Blindness to response-compatible stimuli in the psychological refractory period paradigm

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This study investigated the conditions under which the processing in a speeded response task interferes with concurrent processing in a visual encoding task. Three experiments used a dual-task paradigm, in which a speeded left or right response to a tone was combined with the identification of a masked left- or right-pointing arrow following the tone with variable SOA. Two additional experiments tested the impact of the presentation of pure tone on visual encoding. There were four major findings. First, an unspecific decrease in identification accuracy was observed with decreasing SOA. Second, a blindness to response-compatible stimuli was observed with speeded responses. Third, a specific interference was found between low- and high-pitched tones and left- or right-pointing arrows. Fourth, the specific tone-arrow interference modulated the specific response-arrow interference when the task allowed both to occur simultaneously. The present findings, which suggest both procedural and structural interference between response preparation and stimulus encoding, are discussed in terms of a two-stage model of action planning.

Most studies of the relationship between perception and action have been concerned with the impact of stimulus information on response selection. Only recently has there been an increase of interest in the reversed question of whether and how action-control processes are able to affect perceptual processing. One reason for this reversal can be found in a recent shift towards

theoretical frameworks of action planning in which voluntary actions are seen to be cognitively evoked by the anticipations of their sensory effects. Thus, the assumption is that movements are cognitively represented by their external effects and, thus, could be initiated by the activation of the corresponding *effect codes* (Greenwald, 1970; Hoffmann, 1993; Hommel, Müsseler, Aschersleben, & Prinz, in press; MacKay, 1987; Prinz, 1990, 1997; for early versions of this idea see James, 1890; Lotze, 1852). This view implies that not only stimulus codes (i.e., codes of perceived events), but also response codes represent external events (i.e., codes of yet to-be-produced events). Accordingly, cognitive codes common to perception and action constitute the interface between these domains. Another consequence of this notion is that stimulus processing and response preparation can overlap both in time and in structure and, thus, are able to affect each other in a specific manner (Hommel, 1997; Hommel et al., in press; Müsseler, 1999).

The question of whether action–control processes are able to affect perceptual processing can be put to an empirical test by using a dual-task paradigm; that is, observers' ability to identify a stimulus should be studied in situations in which they are engaged in an unrelated motor task. In the most established experimental dual task, the so-called paradigm of the psychological refractory period (PRP), individuals have to perform two speeded responses to different stimuli presented in close succession. In the case of a short stimulus onset asynchrony (SOA), processing on the two tasks overlaps in time, and the second response slows down (see Pashler, 1994, for an overview). Most authors attributed this latency increase of the second response during the preparation and execution of the first response to a "bottleneck" in cognitive processing. In other words, when the system is occupied with processing in one task, processing in a second task must be postponed when it requires the same cognitive operations (e.g., Pashler, 1994; Welford, 1952, 1980) or cognitive resources (e.g., Kahneman, 1973; Wickens, 1980).

Many studies investigated dual-task interference between two speeded response tasks. The observed costs were assumed to originate from a bottleneck at the response selection stage, that is, from the inability simultaneously to select (e.g., Pashler, 1984, 1989; Welford, 1952, 1980) and/or to execute (e.g., De Jong, 1993; Karlin & Kestenbaum, 1968; Keele & Neill, 1978) two motor responses. Only a few authors were interested in the question of whether the processing of a response task also affects the processing of a perceptual task; and, indeed, they found perceptual impairments (Arnell & Duncan, 1998; De Jong, 1993; De Jong & Sweet, 1994; Jolicoeur, 1999a). For example, Jolicoeur (1999a) reported that the identification of a foveally presented, pattern-masked letter is impaired when the observer is simultaneously engaged in responding to an auditory stimulus. Jolicoeur (1999a) suggested that the "short-term consolidation" of visual information in short-term memory is disturbed by the concurrent processing of the response task. However, it

remained unclear which of the processes in the response task was responsible for this disturbance.

Indeed, most of the studies showing unspecific impairments in perceptual performance when the participants are simultaneously engaged in a response task are not able to unequivocally localize the source of interference. For example, De Jong and Sweet (1994) found a decline in accuracy in a visual encoding task when the SOA was shortened between a tone calling for a manual response and the visual stimulus. Additionally, they observed that the size of the decline in perceptual accuracy varied substantially, depending on which task had been emphasized in the instruction. From this observation, the authors concluded that there are at least two factors limiting perceptual performance under dual-task conditions: The inability to fully prepare two tasks simultaneously and the interference between these two tasks. Thus, both the source and the relative contributions of (unspecific) interference and preparatory limitations remain vague.

A different strategy in the investigation of whether the processing in a motor task can actually affect the concurrent processing in a perceptual task is to look for specific interferences between a motor task and a perceptual task. Specific interferences are observed when the performance in the perceptual task varies as a function of the degree of *feature overlap* between the to-be-identified stimulus and the concurrent response. Because the feature overlap between a response task and a perceptual task can be varied while holding the preparation for the perceptual task constant, the observation of specific interference would indicate a structural crosstalk between response preparation and stimulus encoding.

Recent experiments in our lab revealed such specific interferences. The assumption was that the initiation of an action leads to a temporary insensitivity to a stimulus that shares common codes with the response within the same cognitive system. More concretely, such a code was considered to be used when a right (left) keypress (indicated by a response cue) was generated as well as when an arrow pointing to the right (left) was encoded (Müsseler, 1995; Müsseler & Prinz, 1996). Accordingly, the observer's sensitivity to stimulus events that share features with a response was assumed to decrease during the execution of this response. In other words, the perceptual and the motor event codes come into conflict with respect to the overlapping feature code in the compatible condition, whereas they can coexist without any conflict in the incompatible condition. And, indeed, this was observed in our experiments: The identification of a right arrow was reduced when presented during the execution of a right response as compared to during the execution of a left response and vice versa ("blindness to response-compatible stimuli"; Müsseler & Hommel, 1997a, b; Müsseler, Steininger, & Wühr, 2001; Müsseler, Wühr, & Prinz, 2000; Wühr & Müsseler, 2001; for overviews see Müsseler, 1999; Wühr, 2000).

When these experiments were designed, the main interest was to determine the influence of a pure motor response on the perceptual encoding of visual stimuli. Consequently, the aim was to minimize the contribution of the response-inducing stimulus (i.e., of the response cue). Therefore, participants were instructed to perform the response at leisure after the presentation of the response cue in order to ensure that an already selected and prepared response would be executed when the masked stimulus was presented. Accordingly, the perceptual impairment still occurred when the response cue was omitted from the procedure and participants were instructed to generate the response endogenously (Müsseler et al., 2000). Thus, in contrast to the PRP experiments mentioned earlier (e.g., De Jong & Sweet, 1994; Jolicoeur, 1999a), the encoding of the response cue and the preparation of the corresponding response were not speeded.

