The Role of Cue-Response Mapping in Motorvisual Impairment and Facilitation: Evidence for Different Roles of Action Planning and Action Control in Motorvisual Dual-Task Priming

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Previous research has shown that actions impair the visual perception of categorically action-consistent stimuli. On the other hand, actions can also facilitate the perception of spatially action-consistent stimuli. We suggest that motorvisual impairment is due to action planning processes, while motorvisual facilitation is due to action control mechanisms. This implies that because action planning is sensitive to modulations by cue-response mapping so should motorvisual impairment, while motorvisual facilitation should be insensitive to manipulations of cue-response mapping as is action control. We tested this prediction in three dual-task experiments. The impact of performing left and right key presses on the perception of unrelated, categorically or spatially consistent, stimuli was studied. As expected, we found motorvisual impairment for categorically consistent stimuli and motorvisual facilitation for spatially consistent stimuli. In all experiments, we compared congruent with incongruent cue-key mappings. Mapping manipulations affected motorvisual impairment, but not motorvisual facilitation. The results support our suggestion that motorvisual impairment is due to action planning, and motorvisual facilitation to action control.

Keywords: motorvisual, action-perception, visual attention, dual-task paradigm

Action not only impairs, but can also facilitate, concurrent perception (Schütz-Bosbach & Prinz, 2007; Shin, Proctor, & Capaldi, 2010). Action *impairs* the perception of stimuli that are action consistent on a *categorical* dimension. Kunde and Wühr (2004), for example, applied a dual-task paradigm to investigate the impact of color word speaking on color perception. When speaking color words in the primary task, color perception in a secondary task was selectively impaired for word-consistent colors. When, for example, participants had to say the word 'red,' their perception of red color patches was impaired, relative to their perception of green color patches. Similar effects have been observed for detecting straight/curved forms while drawing straight/curved letters (James & Gauthier, 2009), for perceiving positive/

negative words during execution of approach/avoid lever-movements (Eder & Klauer, 2007, 2009), for perceiving left/right pointing arrows while pressing left/right keys (Müsseler & Hommel, 1997; Nishimura & Yokosawa, 2010; Oriet, Stevanovski, & Jolicoeur, 2003, 2007), and for perceiving previously learned action effects during left/right key presses (Cardoso-Leite, Mamassian, Schütz-Bosbach, & Waszak, 2010). In each of these studies, actions selectively impaired the perception of categorically action-consistent stimuli.

On the other hand, action can also *facilitate* perception by shifting visual attention toward *spatially* action-consistent areas in perceptual space. Deubel, Schneider and Paprotta (1998), for example, applied a dual-task paradigm to investigate the impact of action on the perception of stimuli in action-consistent and action-inconsistent locations. In a primary task, participants had to manually point to one of 10 different locations. In a secondary task, they had to indentify the orientation of the letter 'E,' which was displayed in one out of the 10 locations. Perceptual performance was best when the target location for the pointing movement coincided with the display location of the letter. Comparable effects have been reported for several different spatial consistency-dimensions between actions and stimuli, like location (Koch, Metin, & Schuch, 2003; Müsseler, Wühr, Danielmeier, & Zysset, 2005; Schiegg, Deubel, & Schneider, 2003), orientation (Lindemann & Bekkering, 2009), and size (Fagioli, Hommel, & Schubotz, 2007; Wykowska, Hommel, & Schubö, 2011; Wykowska, Schubö, & Hommel, 2009).

The coexistence of detrimental and facilitative effects from action on perception has often been recognized in the literature (Müsseler, 1999; Muthukumaraswamy & Johnson, 2007; Zwickel, Grosjean, & Prinz, 2007). It is, however, not known *why* action impairs the perception for categorically consistent stimuli, but facilitates the perception of spatially consistent stimuli. Accordingly, Schütz-Bosbach and Prinz note in their review of research on action-perception 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" (2007, p.351). In this paper, we suggest an integrative theoretical account for these seemingly contrasting findings. We propose that motorvisual *impairment* is due to action *planning*, while motorvisual *facilitation* is associated with action *control*. As we explain below, according to this perspective, it makes perfect sense that impairment takes place when stimuli are categorically consistent with action, but that facilitation takes place when stimuli are spatially consistent with actions.

Action Planning and Action Control

Action planning processes primarily *categorical* information in order to select the type of action that is appropriate given a certain intention and situation, while action control processes only *spatial* information about the current state of the action and its target (Glover, 2004). The function of planning is to integrate enough situational information in order to select appropriate starting parameters (e.g., which hand to move; which type of grip) of a movement. At this stage, information about spatial properties of targets is processed only in a gross categorical manner (e.g., Cohen & Rosenbaum, 2004; Stelmach, Castiello, & Jeannerod, 1994; Tubaldi, Ansuini, Dematte, Tirindelli, & Castiello, 2008; Tubaldi, Ansuini, Tirindelli, & Castiello, 2009). Once an action is selected and initiated, control comes into place to detect and potentially correct any spatial mismatch between the current course of the action and the target (e.g., Desmurget & Grafton, 2000; Proteau, Boivin, Linossier, & Abahnini, 2000). This requires the processing of fine-grained metric spatial representations of action and target.

The action planning process integrates and binds representations, so that they cannot be accessed by other cognitive processes (Hommel, 2004; Wiediger & Fournier, 2008), such as perception. This effect has been referred to as "encapsulation" (Müsseler, 1999), or "occupation" (Schubö, Aschersleben, & Prinz, 2001) of mental representation by action plans. Binding of conceptual representations in action plans has the effect that perception of categorically action-consistent stimuli is impaired (Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001).

Action control, on the contrary, requires the fast and precise processing of visual spatial representations so as to constantly monitor visual feedback of the ongoing action (Miall, 1998; Miall, 2003; Wolpert, Miall, & Kawato, 1998). In order to support this process, actions shift visual attention automatically to the regions in perceptual space that are relevant to the action such as the target location of a grasping movement (Miall et al., 2006; Springer et al., 2011; Wilson & Knoblich, 2005). This leads to the motorvisual facilitation effect for spatially action-consistent stimuli.

Effects of Cue-Response Mapping on Planning and Control

Our suggestion, that motorvisual impairment is due to action planning and that motorvisual facilitation is due to action control, has a clear testable empirical prediction. When any aspect of the action planning is manipulated, only motorvisual interference should be affected by this manipulation, but motorvisual facilitation should not. One central aspect of an action, which is clearly associated with planning and not with control, is the cue-response translation. Consequently, we manipulated the cue-response mapping in a primary task, and tested whether stimulus perception in secondary task was differently affected. We hypothesized that detrimental effects from primary responses on categorically consistent secondary-task stimuli would be affected by cue-response mapping, as these effects are due to action planning. But, we also hypothesized, that facilitative effects from primary responses on spatially consistent secondary-task stimuli would not be affected by cue-response mapping, as these effects are due to action control.

General Method

Overview

All experiments apply a dual-task paradigm. In a primary task, participants responded with a speeded key press (R1) to a visual or an auditory stimulus (S1). In a concurrent secondary task, they had to evaluate a hard-to-discriminate target stimulus (S2) by means of a later, nonspeeded, response (R2). In this kind of paradigm, effects from action (R1 processing) on perception (S2 processing) are commonly measured as changes in R2 accuracy that are dependent on R1-S2 consistency. Consequently, we manipulated the consistency between R1 and S2 on a trial-by-trial basis, and tested whether S2-perception (measured by R2 accuracy) was affected.

