the PCM is, to our knowledge, the only model to date that can explain the results of the entire motorvisual dual-task priming studies reviewed above. However, the PCM has not been developed from scratch but instead builds up on several elements from previous motorvisual models. In the following subsections, we discuss which elements have been adopted from previous models but also how the PCM differs from and goes beyond those models.

The most important building block of the PCM is the theory of event coding (TEC; Hommel, Müsseler, Aschersleben, & Prinz, 2001). The basic claim of the TEC is that perceptual representations of action effects are processed in action planning. This claim is also implicitly assumed by the PCM, because it explains why actions can affect perception at all. However, two more specific, TEC-inspired hypotheses have been integrated and modified in the PCM to explain the effect directions in motorvisual priming—namely the *code occupation hypothesis* and the *attentional weighting hypothesis* (see the following subsections).

However, the most important claims of the PCM—the association of impairment with planning and categorical representations, and the association of facilitation with movement control and spatial representations—have not been included in any previous model. Thus, this distinction can be seen as the crucial novelty of our model, and it is also the source of the model’s advantage in explanatory power over previous models (see the Explanatory Power of the PCM section).

The Code Occupation Hypothesis

The first part of our proposal—the claim that action planning binds representations and thereby impairs perception of action

consistent stimuli—has been previously put forward by others (see, e.g., Eder & Klauer, 2007; Hamilton et al., 2004; Müsseler & Hommel, 1997; Müsseler & Wühr, 2002; Schubö, Prinz, & Aschersleben, 2004) to account for motorvisual priming and related phenomena (Eder, Müsseler, & Hommel, 2012; Mattson & Fournier, 2008; Stoet & Hommel, 1999). This assumption is commonly referred to as the code occupation hypothesis (see Wiediger & Fournier, 2008, for a discussion). Most proponents of this hypothesis have not, however, distinguished between categorical and spatial representations in action and perception and have instead assumed explicitly or implicitly that the code occupation hypothesis applies to all kinds of action relevant visual representations. The main difference between the PCM and previous models incorporating the code occupation hypothesis is that we assume code occupation to be effective only for categorical representations, because action planning primarily processes categorical representations. Similar restrictions have been made by two studies in the area of motorvisual judgment bias (Zwicker, Grosjean, & Prinz, 2010) and motor-motor interference (Wiediger & Fournier, 2008). Zwicker et al. (2010) developed a “categorical account” of motorvisual contrast to explain why an effect from hand movements on perceptual bias was not increased when action and perception were matched closer with respect to a metric location scale. The categorical account claims that code occupation affects only categorical representations of visual stimuli. Consequently, effects from action on perception are restricted to categorical overlap. This restriction of code occupation to categorical representation can also be found in the PCM. However, in contrast to us, Zwicker et al. suggested that the direction of a motorvisual effect is determined by the ambiguity of S1 instead of the categorical/spatial nature of R1–S2 consistency.

Wiediger and Fournier (2008) also made a suggestion to restrict the code occupation hypothesis. They proposed that action planning, and thus code occupation, involves only “meaning based representations” (p. 1146), which they define in opposition to metric spatial representations. Based on this assumption, they predicted that actions that do not require planning (e.g., visually guided actions) are not affected by code occupation. This prediction would be fully compatible with the PCM. It has, however, not been applied to motorvisual effects by Wiediger and Fournier.

The Attentional Weighting Hypothesis

The attentional weighting hypothesis was first put forward by Fagioli, Hommel, and Schubotz (2007) and has been developed further by Wykowska and colleagues (Wykowska, Hommel, & Schubö, 2011; Wykowska et al., 2009). It claims that action planning facilitates perceptual processing on action relevant feature dimensions. This assumption is also made by the PCM. Like in the PCM, the facilitation of action relevant stimulus dimensions is functionally associated with movement control but is triggered by action planning. A further commonality is that the attentional weighting hypothesis distinguishes between representations that are subject to motorvisual facilitation and representations that are not (Hommel, 2009). Some features are specified already during action planning, whereas other features need to be specified only during online movement control. Only feature dimensions for the latter kind of features are facilitated (Hommel, 2009, 2010). This distinction clearly inspired the PCM. There are, however, two

crucial differences between the current formulation of the attentional weighting hypothesis and the PCM. First, the attentional weighting hypothesis does not distinguish between categorical and spatial features, whereas the PCM claims that only the latter kind of features are subject to motorvisual facilitation. Second, the attentional weighting hypothesis restricts motorvisual facilitation effects to whole feature *dimensions*, whereas the PCM claims that motorvisual facilitation simultaneously takes place for dimensions and for action-compatible regions within these dimensions. Consequently, the PCM can also explain the previously reported motorvisual facilitation effects on the feature level (Deubel et al., 1998; Lindemann & Bekkering, 2009; Linnell et al., 2005).