The aim of the present study was to further investigate the blindness to response-compatible stimuli with speeded responses; that is, with a PRP-like paradigm. Therefore, an experimental set-up was used similar to that used by Jolicoeur (1999a). He combined a speeded manual keypress to a tone with the visual identification of a briefly presented, pattern-masked stimulus; and he varied the SOA between the tone and the stimulus. As previously mentioned, the observed decrease in identification accuracy with decreasing SOA between tone and stimulus has been taken as evidence for an unspecific dual-task interference. In contrast to Jolicoeur (1999a), the main interest of the present study was to identify specific interferences between these tasks. Therefore, not only was the temporal relationship between the response task and the identification task varied, but also the amount of feature overlap between responses and visual stimuli.

We expected further theoretical insights from the extension of the blindness paradigm to a PRP task. In the previous studies, the response had never been executed immediately. Instead, the execution of the response had to be postponed (suppressed) either until a neutral response had been performed (e.g., Müsseler & Hommel, 1997a) or until a "go" signal had occurred (e.g., Wühr & Müsseler, 2001). Thus, one might argue that the blindness effect was caused by this temporary withholding of the response; and it is unclear whether the blindness effect would occur in a PRP situation at all.

Furthermore, in a PRP situation, the masked stimulus can be presented in all processing phases of the response task. When the stimulus is presented with varying SOAs in regard to the response-cue tone, the encoding of the visual stimulus can coincide with the encoding of the tone, with the selection of the response, or with the initiation and execution of the response. Thus, the question is: In which of these phases does the blindness effect start to emerge? Consequently, the SOA variation in a PRP paradigm can contribute to a better understanding of the nature of the blindness effect.

GENERAL PROCEDURE

In the present task, participants performed a left or a right keypress in response to a tone and identified a briefly presented and masked left- or right-pointing arrowhead, which followed the tone with a variable SOA (Figure 1). Correspondingly, in half of the trials, responses and visual stimuli were symbolically compatible (i.e., left response and left-pointing arrow, right response and right-pointing arrow); whereas in the other half of the trials, responses and visual stimuli were symbolically incompatible (i.e., left response and right-pointing arrow, right response and left-pointing arrow). Five different SOAs (50, 150, 300, 500, and 1000 ms) were used. The main questions to be examined were whether and when a speeded left or right response specifically affected the accuracy of the participants' identification of a symbolically compatible stimulus as compared to the participants' identification of an incompatible stimulus.

In Experiments 1 and 2, the auditory choice task involved a low- or high-pitched tone and a left or right keypress. In Experiment 5, the auditory choice task involved one long tone or two short tones (with the same pitch) and a left or right response. In these dual-task experiments, the auditory choice task was combined with the visual identification of a masked stimulus, which was a
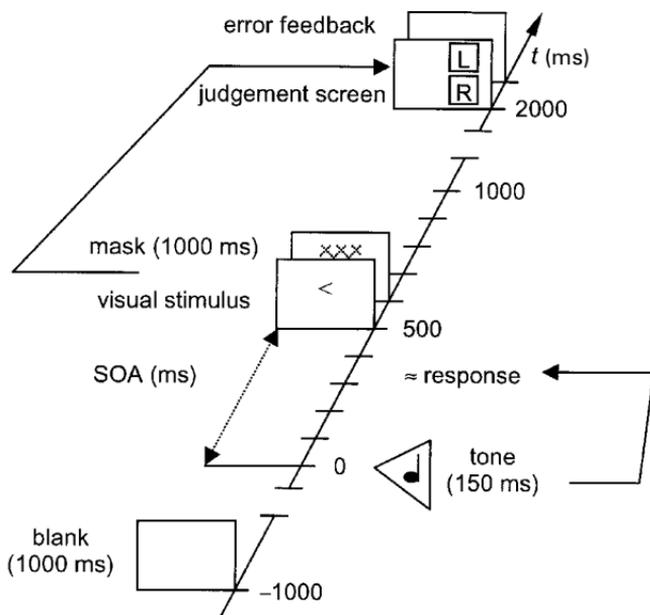
Figure 1. Schematic illustration of the displays and the timing of events (here with an SOA of 500 ms) in Experiments 1, 2, and 5.

left- or a right-pointing arrowhead. Experiments 3 and 4 were control experiments in which the visual stimulus had to be identified simultaneously with or after the presentation of the—now task irrelevant—tones, which had been used as response cues in the dual-task experiments.

EXPERIMENT 1

The main purpose of the first experiment was to examine whether a speeded motor task specifically affects the encoding of a visual stimulus. Following the procedure of Jolicoeur (1999a), a low- or high-pitched tone was used to indicate a speeded left or right keypress. However, in order to introduce a feature overlap between responses and stimuli, masked left- or right-pointing arrowheads were presented with various SOAs. The expectation was that a common LEFT or RIGHT code has to be accessed when a response is generated and when the compatible stimulus is encoded (Hommel et al., 2001). Accordingly, in addition to unspecific interferences, specific interferences were expected between the speeded left and right motor task and the encoding of the left and right stimuli.

Method

Participants.   Sixteen paid volunteers (twelve females, four males; aged 20–31 years) took part in Experiment 1. All reported to be right handed and to have normal or corrected-to-normal vision. The participants were not familiar with the purpose of the experiment.

Apparatus and stimuli.   The visual stimuli were presented on a Macintosh IIci Computer and a 17-inch colour monitor with a screen refresh rate of 75 Hz and a luminance of 35 cd/m. The auditory stimuli were presented by stereo headphones. Responses were recorded with a Macintosh keyboard. The experimental program was written using the software MacProbe (Version 1.8.1; cf., Hunt, 1994). The experiment was carried out in a dimly lit chamber. Participants were seated in front of a table with their chin placed on a chin rest with a fixed height. The viewing distance was 50 cm.

The auditory stimuli were pure tones presented for 150 ms with a frequency of 300 or 900 Hz. They were presented to both ears well above threshold. All visual stimuli were displayed in black on a white background in the centre of the screen. The to-be-identified stimulus was a left-pointing (<) or a right-pointing (>) arrowhead, which subtended vertically about $1.6°$ of visual angle, and horizontally about $0.8°$ of visual angle. The mask consisted of randomly arranged lines, which had the same left or right orientation as the components of the arrowheads and which subtended about $1.0° \times 2.0°$ of visual angle.

Procedure and design.   Each trial started with the presentation of a blank screen for 1000 ms (Figure 1). Then, one of the tones was presented as a response cue for 150 ms. The task was to press as quickly as possible either the left key with the left index finger or the right key with the right index finger according to the pitch of the tone, while making as few errors as possible. Half of the participants had to press the left key if the tone had a low pitch and the right key if the tone had a high pitch, whereas the mapping rule was inverted for the other half of the participants. The instructions stressed the importance of responding quickly to the tone and urged participants not to wait for the visual stimulus to appear before the response is executed.

At an SOA of either 50, 150, 300, 500, or 1000 ms after the tone, the left- or right-pointing stimulus was presented for a brief period of time (see later) and then replaced by the mask, which stayed on the screen for 1000 ms. Half a second after the offset of the mask, the letters "L" and "R", framed by squares, appeared one above the other in the right half of the screen. These letters changed their relative positions randomly from trial to trial. The participants had to report the identity of the visual stimulus in the last trial by clicking on the corresponding letter ("L" for "<" and "R" for ">") with the computer mouse. The instructions for this part of the task stressed the fact that there was no systematic relationship between responses and visual stimuli, and participants were told to guess if uncertain about the identity of the stimulus.