In order to compare motorvisual *impairment* for *categorically* action-consistent stimuli and motorvisual *facilitation* for *spatially* action-consistent stimuli, we applied different sets of S2-stimuli, which overlapped with the set of R1-responses in some conditions on a *categorical* dimension, but in other conditions on a *spatial* dimension. The set of possible R1-responses was identical in all experiments and conditions: a speeded left or right key press. Each one of the two R1 responses had characteristic spatial *and* characteristic categorical properties. A left key press, for example, is executed at a *location* left from the body midline (spatial property), but it is also cognitively represented as one element of a binary left/right *category* (categorical property). It is very important here to clearly distinguish between the meanings of these properties. Left in a *spatial* sense means the metric property of being located in a certain area (e.g., being left of the body midline or being in the left visual field). Left in a *categorical* sense, on the other hand, means belonging to the left category in a binary left/right choice task (e.g., speaking the response-word "Left", or being a stimulus that *symbolizes* a leftward direction/location, like a left pointing arrowhead, whether or not presented on the left). Such categorical representations of stimuli and responses are often referred to as polar codes in the literature (Proctor & Cho, 2006).

S2-stimulus sets have been chosen in a way that they can overlap *either* with the spatial properties of R1, *or* with the categorical properties of R1, or with both. With regard to the spatial dimension, we presented the S2-stimuli laterally (i.e., on the left or right side of the screen) in some conditions. In this case, R1 and S2 can be spatially consistent (e.g., a R1 response left from the body midline, and S2 in the left visual field), or spatially inconsistent (e.g., a R1 response left from the body midline, and S2 in the right visual field). In other conditions, S2 were presented centrally. In the latter case, there was no *spatial* consistency relation between R1 and S2 (see Figure 1).

With regard to the categorical dimension, we presented left or right pointing arrowheads as the S2-stimulus set in some conditions. In this case, R1 and S2 can be categorically consistent (e.g., the left one of a binary R1-response pair, and a left pointing S2-arrowhead), or inconsistent (e.g., the left one of a binary R1-response pair, and a right pointing S2-arrowhead). In other conditions, we applied a S2-stimulus set consisting of circles with either vertical or horizontal gaps. Accordingly, there was no *categorical* consistency relationship between R1 and S2, because processing of R1 did not involve polar codes for vertical/horizontal categories, and processing of S2 did not involve polar codes for left/right categories. These different sets of S2-stimuli allowed the direct comparison between motorvisual impairment (typically found with categorical R1-S2 overlap) and motorvisual facilitation (typically found with spatial R1-S2 overlap) within one paradigm.

In each experiment, we manipulated the cue-response mapping (i.e., the primary task instruction) between subjects. The mapping was fixed throughout the experimental procedure. It was, however, *congruent* for one group of participants and *incongruent* for another group. In the congruent group, an S1 associated to the category "left" was mapped onto the left R1 key press, and a S1 associated to the category "right" was mapped onto the right R1 key press. For participants with this mapping, S1-R2 translation was easy and automatic. In the incongruent condition, the S1 –R1 mapping was reversed. A S1 associated to the category "left" was mapped onto the right R1 key press, and a S1 associated to the category "right" was mapped onto the left R1 key press. For participants with the incongruent mapping, S1-R2 translation was more effortful and less direct.

Experiment	S1	S2	S2-location
1A	♩♪	</>	central
1B	♩♪	◯◑	left/right
2A	</>	</>	central
2B	</>	◯◑	left/right
3A	♩♪	</>	left/right
3B	</>	</>	left/right

Figure 1. Independent variable manipulations in Experiments 1 to 3. Cues were either centrally presented arrow heads, or low and high tones. S2 stimuli were either circles with vertical or horizontal gaps, or arrow heads.

Apparatus

Experiments were controlled by E-Prime (Psychology Software Tools, Version 2.0) run on a PC with a refresh rate of 100Hz. Participants were sitting in front of the computer at a viewing distance of 50 cm, with their right hand on a Serial Response Box (Psychology Software Tools), centrally positioned on the table and occluded from their view. R1 responses were made with the middle and the index fingers of the right hand (irrespective of whether it was the dominant hand). The left button was operated by the index finger while the right button was operated by the middle finger. The participants also operated a computer mouse with their left hand. R2 responses were given by left hand responses on the left mouse-key. Participants wore headphones, irrespective of whether the experimental condition they were assigned to involved auditory stimuli or not.

Stimuli

S1-stimuli. Depending on experiment and condition, the set of possible S1-stimuli was either a low and a high tone, or a left- and a right-pointing arrowhead. The low tone was a sinus tone at 400Hz, and the high tone was a sinus tone at 2000Hz. The tones were presented binaurally over headphones.

Arrowheads were the symbols ' < ' and ' > '. The symbols were displayed centrally, in the font Times New Roman, and subtended an area of $1.8° \times 1.6°$ of visual angle. The fixation cross was a '+' symbol in the same font and size. S1 was presented for 50 ms when it was a tone, and for 100 ms when it was an arrowhead. The fixation cross and the S1-arrowheads were always presented centrally.

S2-stimuli. Depending on experiment and condition, the set of possible S2-stimuli was either a pair of arrowheads, or a pair of circles with a diameter of 2° of visual angle, and with two gaps. The arrowheads were identical to those used as S1 in some conditions (see above). The circles had either two vertical gaps or two horizontal gaps of 0.7°. The mask was a $2° \times 2°$ square, in which each pixel was set to black with a probability of 0.5 on each trial, and was otherwise white.

Depending on experiment and condition, S2-stimuli and mask were presented either centrally or laterally. When presented laterally, stimuli appeared on an imaginary horizontal midline, either to the left or to the right of the screen center, with an eccentricity of 7°. The display time of S2 was individually adjusted by a staircase algorithm throughout the experiment (see below). The mask was always presented for 100 ms. Visual stimuli were displayed in black on a white background.

Procedure

Trial structure. The trial structure is illustrated in Figure 2. Each trial began with the presentation of the fixation cross. After 300ms, S1 was presented for 50ms (when it was a tone), or 100 ms (when it was an arrowhead). Participants had to respond to S1, according to a preinstructed mapping, with a key press (R1) as quickly as possible. The onset of S1 marked the beginning of the stimulus onset asynchrony (SOA), which is the interval between S1 and S2. It was chosen randomly before each trial, and was with equal probability 300 ms, 400 ms, 500 ms, or 600 ms. When S1
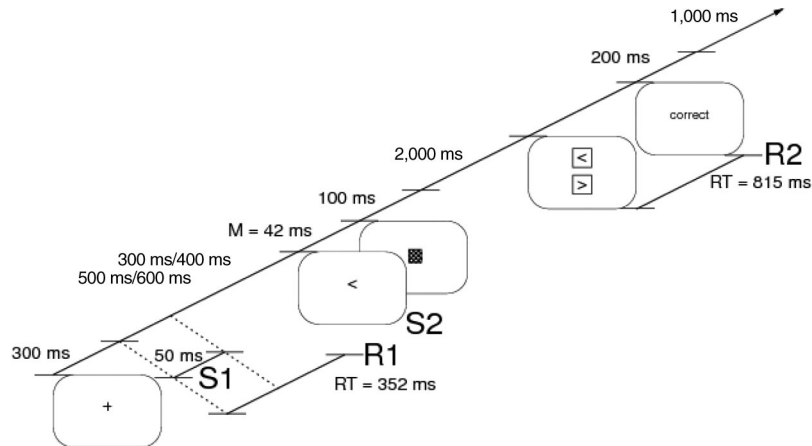
Figure 2. Trial structure. The trial structure is shown for Experiment 1A. The trial started with a fixation cross, which remained on the screen for 300 ms plus the trial's individual SOA (300, 400, 500, or 600 ms). 300 ms after onset of the fixation cross a tone–S1–was presented for 50 ms. R1 was a speeded manual response to the onset of the tone. S2 was a centrally displayed arrowhead. S2 display time was varied over blocks, contingent on participants' average R2 accuracy. S2 was followed by a mask for 100 ms. After a blank interval, both options for S2 were displayed on the screen. R2 was a nonspeeded mouse click on one of the options. R2 was followed by correctness feedback. The ITI was 1000 ms. All experiments followed this temporal structure, with one exception. When S1 was visual, the S1 display time was 150 ms, and the remaining part of the SOA was blank, instead of filled with a fixation cross. This schematic example shows a trial on which a left arrowhead is correctly identified.

was a tone, the fixation cross remained on the screen throughout the SOA. When S1 was an arrowhead, the screen was blank from deletion of S1 to the onset of S2. After the SOA, S2 was displayed for an individually adjusted time, followed by a mask for 100ms, and then by an empty interval.