Facilitation of Spatial Features

Two previous models, the *visual attention model* (Schneider, 1995) and the *premotor view of attention* (Rizzolatti et al., 1987), have postulated that action planning facilitates perceptual processing at action compatible locations. Both models were initially developed to explain the attentional effects of saccades (Deubel & Schneider, 1996; Umiltà, Mucignat, Riggio, Barbieri, & Rizzolatti, 1994) but have later been developed also to account for attentional effects of manual movements (Craighero, Bello, Fadiga, & Rizzolatti, 2002; Gherri & Eimer, 2010; Schiegg et al., 2003) and for spatial dimensions other than location, such as orientation (Craighero et al., 2002; Craighero, Fadiga, Rizzolatti, & Umiltà, 1999). In this respect, these models are similar to the PCM. They cannot, however, explain any detrimental effects from action on perception and, thus, do not account for the numerous dual-task studies showing motorvisual impairment effects (e.g., Eder & Klauer, 2007; James & Gauthier, 2009; Müsseler & Hommel, 1997).

Thus, despite incorporating some elements of previous models, the PCM is, to our knowledge, the only model to account for the entire range of motorvisual dual-task studies reviewed above.

Extending the Scope of the PCM

Action–perception influences have received considerable research interest with a variety of research paradigms in areas such as neurosciences (Kilner, Neal, Weiskopf, Friston, & Frith, 2009; Serino et al., 2010), robotics (Metta, Sandini, Natale, Craighero, & Fadiga, 2006; Riva, Gaggioli, & Mantovani, 2008; Wykowska, Maldonado, Beetz, & Schubö, 2011), and social cognition (Goldman & de Vignemont, 2009; Grafton, 2009). The PCM could, in principle, produce directional predictions for any potential motorvisual effect, given that it is possible to distinguish spatial and categorical consistencies between motor-activity and visual stimulation. The focus in the present article has, however, been on motorvisual dual-tasks, because they provide the most direct evidence for influences from motor processing on perception, and because the dual-task paradigm is extensively applied in behavioral research on these influences. In the following subsections, we discuss potential extensions of the PCM to other motorvisual paradigms. We limit the discussion to three of the currently most intensely researched motorvisual paradigms: human movement perception, motorvisual judgment bias, and motorvisual single tasks.

Action Effects on the Perception of Biological Stimuli

Human perception of conspecifics is currently subject to intense empirical investigation and controversial theorizing (Aleong & Paus, 2010; Giese, Thornton, & Edelman, 2008; Pinto & Shiffrar, 2009). Perception of human motion seems to be in many respects different from the perception of other stimuli (Blake & Shiffrar, 2007; Loula, Prasad, Harber, & Shiffrar, 2005). One peculiarity of action–perception, which is particularly important for the present issue, is its intimate relation to motor processing. Several recent studies have shown that action–perception automatically activates the motor system in a way similar to the activation when performing the observed action (Agnew, Bhakoo, & Puri, 2007; Buccino et al., 2001; Catmur & Heyes, 2011). This covert activation is specific to the muscles that would produce the observed action (Alaerts, Swinnen, & Wenderoth, 2009; Aziz-Zadeh, Maeda, Zaidel, Mazziotta, & Iacoboni, 2002; Borroni, Montagna, Cerri, & Baldissera, 2005; Fadiga, Craighero, & Olivier, 2005; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995) and to the action’s temporal structure (Baldissera, Cavallari, Craighero, & Fadiga, 2001; Gangitano, Mottaghy, & Pascual-Leone, 2001, 2004).

Such covert muscle activation only takes place when the observed movements are of human origin and is not automatically triggered by abstract non-human stimulation (Bertenthal, Longo, & Kosobud, 2006) or robotic motion (Kilner, Paulignan, & Blakemore, 2003). Whether a stimulus activates covert imitation is, however, determined by whether the observer *believes* the movement to be produced by a human or by a machine (see, e.g., Longo & Bertenthal, 2009; Stanley et al., 2007; Zwickel, 2009).