An interval of 2 s followed an error-free trial, then the next trial began. If participant had performed the wrong response and/or reported the wrong stimulus, a corresponding error message occurred for an additional 1 s during the inter-trial interval. If participant did not perform the response within 1 s from the onset of the tone, they received no feedback, but the corresponding trial was repeated at the end of the block. If the reaction time exceeded 1 s in an already repeated trial, this trial was not repeated again. After each block, the participants received feedback about the percentage of trials with wrong responses and/or false stimulus identifications.

To avoid ceiling or floor effects in the identification task, the presentation time for visual stimuli was adjusted to achieve 75% performance accuracy across all SOA conditions. The following staircase procedure was used: After each experimental block, the presentation time was decreased by one screen refresh (13.33 ms) if the error rate in the last block was lower than 10%. It was increased by one refresh if the error rate was above 40%.

The compatibility relationships between the response and the visual stimulus (compatible vs incompatible) were crossed with the five SOAs between the tone and the visual stimulus. Two repetitions of each combination of these factors were presented in each block, which consisted of 20 experimental trials. Each participant completed a total of 30 blocks of experimental trials on 2 different days within 1 week, for a total of 600 trials. On the first day, the experimental phase was preceded by a practice phase consisting of eight

blocks of eight trials. In these practice trials, a constant SOA of 250 ms was used. In the first practice block, the visual stimulus was always presented for 70 ms. For the following practice blocks, the presentation time was adjusted, using the same staircase procedure as in the experimental phase. The mean presentation time of visual stimuli in the last three practice blocks were used for the first block of the experimental phase. The whole experiment lasted about 2 hours, including short breaks between blocks.

The compatibility factor and the SOA factor were varied within participants. Additionally, the mapping between the low-pitched or high-pitched tone and the left or right response was varied between participants. Thus, the experiment was based on a $2 \times 2 \times 5$ mixed design. The performance in the response task and the performance in the identification task were analysed independently.

Results

Response task.   Across all conditions and participants, less than 3% of the reaction times exceeded the criterion of 1000 ms. These trials were excluded from analysis. For the remaining data, mean percentages of the false responses (error percentage) and mean correct reaction times were calculated as a function of all possible combinations of the different levels of the factors mapping, compatibility, and SOA (see Table 1).

Across all conditions, the mean error percentage was 1.5% (SD = 1.5). The error percentages were subjected to $2 \times 2 \times 5$ analyses of variance (ANOVA) with the between-participants factor mapping (two levels), and the within-participant factors compatibility (two levels), and SOA (five levels). The only

TABLE 1
Means of correct reaction times (RT; in ms) and percentages of errors (PE) for the responses in Experiment 1 as a function of the mapping between a tone and the response, the compatibility between the response and a visual stimulus, and the SOA between tone and visual stimulus

	SOA									
	50		*150*		*300*		*500*		*1000*	
Compatibility	*RT*	*PE*	*RT*	*PE*	*RT*	*PE*	*RT*	*PE*	*RT*	*PE*
Mapping low–left, high–right:										
Incompatible	468	1.5	464	1.9	473	1.0	480	0.8	472	0.8
Compatible	469	1.0	456	1.3	474	1.3	476	0.6	473	0.4
Mapping low–right, high–left:										
Incompatible	464	2.3	467	1.3	453	2.1	455	1.9	473	0.8
Compatible	467	3.5	467	1.7	446	1.9	469	0.8	453	2.1

significant effect was the main effect of SOA, $F(4, 56) = 2.75$, $p < .05$, where error percentage increased with decreasing SOA (all other $p > .10$). The mean correct reaction time across all conditions was 466 ms (SD = 92). In an ANOVA with the same factors as in the error analysis, none of the main effects or interactions were significant (all $p > .15$).

Identification task.   The mean presentation time for visual stimuli was 51 ms in both groups of participants with the two different tone-response mappings. To compute the mean proportions of correctly identified stimuli (identification accuracy), only those trials were considered in which the response had been correct and reaction time had been less than 1000 ms. Across all conditions, identification accuracy was 0.72 (SD = 0.19). The mean identification accuracy as a function of all possible combinations of the different levels of the factors mapping, compatibility, and SOA can be seen in Figure 2.

Identification accuracy was also analysed in an ANOVA with the between-participant factor mapping (two levels), and the within-participant factors compatibility (two levels), and SOA (five levels). The main effect of mapping was not significant, $F(1, 14) = 1.72$, $p < .211$. However, the main effects of SOA, $F(4, 56) = 50.29$, $p < .001$, and of compatibility, $F(1, 14) = 8.12$, $p < .013$, were significant. The SOA effect reflects the observation that identification accuracy increased when the SOA between the tone and the visual stimulus increased. There was a difference of 0.25 between the accuracy for the shortest SOA of 50 ms ($M = 0.54$) and accuracy for the longest SOA of 1000 ms ($M = 0.79$).[1] The effect of compatibility is due to the fact that response-compatible stimuli ($M = 0.70$) were identified less accurately than response-incompatible stimuli ($M = 0.74$).

The two-way interactions between mapping and SOA and between compatibility and SOA, both $F(4, 56) < 1$, as well as the three-way interaction $F(4, 56) = 1.82$, $p = .138$, were not significant. However, the two-way interaction between