The duration of the empty interval was determined by subtracting the trial's SOA from 2000 ms. The empty interval was followed by the R2-collection phase. In the R2-collection-phase of each trial, both possible S2-stimuli were displayed in separate rectangular frames, one 4 cm below and the other 4 cm above the screen center. Which option was displayed above and which was displayed below was randomized across trials. Participants had to move the mouse curser into the frame that they felt included the trial's S2-stimulus, and to click on the left mouse button. R2 was nonspeeded, and was followed by a 200ms feedback display saying "richtig" (German for "correct") or "falsch" (German for "incorrect"). The inter-trial-interval was 1 second.

When R1 was given too early (< 100 ms after S1), too late (> 500 ms after S1), or with the wrong response key, immediate specific written error feedback occurred on the screen and the trial was aborted. The eligibility-range of 100 ms−500 ms for valid responses is in line with some previous motorvisual dual-task studies (e.g., Collins, Schicke, & Röder, 2008; Schiegg et al., 2003), while others have chosen slightly higher cutoff criteria as, for instance 150 ms (Baldauf & Deubel, 2008; Hommel & Schneider, 2002), or 200 ms (Baldauf, Wolf, & Deubel, 2006; Deubel et al., 1998). We have chosen the lowest of the commonly applied cutoff criterion in order to, first, avoid by all means any bias in the results by deleting any very fast nonanticipative RTs (see Ulrich & Miller, 1994), and second, not to discourage participants from fast responding. In the case of an R1-error, the procedure paused for 3000 ms.

General procedure. The first screen display informed the experimenter about which subexperiment and which S1-R1 mapping condition the current participant was in. Each instruction was first given verbally by the experimenter and was then to be read by the participant on screen. Participants were informed about the dual-task and about the particular S1-R1 mapping that they had to follow. When participants were in a subexperiment that involved arrowheads as S1 and/or S2, verbal and written instructions explicitly referred to the symbols as "arrowheads", in order to make sure that participants represent the symbol ' < ' with the polar code for "left" (i.e., the polar code that is also used to represent a left key press), and that they represent the symbol ' > ' with the polar code for 'right.' Participants were further informed that the display time of S2 would be dynamically adjusted to their performance in a way that, during the course of the experiment, it becomes impossible to get 100% correct.

Each of the 16 possible combinations of S1-stimuli, S2-stimuli, and SOAs occurred 10 times per experimental block. The order of the 160 trials in each block was randomized. The experiment consisted of 5 blocks. The experimental blocks were preceded by a 4 min break (except the first one), and, by a 2 min eye-fixation in subexperiments with lateral S2 presentation. For fixation training, we applied a method described by Guzman-Martinez, Leung, Franconeri, Grabowecky, and Suzuki (2009). The training provides constant feedback concerning eye movements, which these authors have shown strongly improves eye fixation in subsequent attention demanding tasks.

The initial display time for S2 was set to 150ms. In the first block after each 30 trials, and in the consecutive blocks after each 50 trials, participants' R2-performance was automatically evaluated in order to update S2 display time. When R2-correctness was below 65% in the preceding set of trials, S2-display time was

increased by 20ms, when it was above 85%, S2 display time was decreased by 20ms. Otherwise the display time was not changed.

Data Analysis

We analyzed correctness and RT for R1 and R2, as well as the individually adjusted S2-display time. Only data from blocks 2 to 5 were analyzed. Trials with incorrect R1-responses have been excluded from R1-RT analyses. Those trials are also not included in R2-analyses, as no R2 was collected when R1 was incorrect.

Experiment 1

This experiment is, to our knowledge, the first direct comparison between motorvisual interference with categorical R1-S2 overlap, and motorvisual facilitation with spatial R1-S2 overlap. In Experiment 1A, the R1-response set and the S2-stimulus set overlapped categorically, but not spatially. R1-responses were left and right key presses. Centrally presented left and right pointing arrowheads served as S2-stimuli. The arrowheads can be categorically (binary categories left/right) consistent, or inconsistent with R1 (left/right key presses). In the spatial domain there was no consistency relation between R1 and S2, because S2 was presented *centrally* on every trial. Thus, we expected a motorvisual *impairment* effect.

In Experiment 1B, on the contrary, the R1-response set and the S2-stimulus set overlapped in spatial, but not in categorical, features. Laterally presented vertical and horizontal symbols served as S2-stimuli (see Figure 1). The symbols can be spatially (left/right location) consistent or inconsistent with R1 (left/right key press). In the categorical domain, there was no consistent relationship between R1 and S2, because left/right key presses and vertical/horizontal symbols do not share any common polar categories. As key presses are known to shift visual attention to action-compatible locations (Hommel & Schneider, 2002), we expected a motorvisual facilitation effect on the perception of spatially R1-consistent S2-stimuli in Experiment 1B.

The main aim of this experiment was to investigate whether the congruency of S1-R1 mapping influenced motorvisual impairment and facilitation differently. One group of participants was instructed to respond in a congruent way with R1 to S1 (i.e., with a left key press to a low tone, and with a right key press to a high tone), while another group had to respond in an incongruent way (i.e., with a left key press to a high tone, and with a right key press to a low tone). Previous research on speeded choice-RT tasks has shown that low tones are compatible with 'left,' and high tones are compatible with 'right' (Elkin & Leuthold, 2011; Lidji, Kolinsky, Lochy, & Morais, 2007; Nishimura & Yokosawa, 2009; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006; Wühr & Müsseler, 2002, Exp. 3).

In summary, we expected S1-R1 mapping to modulate the categorical R1-S2 impairment effect in Experiment 1A, but not the spatial R1-S2 facilitation effect in Experiment 1B.

Method

Participants. Participants' ages ranged from 19 to 36 years, $M = 20.9$, $SD = 4.6$. Sixty-nine were female, and 15 were male. Participants were randomly assigned to both S1-R1 mapping groups, so that there were 21 participants in each group, in Experiment 1A and 1B. From two participants in the incongruent mapping group of Experiment 1A, and from one in the congruent mapping group of Experiment 1B, no data were saved due to technical problems.

Stimuli. S1-stimuli were tones. In Experiment 1A, S2-stimuli were centrally presented arrowheads, and in Experiment 1B, they were laterally presented circles with horizontal/vertical gaps.

Results

R1 performance. For all experiments and subexperiments, we tested whether the rates of too early responses, too late responses, or wrong R1 differed between participants in the congruent and the incongruent mapping group. Further, we analyzed whether the R1 RTs differed between these groups. As none of these tests was significant, we do not report any further details here and in the following experiments about R1 performance.

S2 display time. For each experiment and subexperiment, we calculated the average display time for S2-stimuli. We also calculated the mean range of display times. The range for each participant was calculated by subtracting the participant's minimum from his or her maximum display time within the experimental phase. We tested for each experiment and subexperiment whether mean display time or mean range of display times differed between the congruent and the incongruent condition. We report average display times only when the comparisons were significant. The mean range of display times between groups of participants did not significantly differ for any of the experiments reported here.

In Experiment 1A, average display times in the congruent condition (50 ms, $SD = 25$) were significantly longer than in the incongruent condition (36 ms, $SD = 18$; $t(38) = 2.111$, $p = .041$, $d_2 = 0.65$, $\lambda = 0.66$)[1].

R2 performance. The mean R2 accuracy scores for consistent and inconsistent trials with congruent and incongruent mappings are displayed in Figure 3.