It has recently been suggested that the *function* of covert imitation of observed human movements is a perceptual one. According to Wilson and Knoblich (2005), we covertly simulate observed actions with our own motor system to derive predictions of future states of the observed movements (Sparenberg, Springer, & Prinz, 2012; Springer et al., 2011; Tausche, Springer, & Prinz, 2009). These predictions are thought to assist disambiguation of perceptual input during the course of the observed movement. Another currently discussed suggestion is that the motor system assists the perception of the *temporal* structure of observed movements (see, e.g., Graf et al., 2007; Thornton & Knoblich, 2006). If, however, the motor system has any functional role in the perception of human movements, one would have to expect that, in a dual-task, the impact of own movements (R1) on concurrent visual perception (S2) is fundamentally different for human movement S2 and for abstract S2 (for a different account, however, see Engel, Burke, Fiehler, Bien, & Rösler, 2008; Schubotz, 2007). The PCM has been discussed in the context of mostly *abstract* S2. Static arrowheads, letters, or color patches have neither any structural nor dynamic similarities with human motion displays. Thus, the PCM cannot automatically be applied to motor effects on *human movement* perception but requires explicit empirical generalization. Motorvisual dual-task studies with human movements as S2 are rare relative to studies with abstract S2. To our knowledge, the only previous studies on this topic are by Bidet-Ildei and colleagues (Bidet-Ildei, Chauvin, & Coello, 2010; Bidet-Ildei, Sparrow, & Coello, 2011), Jacobs and Shiffrar (2005), Miall et al. (2006), and Christensen et al. (2011).

As discussed in the Motorvisual Facilitation subsection, Miall et al.’s (2006) results, that hand movements facilitate the perception

discrimination of the spatially compatible hand movements, are well in line with predictions of the PCM. Jacobs and Shiffrar (2005) also applied continuous cyclical movements as R1 and S2. In their design, passive standing, stationary treadmill-walking, and stationary cycling movements as R1 were paired with a speed discrimination task between two point-light walkers (Thornton, 2006) as S2. In the discrimination task, participants performed worst when they were walking (i.e., performing the same type of movement that they had to observe)—a motorvisual impairment effect. It is, however, difficult to distinguish whether there was categorical correspondence (type of movement) between R1 and S2 or spatial (positions of the limbs during walking). Thus, the prediction of the PCM would be ambiguous in this case.

Consequently, further research is required to determine whether the PCM can also be applied to the perception of human motion. In particular, tasks that allow a clear distinction to be made between categorical and spatial consistency would be required. The study by Christensen et al. (2011) indicates that the temporal synchrony between R1 and S2 is another important factor to consider in motor effects on biological motion perception.

Motor Induced Bias on Perceptual Judgment

Besides directly affecting perceptual accuracy, concurrent motor activity can also bias perceptual judgments in one or the other direction. Assimilative as well as contrastive motorvisual bias effects have been found in dual-task studies (e.g., Beets et al., 2010; Maruya, Yang, & Blake, 2007; Yabe & Taga, 2008; Zwickel, Grosjean, & Prinz, 2007, 2008). A motorvisual assimilation bias means that S2 stimuli are judged to be more similar than dissimilar to R1 responses. A motorvisual contrast bias, on the other hand, refers to situations in which S2 stimuli are judged to be more inconsistent than consistent with R1 (see Zwickel & Prinz, 2011, for definitions and a review of findings). An example of an assimilative bias effect is a study by Kunde and Kiesel (2006). They had participants observing a fast sequence of short light flashes (S2) while executing a sequence of key presses (R1). The number of observed flashes and executed key presses matched or differed from trial- to-trial. Results showed that when the numbers differed, the number of flashes was judged to be *similar* to the number of key presses, instantiating a motorvisual assimilation bias. Hamilton et al. (2004), on the contrary, observed a contrast bias from weight lifting on weight perception. Participants lifted boxes of different weights (R1) while observing models also lifting boxes of different weights (S2). When participants lifted lighter boxes, the models’ boxes were judged to be heavier. When they lifted heavy boxes, the models’ boxes were judged to be rather light.

Motorvisual judgment bias is often interpreted as evidence for a direct influence of action on perception, in the sense that concurrent action biases the perceptual process in one or the other direction (see, e.g., Schubö et al., 2004). Motorvisual contrast bias is usually discussed in analogy with the motorvisual impairment phenomena, whereas motorvisual assimilation bias is usually seen as analogous to motorvisual facilitation (e.g., Schütz-Bosbach & Prinz, 2007; Zwickel et al., 2010). Accuracy impairment and contrast bias are regarded as rather “negative” influences of action on perception, whereas accuracy facilitation and assimilative bias

are seen as “positive” motorvisual effects (see Schütz-Bosbach & Prinz, 2007; Zwickel et al., 2010).