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[1]Note that in the present series of experiments, the proportions of correctly identified visual stimuli at each SOA should be only interpreted in respect to the values at the other SOAs. The reason is that the presentation time of visual stimuli was adjusted to 75% accuracy across SOAs. The consequence is that accuracy at one SOA is affected by the other SOAs. For example, at first glance, Figure 2 (upper panel) depicts four "easy" levels of SOA (150 to 1000 ms) and one "difficult" level (50 ms). Thus, the majority of "easy" levels has had a greater impact on the mean presentation time to achieve the 75% accuracy level. The consequence is that the adjusted presentation time makes the "difficult" SOA level even more difficult and, therefore, might additionally decrease accuracy at that level. In other words, the absolute accuracy values are affected by the proportion of "easy" and "difficult" SOAs in an experiment. Additionally, it is unlikely that identification accuracy and presentation time constitute a linear relationship. Thus, any *quantitative* conclusions from the accuracy values should be taken with caution.
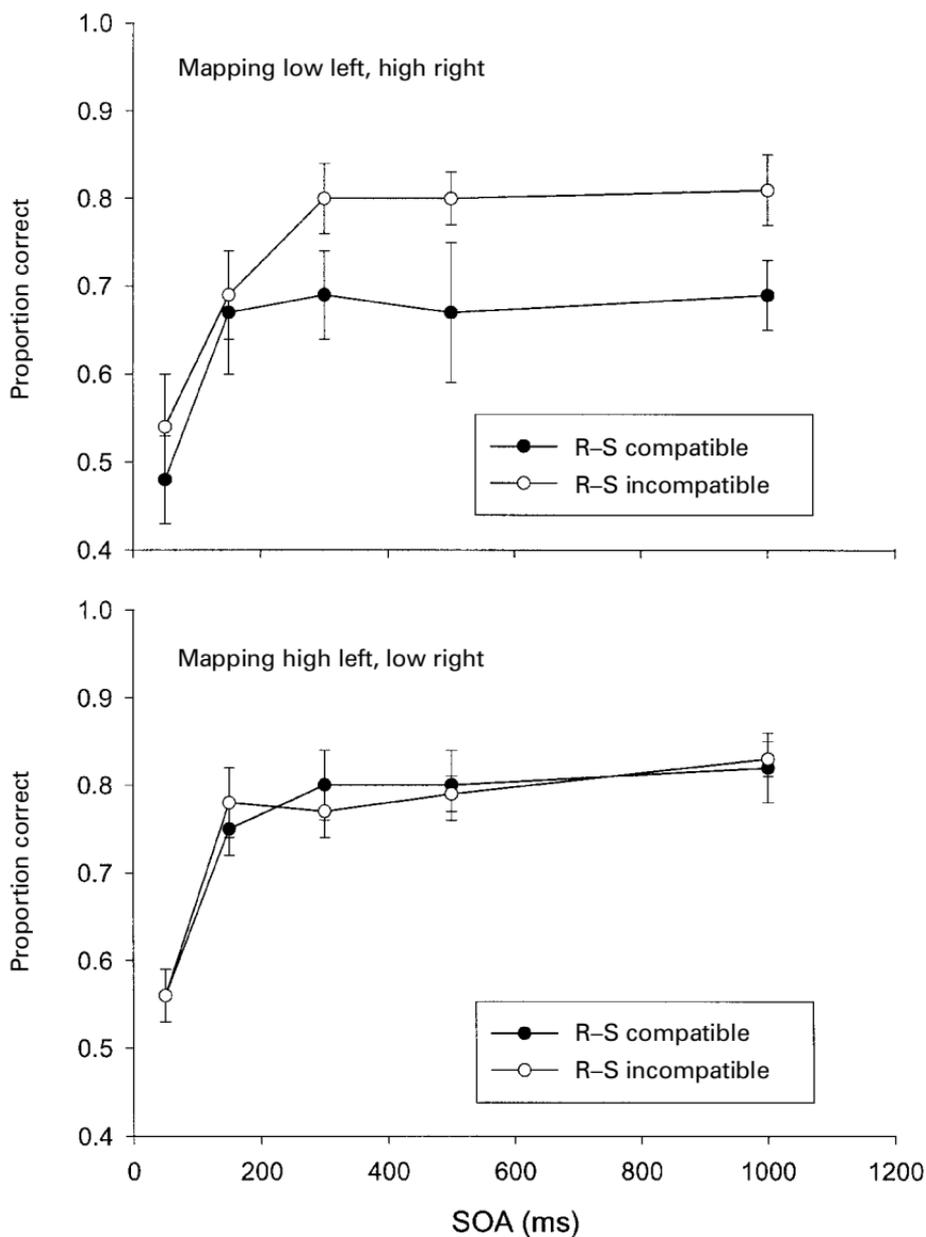
Figure 2. Results from the visual encoding task in Experiment 1. Mean proportion of correctly identified visual stimuli (with standard errors between participants) as a function of the tone–response mapping (upper panel: low–left vs high–right; lower panel: low–right vs high–left), the response-arrow compatibility (compatible vs incompatible), and the tone–arrow SOA. Each data point is based on about 480 observations.

mapping and compatibility was significant, $F(1, 14) = 7.40, p = .016$. This interaction means that—in fact—only that group of participants who had responded according to the tone-response mapping "low–left vs high–right", was less accurate in identifying response-compatible stimuli ($M = 0.64$) than response-incompatible stimuli ($M = 0.73$). In contrast, the other group of participants, who had responded according to the reversed tone-response mapping, showed equal identification accuracy for response-compatible and response-incompatible stimuli ($M = 0.75$ in both cases).

In order to qualify the observed interaction between the factors mapping and compatibility, two-way ANOVAs with the within-participant factors SOA and compatibility were conducted on the identification rates of both groups (i.e., mappings), separately. For the first group that had followed the tone-response mapping "low–left vs high–right", the main effect of SOA, $F(4, 28) = 21.32, p < .001$, and the main effect of compatibility, $F(1, 7) = 15.11, p = .006$, were significant. The interaction was not significant, $F(4, 28) = 1.39, p = .263$. For the second group, which had followed the tone-response mapping "low–right vs high–left", only the main effect of SOA, $F(4, 28) = 30.79$, $p < .001$, was significant (other $F < 1$).

Discussion

In the response task, the increase of falsely executed responses with decreasing SOA indicates an unspecific effect between both tasks. Correspondingly, in the identification task the SOA effect reflects an unspecific interference in visual encoding, similar to the results observed previously by Arnell and Duncan (1998) and by Jolicoeur (1999a). Identification accuracy for visual stimuli decreased with decreasing SOA between the visual stimulus and the response-cue tone. However, the present unspecific effect probably did not only originate from an overlap of the response-generation phase with visual encoding. Instead, the observed accuracy decrements at the very early SOAs of 50 and 150 ms indicates that the interference was also caused—at least in part—by an overlap in the encoding of the tone and the visual stimulus.

More importantly, identification accuracy depended systematically on which response was performed in a trial. When a left response was required, the identification of a left-pointing stimulus was impaired compared to the identification of a right-pointing stimulus (and vice versa). This finding demonstrates the blindness effect to response-compatible stimuli in a PRP paradigm (Müsseler & Hommel, 1997a). Most surprisingly, however, this effect was only observed with a low–left and high–right mapping in the response task. Before explaining this effect, more empirical evidence is needed. Because the tone-response mapping was varied between participants, it is possible that the different results originated from a pure sample bias. Therefore, the subsequent experiment was designed to replicate the present findings.

EXPERIMENT 2

The present experiment aimed to replicate the findings of Experiment 1. Instead of a between-participants design, a within-participants design was applied to further examine the unexpected influence of the mapping in the response task on the blindness to response-compatible stimuli.

Method

Participants.   Eighteen paid volunteers (nine females and nine males; aged 18–32 years) participated in Experiment 2. All of them declared to have normal or corrected-to-normal vision; two participants reported to be left handed. None had participated in Experiment 1.

Apparatus and stimuli.   The apparatus and the stimuli were the same as those used in Experiment 1.

Procedure and design.   The design was the same as in Experiment 1, except that the factor mapping was now varied within participants. This caused the following changes in the procedure. Participants responded either with the low–left and high–right tone-response mapping in the first experimental session, and with the low–right and high–left response mapping in the second experimental session or vice versa (15 blocks per session). This sequence was balanced across participants.