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[1] All significance tests were two-tailed *and* directional (This approach to significance testing has been referred to as directional two-tailed or three-choice test, see, e.g., Jones & Tukey, 2000; Leventhal, 1999a; Leventhal, 1999b; Leventhal & Huynh, 1996), with an α-level of 0.05. For binary significance tests, we report two effect sizes, and a Bayes factor, λ. The effect size d_1 estimates Cohen's d for *difference* scores in a within-subjects test, and was bias-corrected according to Gibbons, Hedeker and Davis (1993, equations 3,17,19). The effect size d_2 estimates Cohen's d, independently of whether the experimental design was within-subjects or between-subjects (see Becker, 1988; Dunlap, Cortina, Vaslow, & Burke, 1996; Glass, 1976). It is the difference between condition means, standardized by the pooled standard deviation, and bias-corrected according to Hedges (1981). Although d_1 usually overestimates the effect size (see Ashford, Davids, & Bennett, 2009), sometimes to a dramatic extent (see Hadzi-Pavlovic, 2008), we report it here, because it allows direct comparisons with previous within-subject studies that do not report the intersubject correlation (Morris & DeShon, 2002). λ estimates the Bayes analogy of a *t* test according to Rouder, Speckman, Sun, Morey, and Iverson (2009). It estimates the odds in favor of the null-hypothesis over a standard effect-hypothesis. Where we report estimates of t-values, positive values indicate that the consistent/congruent condition has a higher score than the inconsistent/incongruent condition.
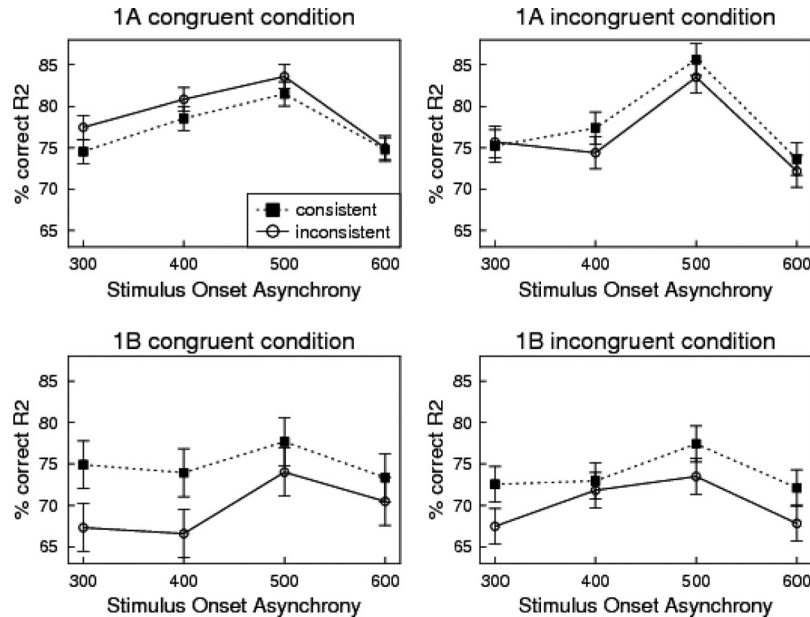
Figure 3. Mean R2 accuracy in Experiment 1 for each condition in relative to SOA. Filled squares represent consistent trials, and empty circles represent inconsistent trials. The four panels represent groups of participants that differed in the R1-S1 mapping (congruent vs. incongruent) and in experiment (Experiment 1A vs. Experiment 1B). Confidence intervals have been calculate according to Loftus and Masson (1994; Masson & Loftus, 2003) for within-subjects comparisons of consistency, collapsed over SOA, but separately for each congruency group.

Experiment 1A. In order to analyze whether potential effects of R1-S2 consistency on R2 accuracy were modulated by S1-R1 congruency, a mixed 2×2 ANOVA with the between-subjects factor S1-R1 mapping (congruent vs. incongruent) and the within-subjects factor R1-S2 consistency (consistent vs. inconsistent) was employed. The main effect for R1-S2 consistency was not significant, $F(1, 38) = 0.025$, $MSE = 0.32$, $p = .875$, $\eta_p^2 = .001$. However, most importantly, the interaction was significant, $F(1, 38) = 4.57$, $MSE = 59.21$, $p = .039$, $\eta_p^2 = .107$. The interaction was qualified further by separate planned t tests for both mapping conditions. In the S1-R1 *congruent* condition, accuracy on R1-S2 consistent trials was lower than on R1-S2 inconsistent trials, and the difference approached significance, $t(20) = -1.889$, $p = .073$, $d_1 = -0.40$, $d_2 = -0.25$, $\lambda = 1.23$. In the S1-R1 *incongruent* condition, accuracy on R1-S2 consistent trials was even numerically higher than on R1-S2 inconsistent trials (see Figure 3). This difference was not significant, $t(18) = 1.222$, $p = .237$, $d_1 = 0.27$, $d_2 = 0.30$, $\lambda = 2.87$.

In order to investigate whether the effects of R1-S2 consistency on R2 accuracy were modulated by SOAs, a 2×4 repeated measures ANOVA was computed for each experiment and subexperiment, reported here. The results are reported only when the interaction between SOA and consistency were significant.

All analyses that have been done on R2 error rates have also been completed for R2 RT. As our main focus was on R2 accuracy, we only report R2 RT when any of the differences was statistically significant.

Experiment 1B. In order to analyze whether potential effects of R1-S2 consistency on R2 accuracy were modulated by S1-R1 congruency, a mixed 2×2 ANOVA with the between-subjects

factor S1-R1 mapping (congruent vs. incongruent) and the within-subjects factor R1-S2 consistency (consistent vs. inconsistent) was used. The pattern of results was opposite to those in Experiment 1A. The main effect for R1-S2 consistency was significant, $F(1, 39) = 10.097$, $MSE = 424.44$, $p = .003$, $\eta_p^2 = .206$, but the interaction was not, $F(1, 39) = 0.361$, $MSE = 15.19$, $p = .551$, $\eta_p^2 = .009$. Statistical power for the interaction was, relatively low ($p = .37$, when assuming a medium effects size, Cohen's $d = 0.5$). Thus, the lack of an interaction can, alone, not support our hypothesis that the facilitation effect was present in both groups. Accuracy was, however, *higher* on R1-S2 consistent trials than on R1-S2 inconsistent trials (see Figure 3), and this difference was significant with congruent S1-R1 mapping, $t(19) = 2.165$, $p = .043$, $d_1 = 0.46$, $d_2 = 0.54$, $\lambda = 0.78$, as well as with incongruent S1-R2 mapping, $t(21) = 2.517$, $p = .020$, $d_1 = 0.54$, $d_2 = 0.39$, $\lambda = 0.42$.

Discussion

We conducted two subexperiments to investigate the effects of S1-R1 mapping on motorvisual impairment for categorical R1-S2 consistency (Experiment 1A) and on motorvisual facilitation for spatial R1-S2 consistency (Experiment 1B). We hypothesized that motorvisual impairment would be affected by the congruency of S1-R1 mapping, and that motorvisual facilitation would be present in both mapping groups in Experiment 1B.

Our hypotheses were confirmed by the data. Analyses of R2-accuracy have shown that a motorvisual impairment effect was present (yet only marginally significant) in the congruent group of Experiment 1A. In the incongruent group, the motorvisual impair-

ment effect was not observed, and, most importantly, the interaction between S1-R1 mapping congruency and R1-S2 consistency was significant (see also Wühr & Müsseler, 2002, for a similar result). That interaction shows that action context affects motorvisual impairment. In Experiment 1B, however, there was no interaction between congruency and consistency. A significant motorvisual facilitation effect was observed in both congruency mapping conditions.

With regard to motorvisual impairment, we interpret the interaction between S1-R1 congruency and R1-S2 consistency in Experiment 1A, as evidence for a central role of context-integrative action *planning* in motorvisual impairment. In the congruent group, the common categorical representation of S1 and R1 is unambiguous, and is, thus, tightly bound into an action plan. Consequently, the representation cannot be processed in the perception of R1-consistent S2-stimuli, and R1-S2 consistency impairment is observed. In the incongruent mapping group, S1 and R1 categories are in opposition, and action planning has to process ambiguous categorical representations. Thus, none of them can be bound into the action plan, and no R1-S2-consistency impairment is observed.