When contrast bias is associated with impairment and assimilation bias is associated with facilitation, the PCM cannot account for all previous motorvisual bias findings. For example, Zwickel et al. (2007) found a contrast bias for clearly spatial R1–S2 consistency, whereas the R1–S2 consistency in Kunde and Kiesel’s (2006) assimilative bias was clearly categorical. These findings run contrary to the prediction of the PCM, given that the bias effects reflect direct influences from action planning or movement control on perception.

This qualification should, however, not be seen as weakening the PCM model, because it is questionable whether all of the abovementioned bias effects are really due to influences from motor activity on the perceptual processing. Instead of S2 perception itself, evaluative processes concerning the already perceived S2 stimuli could have been influenced by R1. Such “motor-evaluative” effects have been shown, for instance, by Topolinski and Strack (2009) for action effects on stimulus-likability or by Bach and Tibber (2007) for one’s own actions affecting attribution of features to observed actors. If some of the motorvisual bias phenomena are due to effects from action on evaluation, instead of being due to effects from action on perception, it is not surprising that the PCM’s predictions are not always met by motorvisual bias findings. The predictions of the PCM can rather be seen as an indicator for which of the bias effects can be ascribed to motor effects on perception and which should rather be explained in terms of motor effects on post-perceptual evaluative processes. Note, however, that in the dual-task studies reviewed in the Motorvisual Facilitation and Motorvisual Impairment subsections, the main explanatory target of the PCM, cannot be ascribed to motorvisual bias. Either the R1–S2 overlap was on a dimension different from the S2–R2 task relevant dimension (e.g., Deubel et al., 1998; Hommel & Schneider, 2002), or signal detection analyses have shown action effects on sensitivity but not on criteria (e.g., Cardoso-Leite et al., 2010; Eder & Klauer, 2007; Müssele, Steininger, & Wühr, 2001).

Effects From Action on Perception in Single Tasks

Motorvisual effects have also been studied with single tasks. These tasks typically require the participant to hold a response in preparation while waiting for a Go-signal. The Go-signal is either compatible or incompatible with the prepared response (e.g., Craighero, Fadiga, Rizzolatti, & Umiltà, 1998). The common finding is that response latencies are shorter when prepared action and Go-signal match than when they do not (Hommel, 1996). For example, Craighero et al. (1999) had participants prepare a grasping movement either aiming at a horizontal or at a vertical bar. The Go-signal for execution of the movement was either a horizontal or a vertical bar. Responses were initiated faster when the orientation of the to-be grasped bar matched the orientation of the Go-signal. These effects are often interpreted as being due to a facilitative effect from action preparation on the perception of action compatible stimuli (Bortolotto, Mattingley, & Cunnington, 2011; Craighero et al., 2002, 1999). The results of these studies are largely in agreement with the PCM, because most of them show facilitative effects, and the compatible dimensions are mostly spatial (see Gozli & Pratt, 2011, for an exception). We did, however, not focus

the review so far on single tasks, because the interpretation of compatibility effects in these tasks as motorvisual effects has frequently been criticized (e.g., Miall et al., 2006; Vogt, Taylor, & Hopkins, 2003). An alternative explanation for the observed facilitation effect could be that perception of the Go-signal facilitated execution of the compatible response, as has been shown in many visuomotor priming studies (e.g., Bub & Masson, 2010; Pavese & Buxbaum, 2002; Stürmer, Aschersleben, & Prinz, 2000; see Vogt & Thomaschke, 2007, for a review).

Conclusions

We have proposed a new model—the PCM—to explain seemingly contrasting findings from previous motorvisual priming research. According to the proposed model, motorvisual impairment is due to the binding of categorical representations in action plans, and motorvisual facilitation is due to the activation of spatial representations in movement control. The PCM predicts that motorvisual impairment can be observed with categorical response–stimulus overlap, and that motorvisual facilitation can be found with spatial response–stimulus overlap. We have reviewed the previous literature on motorvisual priming and have shown that the currently available evidence indeed meets this prediction.

Further, we have discussed untested predictions from the PCM. Motorvisual impairment should be sensitive to context, whereas motorvisual facilitation should be unaffected by context manipulations. With regard to the temporal dimension of both effects, we would expect that motorvisual impairment and motorvisual facilitation should be effective throughout the whole course of a movement.

The PCM has been introduced to explain findings in motorvisual dual-task priming with manual actions. We have also suggested that the model can be extended to further motorvisual research areas, such as biological motion perception, or motorvisual judgment bias. Such extensions would, however, require further research.

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