The first session in Experiment 2 was identical to the first session in Experiment 1. However, at the beginning of the second session in Experiment 2, the participants were told that the mapping rule had changed. Then, participants were given one practice block of 20 trials to become familiar with the new mapping.

Results

One participant exceeded the reaction time criterion of 1000 ms in 25% of the trials, whereas the average value for the whole sample was 5% (SD = 7). Another participant achieved 13% of trials with false responses, compared to 5% (SD = 3) of the whole sample. Both participants were excluded from the analysis.

Response task.   Across all conditions and participants, less than 4% of the reaction times exceeded the criterion of 1000 ms. These trials were excluded from further analyses. Across all conditions, the mean error percentage was 4.4% (SD = 2.3). The error percentages were subjected to a $2 \times 2 \times 5$ ANOVA with the within-participants factors mapping, compatibility, and SOA. The main effects for mapping and compatibility were not significant, both $F < 1$, but the error percentage increased again with decreasing SOA, $F(4, 60) = 8.68$,

$p < .001$. The mean correct reaction time was 474 ms (SD = 95). An ANOVA of the reaction times showed no significant effect.

Identification task.   The mean presentation time for visual stimuli was 37 ms for the low–left and high–right tone-response mapping, and 35 ms for the low–right and high–left mapping. The difference was not significant, $t(15) = 1.23$, $p < .20$, two-tailed. Across all conditions, identification accuracy for visual stimuli was 0.74 (SD = 0.07).

The proportions of correctly identified visual stimuli were analysed in an ANOVA with mapping, compatibility, and SOA as within-participants factors. The only significant result was the increase of accuracy with increasing SOA, $F(4, 60) = 45.65$, $p < .001$. However, neither the main effect of compatibility, $F(1, 15) = 1.88$, $p = .191$, nor the two-way interaction between mapping and compatibility, $F(1, 15) = 1.96$, $p = .182$, was significant (all other $p > .10$).

It is possible, however, that the expected two-way interaction between mapping and compatibility failed to reach significance because it occurred in the first session only. In the second session, when the participants had to invert the mappings, carry-over effects from the first session might have diminished or even eliminated mapping effects on the blindness effect. Accordingly, identification accuracy was analysed for each session separately in ANOVAs with the between-participant factor mapping and the within-participant factors compatibility and SOA. The main effect of SOA was significant for the first session, $F(4, 56) = 33.75$, $p < .001$, and for the second session, $F(4, 56) = 30.27$, $p < .001$. The main effects of compatibility and of mapping were not significant in both sessions (all $p > .20$). The two-way interaction of compatibility and mapping approached significance for the first session, $F(1, 14) = 4.02$, $p < .065$, but it was far from significance for the second session ($F < 1$; all remaining interactions: $p > .25$). Figure 3 shows the mean identification accuracy values from the first session in Experiment 2, as a function of the factors mapping, compatibility, and SOA. For the second session in Experiment 2, both groups showed slightly lower identification accuracy for response-compatible stimuli than for response-incompatible stimuli.

In order to qualify the interaction between the factors mapping and compatibility for the first session of Experiment 2, two-way ANOVAs with the within-participant factors SOA and compatibility were conducted on the identification rates of both groups (i.e., mappings), separately. For the first group, with the tone-response mapping "low–left vs high–right", the main effect of SOA, $F(4, 28) = 15.31$, $p < .001$, and the main effect of compatibility, $F(1, 7) = 5.97$, $p < .045$, were significant. The main effect of compatibility means that response-compatible stimuli ($M = 0.71$) were identified less accurately than incompatible stimuli ($M = 0.76$). The interaction between compatibility and SOA was not significant, $F(4, 28) = 1.56$, $p < .211$. For the second group, with the tone-response mapping "low–right vs high–left", only the main effect of
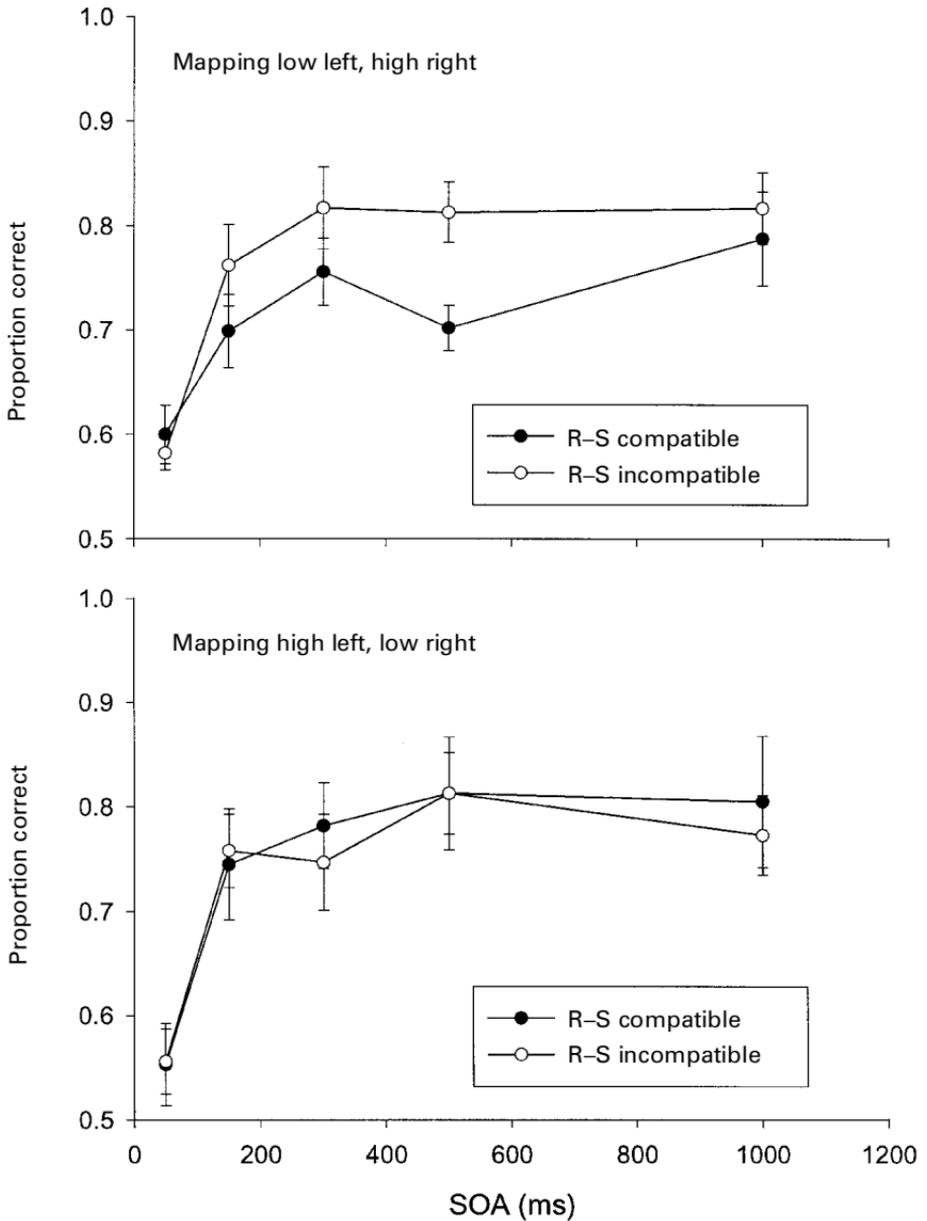
Figure 3. Results from the visual encoding task in the first session of Experiment 2. Mean proportion of correctly identified visual stimuli (with standard errors between participants) as a function of the tone–response mapping (upper panel: low–left vs high–right; lower panel: low–right vs high–left), the response–arrow compatibility (compatible vs incompatible), and the tone–arrow SOA. Each data point is based on about 240 observations.