With regard to motorvisual facilitation, the effects of context on R1-S2 consistency effects have not been previously investigated. We interpret our results as evidence for the association of motorvisual facilitation with context-independent action control. Visual attention is shifted to action-consistent locations, irrespective of how the action was selected and planned.

Experiment 2

In Experiment 1A, the R1-S2 impairment effect was modulated by S1-R1 congruency. We interpret this modulation as reflecting a rather indirect influence from S1 perception on S2 perception. When S1 and R1 are congruent, one left/right category is unambiguously bound into the action plan, and that binding in turn influences consistent S2 perception. When S1 and R1 are incongruent, neither of the left/right categories is bound into the action plan. Hence, that action plan influences neither consistent nor inconsistent S2 perception (so that R2 error rates do not differ between consistent and inconsistent conditions). Thus, the R1-S2 impairment effect was present in the congruent group, but not in the incongruent group (see Müsseler, Wühr, & Prinz, 2000, for an analogous explanation).

An alternative explanation would ascribe the S1-R1-congruency modulation of the R1-S2 impairment effect to a more direct influence from S1 perception on S2 perception. If one assumes that perceiving a tone negatively primes the perception of consistent arrowheads, then this perceptual priming effect would support the motorvisual effect in the congruent group, but not in the incongruent group. When in the congruent S1-R1 mapping group one has to respond (e.g., with the left key to a low tone), then perception of a left pointing S2-stimulus could be impaired by two sources. It would be negatively primed by the low tone (S1-S2 effect), *and* the required representation of the category "left" would be occupied by the action plan for R1 (R1-S2 effect). This would explain the motorvisual impairment effect in the congruent group of Experiment 1A. In the incongruent S1-R1 mapping group, on the other hand, perception of both categories would be always impaired. Consider a right key press (R1) in response to a

low tone (S1): planning of the right key press would impair the perception of a *right* pointing S2, *and* negative priming from the low tone would impair the perception of a *left* pointing S2 stimulus. Thus, in each trial, both possible S2-stimuli would be impaired. This would explain why we did not observe a motorvisual impairment effect in the incongruent group of Experiment 1A (see, Wühr & Müsseler, 2002, for an analogous explanation).

The aim of Experiment 2 was to distinguish between these two explanations by identifying potential direct S1-S2 priming in the present paradigm, which might have interacted with the motorvisual impairment effect in Experiment 1A. Doing so would then allow us to better understand the modulation of the motorvisual impairment effect by action setting in Experiment 1A. Was it due to the absence of motorvisual impairment in the congruent group, or to a motorvisual impairment effect being counteracted by a negative S1-S2 priming effect in the incongruent condition? Additionally, we were interested in whether a potential S1-S2 priming effect would also interact with motorvisual *facilitation* (Experiment 2B).

We replicated Experiment 1, with the exception that we applied left and right pointing arrowheads instead of low and high tones as S1 stimulus set. Any direct priming effect from S1-perception on S2-perception should be much more pronounced when the S1-stimulus set is presented in the same modality as S2. Such an effect should be particularly pronounced in Experiment 2A, where the S1 stimulus set is now identical to the S2 stimulus set.

Method

Participants. Ages ranged from 19 to 42 years, $M = 23.6$, $SD = 4.2$, with 46 females and 38 males. Participants were randomly assigned to both S1-R1 mapping groups, so that there were 21 participants in each group for both Experiment 2A and 2B.

Stimuli. S1-stimuli were arrowheads. In Experiment 2A, S2-stimuli were centrally presented arrowheads, and in Experiment 2B, they were laterally presented circles with horizontal/ vertical gaps.

Results

R2 performance. The mean R2 accuracy scores for consistent and inconsistent trials with congruent and incongruent mappings are displayed in Figure 4.

Experiment 2A. In order to analyze whether potential effects of R1-S2 consistency on R2 accuracy were modulated by S1-R1 congruency, a mixed 2×2 ANOVA, with S1-R1 mapping (congruent vs. incongruent) as the between-subjects and R1-S2 consistency (consistent vs. inconsistent) as the within-subject factor, was computed. The main effect for R1-S2 consistency was not significant, $F(1, 40) = 0.777$, $MSE = 108.00$, $p = .383$, $\eta_p^2 = .019$. The interaction was also not significant $F(1, 40) = 2.076$, $MSE = 288.42$, $p = .157$, $\eta_p^2 = .049$ (see Figure 4).

To gauge whether potential effects of R1-S2 consistency on R2 accuracy were modulated by SOAs, a 2×4 repeated measures ANOVA with the factors SOA and consistency was applied to the data. At the longer SOAs in the incongruent mapping condition, there was a salient numerical difference between average R2 accuracy on consistent and on inconsistent trials (see Figure 4). Consequently, we computed separate ANOVAs for the congruent
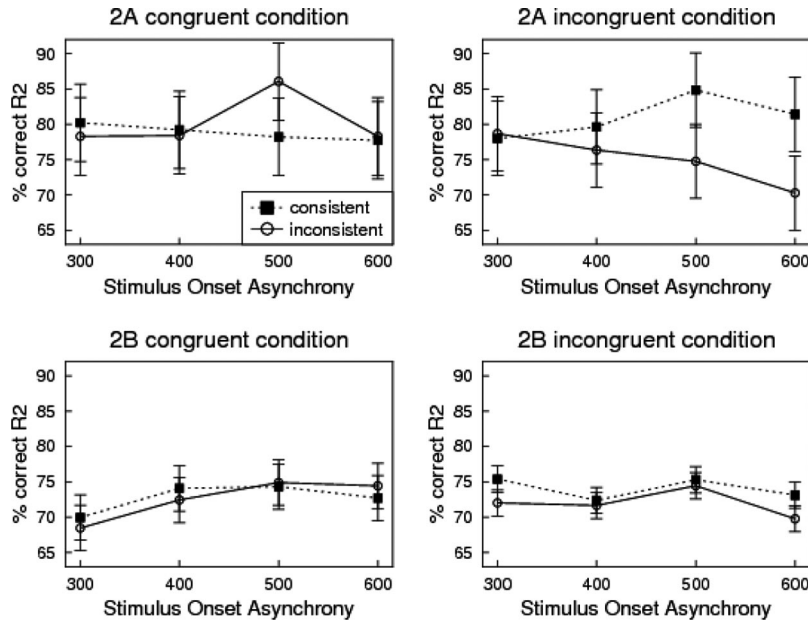
Figure 4. Mean R2 accuracy in Experiment 2 for each condition relative to SOA. Filled squares represent R1-S2 consistent trials, and empty circles represent R1-S2 inconsistent trials. Note that, in the incongruent condition of Experiment 2A (top left panel), categorical R1-S2 consistency means categorical S1-S2 inconsistency, and vice versa. The four panels represent groups of participants that differed in the R1-S1 mapping (congruent vs. incongruent) and in experiment (Experiment 2A vs. Experiment 2B). Confidence intervals have been calculate according to Loftus and Masson (1994; Masson & Loftus, 2003) for within-subjects comparisons of consistency, collapsed over SOA, but separately for each congruency-group.

S1-R1 mapping group, and the incongruent S1-R1 mapping group. In the congruent mapping group, the interaction, $F(3, 60) = 2.317$, $MSE = 0.020$, $p = .085$, $\eta_p^2 = .104$, just failed to reach significance. Accuracy on consistent trials was significantly lower than in inconsistent trials, only at the SOA of 500 ms, $t(20) = -2.871$, $p = .009$, $d_1 = 0.60$, $d_2 = 0.86$, $\lambda = 0.21$. The difference was not significant at the other three SOAs (all $ps > .7$). In the incongruent mapping group, the interaction was significant, $F(3, 60) = 6.848$, $MSE = 0.034$, $p < .001$, $\eta_p^2 = .255$. Accuracy on consistent trials was significantly higher than on inconsistent trials, at the SOAs of 500 ms, $t(20) = 2.649$, $p = .015$, $d_1 = 0.56$, $d_2 = 0.78$, $\lambda = 0.33$, and 600 ms, $t(20) = -2.295$, $p = .033$, $d_1 = 0.48$, $d_2 = 0.56$, $\lambda = 0.63$. The difference was not significant at 300 ms and 400 ms (both $ps > .4$).

Experiment 2B. In order to analyze whether potential effects of R1-S2 consistency on R2 accuracy were modulated by S1-R1 congruency, we resorted to a mixed 2×2 ANOVA with the between-subjects factor S1-R1 mapping (congruent vs. incongruent) and the within-subjects factor R1-S2 consistency (consistent vs. inconsistent). The main effect for R1-S2 consistency was not significant, $F(1, 40) = 0.882$, $MSE = 27.25$, $p = .370$, $\eta_p^2 = .020$. The interaction was also not significant $F(1, 40) = 0.544$, $MSE = 18.03$, $p = .465$, $\eta_p^2 = .013$.

Discussion

We aimed at identifying any direct S1-S2 priming effects, by using visual S1-stimuli. In Experiment 2A, we did indeed find a negative S1-S2 priming effect, in the congruent *and* in the incon-

gruent condition. In both congruency conditions, S1-inconsistent S2-stimuli were perceived better than S1-consistent S2-stimuli (See Figure 4, and note that in the incongruent group, S1-*consistent* S2-stimuli are R1-*inconsistent*). Comparable negative priming effects from arrowheads on arrowheads have previously been observed by Stevanovski, Oriet, and Jolicoeur (2003; see also Hommel & Müsseler, 2006, Exp. 1B, 2A). The effect was, however, restricted to late SOAs. In the congruent condition, it was observed only at an SOA of 500 ms, and in the incongruent condition the effect was confined to 500 ms, and 600 ms. How do these results relate to the possible explanations of modulation of R1-S2 impairment by S1-R1 congruency in Experiment 1A?

A potential explanation would be that motorvisual impairment was effective in the congruent and incongruent group in Experiment 1A, but in the incongruent group it was neutralized by counteracting negative S1-S2 priming. However, the results of Experiment 2A speak against this interpretation. By increasing the similarity of S1 and S2, a clear negative S1-S2 effect has become visible. But this S1-S2 priming effect was not responsible for the modulation of the R1-S2 impairment effect by congruency in Experiment 1A, because the S1-S2 priming effect was clearly restricted to late SOAs. Thus, according to a S1-S2 explanation of the modulation in Experiment 1A, the S1-S2 priming effect should have supported the motorvisual R1-S2 effect only at 500 ms in the congruent group, and it should have counteracted it only at 500 ms and 600 ms in the incongruent group. But this was obviously not the case. As visual inspection of Figure 3 shows, the motorvisual impairment effect in Experiment 1A was more pronounced at

shorter, instead of longer, SOAs. Furthermore, in the incongruent group there was no motorvisual impairment effect, not even at the short SOAs.

Consequently, we retain our original interpretation that motorvisual impairment was not present in the incongruent group of Experiment 1A, because the ambiguous left/right category was not bound into an action plan. The absence of any R1-S2 consistency effect with short SOAs in Experiment 2A suggests that the negative S1-S2 priming overshadows the motorvisual impairment effect in general. The S2 display time was significantly higher than in Experiment 1A. This suggests that negative S1-S2 priming impairs S2 perception to such a degree that the rather small motorvisual impairment effect observed in Experiment 1A becomes negligible, and is thereby not visible in the data.

In Experiment 2B, we observed neither main effects from S1 or R1 on S2-perception, nor any interaction with congruency or SOA. This was unexpected, as some previous studies on motorvisual facilitation had also used speeded R1 response to visual S1-stimuli (e.g., Baldauf et al., 2006; Linnell, Humphreys, McIntyre, Laitinen, & Wing, 2005). An interesting difference between those studies and the present one was, however, that S1 perception was relatively attention demanding in our experiment. We displayed the arrowhead for only 100 ms. When arrowheads were the secondary target stimuli (S2), average display time (i.e., display times where participants perceive ca. 75% of S2 correct) ranged from 38 ms, CI[30, 46] (Experiment 3A), to 80 ms, CI[65, 94] (Experiment 2A). Thus, perception of a 100 ms arrowhead as S1 can be assumed to require sharply focused visual attention, given the remarkably low R1 error rates in all experiments with visual S1 (< 1.5%). In previous studies on motorvisual facilitation, S1 remained on the screen throughout the SOA (Baldauf et al., 2006; Deubel & Schneider, 2003; Deubel & Schneider, 2004; Linnell et al., 2005; Paprotta, Deubel, & Schneider, 1999), or was visible for at least 150 ms (Deubel et al., 1998). The high attention demand to discriminate the centrally presented S1 has probably blocked visual attention from being shifted to lateral locations by R1-control mechanisms (as was the case in Experiment 1B). The attention shift to action-consistent locations for R1 control seems to be restricted to a situation where visual attention was not engaged in another demanding perceptual task.

Experiment 3

In Experiments 1 and 2, and in separate subexperiments, we compared motorvisual impairment for categorically overlapping stimuli with motorvisual facilitation for spatially overlapping stimuli. Now, we investigate whether motorvisual impairment and motorvisual facilitation can co-occur in one and the same experiment. We applied a S2-stimulus set that overlapped with the R1-response set on a categorical *and* on a spatial dimension. Left or right pointing arrowheads were presented laterally. We expected both effects to be observable in an additive manner. When R1 was, for example, a left key press, and S2 was a right pointing arrowhead on the right side of the screen, we expected S2 perception to be, on the one hand, impaired (relative to left pointing arrowheads) by the category "left" being occupied by the R1-action plan. But, on the other hand, it should also be facilitated (relative to stimuli on the left side) by R1-control shifting visual attention to spatially compatible visual areas. When, on the contrary, R1 was a left key

press and S2 was a left pointing arrowhead on the right side, it should not be impaired by R1 planning, but only facilitated by action control.

In Experiment 1, we found motorvisual impairment to be affected by S1-R1 mapping, and motorvisual facilitation to be independent of S1-R1 mapping. To investigate, whether this also holds, when impairment and facilitation are compared within-subjects, we compared congruent and incongruent S1-R1 mapping groups again.

In Experiment 2A, we also detected some direct influences from S1-perception on S2-perception. In order to disentangle potential S1-S2 effects from potential R1-S2 effects, we applied a merely categorically S2-*consistent* S1-stimulus set (a low and a high tone in Experiment 3A), as well as a categorically S2-*identical* S1-stimulus set (centrally presented left and right pointing arrowheads in Experiment 3B).

Method

Participants. Ages ranged from 20 to 28 years, $M = 22.4$, $SD = 3.9$, and 57 were female and 27 male. Participants were randomly assigned to both S1-R1 mapping groups, so that there were 21 participants in each group, in Experiment 3A and 3B. Data from one participant in the congruent mapping group of Experiment 3A were not saved by the computer program.

Stimuli. In Experiment 3A, S1-stimuli were tones, and in Experiment 3B they were arrowheads. S2-stimuli were laterally presented arrowheads.

Results

R2 performance. The mean R2 accuracy scores for consistent and inconsistent trials with congruent and incongruent mappings, are displayed in Figure 5.

Experiment 3A. To answer the questions whether either categorical R1-S2 consistency or spatial R1-S2 consistency influenced R2 accuracy and whether a potential influences was modulated by S1-R1 mapping, a mixed $2 \times 2 \times 2$ ANOVA was employed. The between-subjects factor was S1-R1 mapping (congruent vs. incongruent), and the within-subjects factors were categorical R1-S2 consistency and spatial R1-S2 consistency. While there were no significant main effects, $p > .391$, there was a significant interaction between categorical and spatial consistency, $F(1, 39) = 6.896$, $MSE = 1324.29$, $p = .012$, $\eta_p^2 = .150$. Accuracy was lower when categorical meaning and spatial locations of S2 matched (i.e., on trials with categorical *and* spatial consistency, or with categorical *and* spatial inconsistency) than when they did not match (i.e., on trials with R1-S2 consistency on either only categorical, or only spatial dimension, and R1-S2 inconsistency on the respective other dimension). Any dependence of this regularity on either categorical R1-S2 consistency, or spatial R1-S2 consistency, was not found (see Figure 5).