SOA, $F(4, 28) = 19.45$, $p < .001$, was significant (other $F < 1$). Thus, the pattern of results observed in the first session of Experiment 2 is exactly the same as that observed in Experiment 1 across both sessions.

Discussion

The present experiment replicates the main findings of Experiment 1. The blindness effect was again observed in a PRP task, but only with a low–left and high–right tone-response mapping and not with the low–right and high–left mapping. However, this pattern of results was only observed in the first session of Experiment 2, when the mapping had been manipulated between participants, as in Experiment 1. When the participants had to invert the tone-response mapping in the second session of Experiment 2, the influence of the mapping on the blindness effect disappeared. This suggests that carry-over effects from the first session eliminated both the blindness effect and the influence of the tone-response mapping on the blindness effect. It seems that in the second session each response-cue tone activated both responses: The response that had to be made to the tone in the first session, and the response that had to be made to the tone in the second session. This interpretation is supported by the observation of a significantly higher percentage of false responses in the second session, $t(15) = 2.22$, $p = .042$, two-tailed, whereas the reaction times did not differ between sessions (478 vs 471 ms), $t(15) = 0.38$, $p = .712$, two-tailed. The simultaneous activation of both responses, however, could have led to impairments in the encoding of stimuli that were compatible and of stimuli that were incompatible to the actually performed response and, thus, could have eliminated the blindness effect.

Now, let us turn to the interaction between the tone-response mapping and the blindness to response-compatible stimuli. Why did the blindness effect exclusively occur with the low–left/high–right mapping? At first sight, this observation points to similar effects already known from compatibility research. In several studies on orthogonal compatibility effects, advantages in accuracy and in reaction time were observed when participants were required to press a left button in response to a visual stimulus appearing below a fixation point and to press a right button in response to a stimulus appearing above the fixation point, as compared to the reversed mapping (e.g., Lippa, 1996a, b; Weeks & Proctor, 1990). From these observations, it was concluded that "below" (or "down") is more strongly associated with "left" than with "right", whereas "above" (or "up") is more strongly associated with "right" than with "left" (Lippa, 1996a, b). This kind of preference was observed not only between orthogonal spatial dimensions but also between tone pitch and spatial position. In a preferred matching task, Mudd (1963) found that low tones were preferably associated with left positions, whereas high tones were preferably associated with right positions.

Thus, it is possible that the present impact of the tone-response mapping on the blindness effect originated either from a preferred mapping between tones and responses or from a preference to associate a low (high) tone preferably with a left (right) stimulus. With respect to the first possibility, Simon and co-workers did not find any performance differences in response latencies and errors when comparing the possible mappings of low and high tones to left and right responses (cf., Simon, Meewaldt, Acosta, & Hu, 1976). We were able to confirm these results (Wühr, 2000). In addition, in an experiment on the blindness to response-compatible stimuli, a variation of the strength of association between the response cue and the response did not lead to any observable effects on identification performance (Müsseler et al., 2000). Thus, it is not likely that the present modification of the blindness effect originated from the tone-response mappings being different in their stimulus–response compatibility.

Another way to explain the present blindness effect and its dependence on the tone-response mapping is to assume two different kinds of interference. The first interference might originate from the preparation and the generation of a left (right) response, which impairs the visual encoding of a left (right) arrow, but not that of a right (left) arrow. This is the response-arrow interference that has been assumed in the previous studies (Müsseler & Hommel, 1997a; Müsseler et al., 2000). The second interference might be that the encoding of a low (high) tone impairs the encoding of a left (right) arrow, but not that of a right (left) arrow. This possible tone-arrow interference between the encoding of a frequency-coded tone and the encoding of an arrow is the subject of the next experiment.

Given these two kinds of interference, the present pattern of results could have emerged as follows: In the low–left and high–right mapping, the two kinds of interference may have worked in the same direction and their effects may have added up. In this case, for example, the encoding of a low tone and the subsequent execution of a left response both impaired the identification of a left stimulus, whereas neither the encoding of a low tone nor the execution of a left response interfered with the identification of a right stimulus. In contrast, in the low–right and high–left mapping, the two kinds of interference may have worked in opposite directions and their effects may have nullified each other. In this case, for example, the encoding of a high tone impaired the identification of a right stimulus; but the subsequent execution of a left response impaired the identification of a left stimulus.

If these considerations are correct, it should be possible to demonstrate both interferences independently. Experiment 3 attempted to show that the tone-arrow interference occurs without manual responses. Experiment 4 was a control for Experiments 3 and 5. Finally, Experiment 5 attempted to demonstrate the response-arrow interference without a modulation by frequency-coded tones.

EXPERIMENT 3

A possible interpretation of Experiments 1 and 2 rests on the assumption that the present blindness effect originated from two independent sources of inter-ference: The tone-arrow interference and the response-arrow interference. Both interferences converge in the low–left and high–right tone-response mapping; but they nullify each other with the low–right and high–left mapping. Accordingly, the blindness effect occurred in the low–left and high–right mapping but not in the low–right and high–left mapping.

In this experiment, the implication of this interpretation was examined, which states that the tone-arrow interference should also occur in the absence of the primary response task. In other words, it was examined whether the pure presentation of a low (high) tone specifically impairs the encoding of a left (right) arrow, but not so much the encoding of a right (left) arrow. Thus, in contrast to the previous experiments, the tone did not serve as a response cue. Instead, the tone could be ignored. In order to also examine the unspecific effects of tone presentation on identification, additional trials were introduced, in which no tone was presented.

Method

Participants.   Twelve paid volunteers (six females and six males; aged 21–32 years) took part in Experiment 3. All of them reported to be right handed and to have normal or corrected-to-normal vision. None had participated in Experiments 1 and 2.

Apparatus and stimuli.   The same apparatus and stimuli as in Experiments 1 and 2 were used.

Procedure and design.   Each trial started with the presentation of a blank screen for 1000 ms. Then—with equal probability—either the low-pitched tone, the high-pitched tone, or no tone was presented for 150 ms. There were two differences between the procedure of the present experiment and the proce-dures of Experiments 1 and 2. First, participants did not have to perform any response to the tones. On the contrary, participants were told that the tones were completely irrelevant for the task and, thus, could be ignored. Second, the five SOAs between the tone and the visual stimulus were changed to 0, 50, 150, 300, and 500 ms. Due to technical difficulties, the SOA of 0 ms was dropped from the analysis, and only the results for the remaining four SOAs are reported. In all other respects, the procedure was identical to the previous experiments.