A mixed $2 \times 2 \times 2 \times 2$ ANOVA with the between-subjects factor congruency, and the within-subjects factors SOA (300 ms, 400 ms, 500 ms, and 600 ms), categorical R1-S2 consistency, and spatial R1-S2 consistency was used in order to determine whether any potential effects are modulated by time. SOA was significant, $F(3, 117) = 18.115$, $MSE = 2688.27$, $p < .001$, $\eta_p^2 = .317$, and its interaction with categorical R1-S2 consistency was also significant
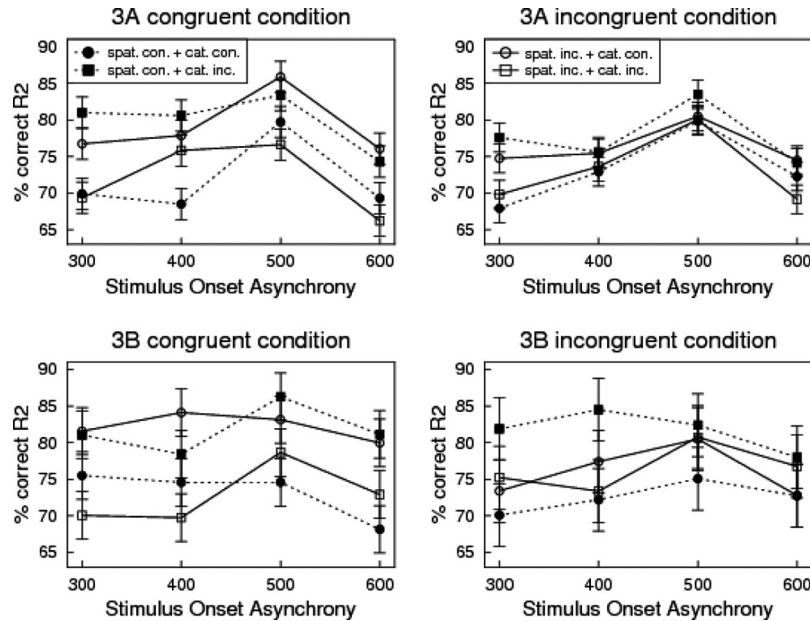
Figure 5. Mean R2 accuracy in Experiment 3 for each condition relative to SOA. Filled cycles represent trials on which R1 and S2 are consistent on both the spatial, and the categorical dimensions (spat. con + cat. con). Filled squares represent trials on which R1 and S2 are consistent on the spatial dimension, but are inconsistent on the categorical dimension (spat. con + cat. inc.). Empty circles represent trials on which R1 and S2 are inconsistent on the spatial dimension, but are consistent on the categorical dimension (spat. inc. + cat. con.). Empty squares represent trials on which R1 and S2 are inconsistent on the spatial, and on the categorical dimension (spat. inc. + cat. inc.). The four panels display groups of participants that differed in the R1-S1 mapping (congruent vs. incongruent) and in experiment (Experiment 3A vs. Experiment 3B). As the focus is on comparisons for categorical consistency, the confidence intervals represent within-subjects comparisons of categorical consistency.

$F(3, 117) = 2.727$, $MSE = 201.34$, $p = .047$, $\eta_p^2 = .065$. The interaction was followed up by separate t tests for an effect of categorical R1-S2 consistency at each SOA. Although the three-way interaction between SOA, categorical consistency and congruency did not reach significance, $F(3, 117) = 1.802$, $MSE = 138.97$, $p = .151$, $\eta_p^2 = .044$, we tested each congruency group separately, as the motorvisual interference effect in Experiment 1A was observed only in the congruent group. In the congruent group, the difference between categorical R1-S2 consistent trials (73.20%, $SD = 11.21$) and categorically R1-S2 inconsistent trials (78.20%, $SD = 8.70$) was significant only at the SOA of 400 ms, $t(19) = -2.270$, $p = .035$, $d_1 = -0.49$, $d_2 = -0.48$, $\lambda = 0.65$. The difference was not significant at any other SOA (all $ps > .12$). In the incongruent group, the difference was not significant at any 4 SOA (all $ps > .3$).

With regard to R2 *speed,* we employed a mixed $2 \times 2 \times 2$ ANOVA, with the between-subjects factor S1-R1 mapping (congruent vs. incongruent), the within-subjects factor *categorical* R1-S2 consistency (consistent vs. inconsistent), the within-subjects factor *spatial* R1-S2 consistency (consistent vs. inconsistent), and R2-RT as dependent variable. Categorical consistency and spatial consistency interacted significantly, $F(1, 39) = 4.676$, $MSE = 9558.26$, $p = .037$, $\eta_p^2 = .107$. The interaction was qualified further by t tests between the four combinations of categorical and spatial consistency. The only significant difference was between shorter responses on categorically R1-S2-

inconsistent trials than on categorically R1-S2-consistent trials, when R1 and S2 were spatially consistent, $t(40) = 2.082$, $p = .044$, $d_1 = 0.65$, $d_2 = 0.18$, $\lambda = 1.09$.

Experiment 3B. We addressed whether categorical R1-S2 consistency or spatial R1-S2 consistency influenced R2 accuracy and whether a potential influence was modulated by S1-R1 mapping by means of a mixed $2 \times 2 \times 2$ ANOVA. The between-subjects factor was S1-R1 mapping (congruent vs. incongruent), and the within-subjects factors were categorical R1-S2 consistency and spatial R1-S2 consistency. No main effect or interaction was significant (all $p > .16$) except the interaction between categorical and spatial R1-S2 consistency, $F(1, 40) = 9.527$, $MSE = 1819.23$, $p = .004$, $\eta_p^2 = .192$ (see Figure 5). As in Experiment 3A, this interaction was due to lower accuracy when categorical meaning and spatial location of S2 matched than when they did not match, independent of any form of R1-S2 consistency.

Discussion

In Experiment 3, we manipulated both categorical and spatial R1-S2 consistency within one experiment. Also S1-R1 congruency and S1 modality were modulated. With regard to the motorvisual impairment effect for categorically consistent stimuli, the results support our conclusion from Experiment 1A, namely, that the effect is due to representation binding in action planning. As in Experiment 1A, we found evidence for a motorvisual impairment

effect only in the congruent group of Experiment 3A, but not in the incongruent mapping group.

The impairment effect in the congruent group was, however, temporally more focused than it was in Experiment 1A. In Experiment 1A, the effect was overall only marginally significant and did not interact with SOA, although a numerical tendency toward a stronger effect with shorter SOAs was present. In Experiment 3A, the effect was significant, but only at the relatively short SOA of 400 ms. That the motorvisual impairment effect is strongest at 400 ms supports our conclusion in relation to Experiment 2A that the motorvisual impairment effect is distinct from the negative S1-S2 priming effect at later SOAs. The slightly different pattern of results in both experiments suggests that the effect is stronger when S2-display times are longer due to the lateral presentation of stimuli. That would explain why the effect was significant at 400 ms in 3A, but only marginally significant overall in 1A. The nonsignificance of the effect in Experiment 3A at later SOAs is probably due to overshadowing by the large interaction effect between categorical and spatial consistency. This interaction effect was very pronounced at all SOAs, except 400 ms. Note that the three-way interaction between S1-R1 congruency, categorical R1-S2, and SOA was not significant. This suggests that any effect of categorical consistency in the incongruent mapping group was also modulated by SOA in a similar way, as it was in the congruent mapping group. Such a potential effect was, however, below even marginal statistical significance at all SOAs.

The motorvisual impairment effect was not found in Experiment 3B. As discussed in the context of Experiment 2A, we propose that negative priming from the S1 arrowhead on S2 impaired S2 perception to a degree such that the rather small detrimental effect from R1-planning on S2 perception was negligible, and thus statistically not visible.