Two independent variables were crossed in a 3×4 within-participants design. The first factor was the relationship between the three tone conditions and the two visual stimuli. The six possible combinations formed three levels: The first level consisted of the two combinations of no tone and the presentation

of a left- or right-pointing arrow. The second level consisted of the two combi-
nations of a low-pitched tone with a left-pointing arrow and of a high-pitched
tone with a right-pointing arrow. The third level consisted of the two combina-
tions of a low-pitched tone with a right-pointing arrow and of a high-pitched
tone with a left-pointing arrow. The second factor was the SOA between the
tone and the visual stimulus, with the four levels 50, 150, 300, and 500 ms. The
intention was to separately test for the unspecific effects and for the specific
effects of the presentation of a low- or high-pitched tone on the identification of
a left- or right-pointing arrow.

The experimental phase was preceded by a practice phase of 8 block of 12
trials each (3 tone conditions × 2 visual stimuli; fixed SOA of 250 ms). The
whole experiment consisted of one session that lasted approximately 1 hour
and 15 minutes.

Results

The mean presentation time for visual stimuli was 33 ms. Across all conditions,
the proportion of correctly identified stimuli was 0.80 (SD = 0.04). First, the
specific effects of the presentation of a low- or high-pitched tone on the identifi-
cation of a left- or right-pointing arrow were analysed. The identification
accuracy was computed for the two combinations of a low-pitched tone with a
left-pointing arrow, and of a high-pitched tone with a right-pointing arrow.
Additionally, the identification rates for the visual stimuli were computed for
the remaining two combinations of a low-pitched tone with a right-pointing
arrow, and of a high-pitched tone with a left-pointing arrow. The resulting
proportions of correct judgements, which are depicted in Figure 4, were
analysed as a function of these two tone–arrow relationships and of the SOA.
The ANOVA revealed a significant main effect of SOA, $F(3, 33) = 33.73$,
$p < .001$. Furthermore, the main effect of tone–arrow relationship was also
significant, $F(1, 11) = 7.51$, $p = .019$. The latter result means that the com-
binations of a low-pitched tone with a left-pointing arrow and of a high-pitched
tone with a right-pointing arrow led to significantly inferior identification
performance ($M = 0.77$) than did the two alternative combinations ($M = 0.81$).
The two-way interaction was not significant ($F < 1$).

In a second analysis, the unspecific effects were examined for the presence
or absence of a low- or high-pitched tone on the identification of a left- or right-
pointing arrow. The identification rates for the visual stimuli were computed
for all possible combinations of a low- and high-pitched tone with a left- or
right-pointing arrow (the filled and unfilled circles in Figure 4), and they were
compared with identification performance in the absence of a tone (the filled
triangles in Figure 4). This was done in a two-factorial ANOVA with tone
(present or absent) and SOA (50, 150, 300, or 500 ms). The main effect of SOA,
$F(3, 33) = 19.36$, $p < .001$, was significant, whereas the main effect of tone was
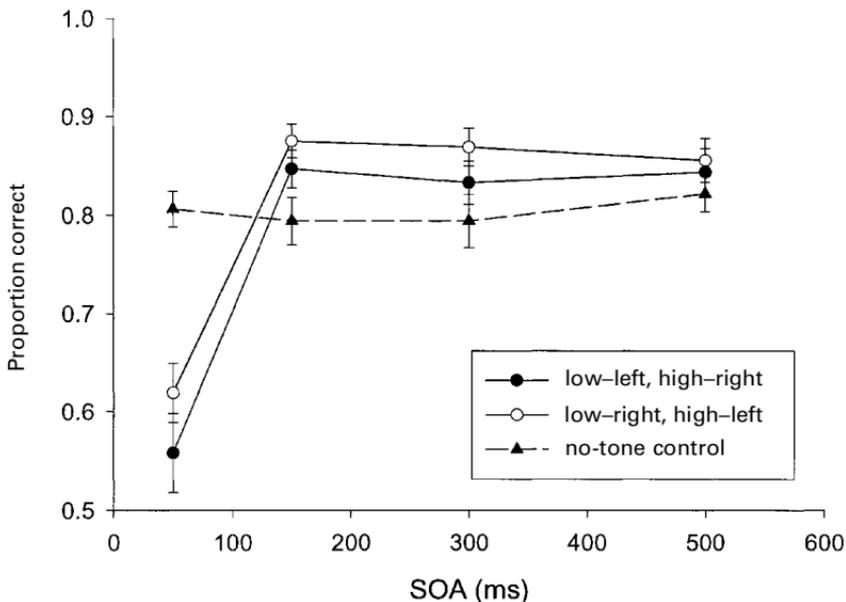
Figure 4.   Results from Experiment 3. Mean proportion of correctly identified visual stimuli (with standard errors between participants) as a function of three combinations between the presence or absence of irrelevant tones and the visual stimuli (low-pitched tone/left-pointing arrow and high-pitched tone/right-pointing arrow; low-pitched tone/right-pointing arrow and high-pitched tone/left-pointing arrow; left- and right-pointing arrow without tone), and the tone–arrow SOA. Each data point is based on 360 observations.

not ($F < 1$). The main effect of SOA means that—across all tone conditions—identification accuracy for the SOA of 50 ms ($M = 0.70$) was worse than for the remaining three SOAs of 150 ms ($M = 0.83$), 300 ms ($M = 0.82$), and 500 ms ($M = 0.84$). The interaction between tone and SOA, $F(3, 33) = 23.51, p < .001$, was also significant, which reflects the significant effect of SOA on identification performance when a tone had been presented (see earlier). The SOA had, however, no effect on identification performance when no tone had been presented.

Discussion

The most important finding was the specific interference effect between the presentation of a tone and the identification of a visual stimulus. A left arrow was identified less frequently when it was presented with a low tone than when it was paired with a high tone. In contrast, a right arrow was identified less frequently when it was presented with a high tone than when it was paired with a low tone. In contrast to the previous experiments, this effect was observed

with task-irrelevant tones. Thus, the pure presentation of the low–high tone seems to be sufficient to specifically affect the encoding of a left–right arrow-head. This finding presents evidence that the blindness effect observed in Experiments 1 and 2 was modulated by a tone–arrow interference.

A possible interpretation of the specific tone–arrow interference is that when a low (high) tone is presented, it is preferably associated with a left (right) spatial orientation and this affects the identification of a left (right) stimulus. These preferences are in line with Mudd's (1963) observation that low tones were preferably associated with left than with right positions, and that high tones were preferably associated with right than with left positions. In addition, these preferences are similar to the results reported by Lippa (1996a, b) and by Weeks and Proctor (1990), who found that in choice reaction-time tasks observers prefer to associate visual stimuli presented below a fixation point with left responses and stimuli presented above a fixation point with right responses. The specific tone–arrow interference effect observed in the present experiment suggests that not only a feature overlap between a response and a visual stimulus leads to performance decrements, when the visual stimulus has to be encoded during the execution of the compatible response. Rather, also the existence of an association between the features of a tone and the features of a visual stimulus seems to be able to create similar performance decrements. We return to this point in the General Discussion.