With regard to motorvisual facilitation of spatially consistent stimuli, no evidence for motorvisual facilitation was found in any of the subexperiments. This result was unexpected, particularly for Experiment 3A. In Experiment 3B, the attention demanding S1-perception probably focused spatial attention on the screen center, as discussed in the context of Experiment 2B. But Experiment 3A exactly resembled Experiment 1B, with the only exception that now arrowheads are presented instead of horizontal/vertical circles. In Experiment 1B, a pronounced motorvisual facilitation effect was observed, in the sense that visual attention was shifted to R1 consistent locations. Why did we not observe an analogous effect for arrowheads in Experiment 3B? One suggestion is that the visual task at the target location is not a spatial one in Experiment 3B. Burnett, d'Avossa, Close, and Sapir (2010) have recently shown that endogenous spatial attention can be specific for certain visual features to be processed at the attended location. In their study, endogenous location cueing facilitated *only* motion perception in the attended location, while color detection was unaffected by the location cueing.

As discussed in the introduction, action control processes primarily spatial information such as location, orientation, or size (Glover, 2004). So it seems reasonable to assume that the shift of spatial attention for action control concerns only the perceptual processing of *spatial* features. This means that in our dual-task paradigm, R1-control shifts visual attention to spatially R1-consistent locations, only for spatial perceptual tasks (e.g.,

orientation-discrimination, or size detection), but not for categorical perceptual tasks like symbolic evaluation.

The discrimination of circles with vertical gaps from circles with horizontal gaps, as required in Experiment 1B, is clearly a spatial perceptual task, as the orientation of an otherwise identical figure has to be identified. Thus, we observed a pronounced motorvisual facilitation effect of stimuli in R1-consistent locations. The discrimination between left and right pointing arrowheads, as required in Experiment 3A, is a symbolic, categorical evaluation task. One might object that, in some respect, the arrowheads can also be seen as a geometrical figure that differs only in orientation. But arrowheads are charged with categorical meaning by their common symbolic use. Due to their role in communication, arrowheads are automatically distinguished by their categorical semantic value. Thus, the perceptual S2-task in Experiment 3A was a categorical evaluation task, and, consequently, no motorvisual facilitation effect was observed at R1-consistent locations.

Summary and General Discussion

We carried out three experiments to investigate the effects of cue-response congruency on motorvisual impairment and motorvisual facilitation. In the first experiment, we found a tendency for motorvisual impairment only when the cue-response mapping was congruent. Motorvisual facilitation was observed with congruent and incongruent cue-response mapping. Motorvisual impairment was modulated by cue-response mapping, but motorvisual facilitation was not. In a second experiment, we investigated whether potential visuovisual effects could have confounded the cue-response mapping induced modulation of motorvisual impairment effects in Experiment 1. This possibility can be excluded, as we found that visuovisual effects were restricted to long SOAs. In a third and last experiment, we tested motorvisual impairment and facilitation within-subjects, with stimuli that overlapped categorically and spatially with responses. The results confirmed our conclusions from Experiments 1 and 2: Motorvisual interference was observed with a congruent cue-response mapping, but not with an incongruent mapping. With regard to motorvisual facilitation, Experiment 3 suggests that actions shift attention to relevant areas in perceptual space, only specific for *spatial* perceptual tasks (see Burnett et al., 2010). In summary, our experiments have confirmed our hypothesis that motorvisual impairment is modulated by cue-response mapping, while motorvisual facilitation is not. This supports our suggestion that motorvisual impairment is due to action planning and motorvisual facilitation to action control. The planning process binds categorical representations of cues and response codes into action plans, and is consequently highly sensitive to cue-response congruency.

Consequently, tight binding only takes place when cues and response codes are unambiguous (e.g., when action cueing is congruent). Thus, motorvisual impairment is restricted to cue-response mappings that are unambiguous with respect to the bound features. The action control process shifts visual attention to spatially action-consistent areas in perceptual space. As control is independent of cue-response mapping, the mapping congruency is irrelevant for the shifting of attention, with the consequence that motorvisual facilitation is observed with congruent and incongruent cue-response mappings.

Working Memory and Response Coding in Motorvisual Priming

In the present study, we manipulated only one specific aspect of action planning, and have shown that it affects motorvisual impairment and facilitation differently. Our suggestion that motorvisual impairment is due to action planning and motorvisual facilitation to action control, would, however, predict that any other aspect of action planning, which is independent of action control, would affect motorvisual priming in comparable way.

There is, for instance, evidence from single-task visuomotor priming, that the way responses are categorized considerably affects visuomotor interactions in the Simon effect (Ansorge & Wühr, 2004; see Metzker & Dreisbach, 2009, for an overview), and in affordance priming (Bub & Masson, 2010). Ansorge and Wühr (2004) displayed task relevant color stimuli in 4 task-irrelevant locations, which differed on the horizontal and vertical axis. Binary choice responses to colors also differed on the horizontal and vertical axis, while only one axis was relevant to distinguish between responses. A Simon effect was observed only along the response discriminative axis.

We suppose that a similar manipulation of response coding would affect motorvisual impairment, but not motorvisual facilitation. Responses should impair consistent stimuli only when the dimension of consistency is response discriminative, while motorvisual facilitation should be independent of how responses are distinguished from each other.

Another aspect central to action planning, but rather unrelated to action control, is working memory (WM) processing. There is a considerable amount of evidence showing that WM is involved to a much stronger degree in planning than in control. For instance, interference effects from a secondary WM task are greater on planned, delayed actions than on visually guided ones (Singhal, Culham, Chinellato, & Goodale, 2007). Furthermore, Westwood, Robertson, and Heath (2005) have shown that increasing WM demands in action planning had detrimental effects on performance, but these effects were *independent* of impairments due to reduced spatial vision by occlusion of one eye. The independence of WM-based effects on movement from visual-control based effects, suggests that WM processing is largely independent of action control. WM processing in action planning might serve as an explanation for the modulation effect of cue-mapping congruency on motorvisual impairment in the present study. The incongruent mapping requires actively maintaining the translation rule in WM, while the congruent mapping allows a rather automatic cue-response translation. Determining whether different WM processing demands in the congruency groups was crucial for the different effect on motorvisual impairment and facilitation, would, however, require a more direct manipulation of WM. One would need to load WM differently in different groups, for example by a third task, while keeping the cue-response mapping constant.

Timing in Motorvisual Impairment and Facilitation

It might seem at first surprising that motorvisual impairment and motorvisual facilitation were present in about the same time frame relative to the action (i.e., with the same range of SOAs). At 400 ms after S1, for example, perception of categorically consistent stimuli was impaired (Experiment 1A, 3A), and perception of

spatially consistent stimuli was facilitated (Experiment 1B). Action planning is, however, usually assumed to *precede* action control (see Crossman & Goodeve, 1983; Meyer, Kornblum, Abrams, Wright, & Smith, 1988). If, as we propose, motorvisual impairment is due to action planning and motorvisual facilitation is related to action control, one might expect impairment to *precede* facilitation, but not to temporally *coincide* with it. This raises the question of how exactly motorvisual facilitation is related to action control? Above, we proposed that action control is the cognitive *function* of motorvisual facilitation. The fast online processing of action-consistent spatial representation in control *requires* attentional prioritization of these representations, and benefits from it. This does not automatically imply that action control also *determines* this attentional facilitation. As action *planning* processes are, at least in healthy adults, usually followed by corresponding *control* processes, it might well be that the *planning* process already evokes the spatial attentional shift for later use by the *control* process. Gherri, Van Velzen, and Eimer's (2009) recent findings of ERP correlates of spatial attention shifts during preparation of aiming movements can be seen as support for the latter possibility.

In conclusion, the present experiments have shown that motorvisual impairment is associated with action planning, as it is affected by cue-response mapping, and that motorvisual facilitation is functionally associated with action control, as it is independent of cue-response mapping. Whether motorvisual facilitation is *due to* planning or control remains, however, an empirical issue.

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