In addition to producing the specific effect, the presentation of a low or a high tone seemed to produce both an unspecific impairment in identification performance at the 50 ms SOA and an unspecific facilitation at the remaining SOAs. This conclusion should, however, be examined carefully. Any proportion correct value above or below the no-tone control cannot be unequivocally interpreted as impairment or as facilitation. For example, if the tone served as a warning signal for all SOAs of 150 ms and longer (cf., Bertelson, 1967; Bertelson & Tisseyre, 1968), and thus improved visual identification generally, then the identification rate at the 50 ms SOA had to be below the no-tone control due to the adjustment procedure of presentation time (cf., Footnote 1). So it is unclear whether there was an improvement at the longer SOAs, or an impairment at the shorter SOA, or both.

Given that the encoding of visual stimuli at the 50 ms SOA was actually impaired, such an impairment seems to be inconsistent with recent observations by Jolicoeur (1999b). This author had his participants to monitor a stream of briefly presented visual stimuli (letters) for the presence of a target stimulus. The visual target letter followed a low or a high tone with a variable SOA. When the tones required a speeded left or right keypress, the accuracy in letter detection suffered markedly, showing unspecific response–arrow interference. When the tones required no response, no deficit was observed in the visual task. Thus, whereas to-be-ignored low or high tones did not affect concurrent visual encoding in Jolicoeur's (1999b) study, we found such an unspecific

impairment in the present experiment. There are two possible explanations for this discrepancy. First, different temporal relationships between the to-be-ignored tones and the visual stimuli in the two studies might account for the different results. In Jolicoeur's (1999b) study, the tones were presented for 100 ms and the shortest SOA was 100 ms. Thus, even for the shortest SOA, there was no concurrent presentation of tones and visual stimuli. In the present experiment, the tones were presented for 150 ms and outlasted the presentation of the visual stimuli at the shortest SOA of 50 ms. Thus, the early impairment of visual encoding in our experiments might be due to the concurrent presentation of a tone (via headphones), whereas there was no concurrent presentation of tones and visual stimuli in Jolicoeur's (1999b) experiment. Second, the existence or non-existence of associations between the to-be-ignored tones and the visual stimuli might also account for the discrepant results. The observation of the specific tone–arrow interference in the present experiment was explained by automatically associating "low" with "left" and "high" with "right" (see previously). It is possible that the association process, which led to the specific interference effect, also caused the (short-lasting) unspecific interference effect. In contrast, there are most likely no associations between low and high tones and the letters "X" and "Y", which were the target letters in Jolicoeur's (1999b) study. Thus, the lack of associations between the tones and the letters might explain the absence of an unspecific interference effect. Experiment 4 examined the question, whether the unspecific interference effect observed in the present experiment is more likely due to the concurrent presentation of tone and visual stimuli or to the existence of associations between features of the tones and features of the visual stimuli.

EXPERIMENT 4

The major aim of the present experiment was to test, whether the to-be-ignored tones in Experiment 3 caused unspecific impairments in the encoding of simul-taneously presented visual stimuli because of their simultaneous presentation or because of associations between tones and visual stimuli. Therefore, in Experiment 4, two short tones and one long tone of the same frequency were used as the to-be-ignored auditory stimuli, which were presented before the presentation of a to-be-identified left- or right-pointing arrowhead. We assumed that there were no preferred associations between two short tones or one long tone with either "left" or "right". Accordingly, no specific tone–arrow interference was expected in Experiment 4. If the tones in Experiment 4 caused unspecific impairments in the concurrent processing of visual stimuli without causing specific interference, then the unspecific impairments observed in Experiment 3 can be mainly attributed to their simultaneous presentation, and not to the activation of specific associations. The opposite interpretation would

be suggested, however, if the tones in Experiment 4 caused neither specific impairments, nor unspecific impairments on the concurrent processing of visual stimuli. In addition, the demonstration that two short tones and one long tone do not specifically affect the encoding of left- and right-pointing arrows is important for the use of these tones as response cues in Experiment 5.

Method

Participants.   Twelve paid volunteers (five females, seven males; aged 21–28 years) took part in the experiment. All of them reported to be right handed and to have normal or corrected-to-normal vision. None had participated in Experiments 1–3.

Apparatus and stimuli.   The apparatus and the visual stimuli were the same as in Experiment 3, except that now a Macintosh Quadra was used to control the experiment. The major difference between the present experiment and Experiment 3 was that the low-pitched and the high-pitched tone, used as auditory stimuli in Experiments 1–3, were replaced by one long tone presented for 150 ms and two short tones presented for 50 ms each with an inter-stimulus interval of 50 ms. These tones had an equal pitch of 600 Hz and were again presented concurrently to both ears.

Procedure and design.   The procedure was the same as in Experiment 3, except that different auditory stimuli were used as distracters. In the present experiment, after a blank interval of 1000 ms either a long tone of 600 Hz, two short tones of 600 Hz, or no tone was presented with equal probability. As in Experiment 3, participants did not have to respond to the tones and were told that these tones were task-irrelevant.

Two independent variables were crossed in a 3 × 4 within-participants design. The first factor was the relationship between the three tone conditions and the two visual stimuli. The six possible combinations were grouped to form three levels of this factor in the following way. The first level consisted of the two combinations of no tone and the presentation of a left- or right-pointing arrowhead. The second level consisted of the two combinations of a long tone with a left-pointing arrow and of two short tones with a right-pointing arrow. The third level consisted of the two combinations of a long tone with a right-pointing arrow and of two short tones with a left-pointing arrow. The second factor was the SOA between the tone and the visual stimulus, with the four levels 50, 150, 300, and 500 ms. As in Experiment 3, it was planned to separately test for the unspecific effects and for the specific effects of the presentation of one long tone or two short tones on the identification of a left- or right-pointing arrow.

Results

The mean presentation time for visual stimuli was 34 ms. Across all conditions, the proportion of correctly identified visual stimuli was 0.80 (SD = 0.05). In a first analysis, the specific effects of the presentation of a long tone or two short tones on the identification of a left- or right-pointing arrow were examined. Therefore, visual identification accuracy was computed for the two combinations of one long tone with a left-pointing arrow and of two short tones with a right-pointing arrow. In addition, visual identification accuracy was computed for the remaining two combinations of one long tone with a right-pointing arrow and of two short tones with a left-pointing arrow. The resulting proportions of correctly identified visual stimuli, which are depicted in Figure 5, were analysed as a function of the two tone–arrow relationships and of the four SOAs. An ANOVA revealed a significant main effect of SOA, $F(3, 33) = 2.93$, $p = .048$, which reflects lower identification accuracy for the SOAs of 50 and 150 ms (both $M = 0.82$) than for the SOAs of 300 ($M = 0.86$) and 500 ms ($M = 0.84$). This effect can be explained by assuming that the tone served as
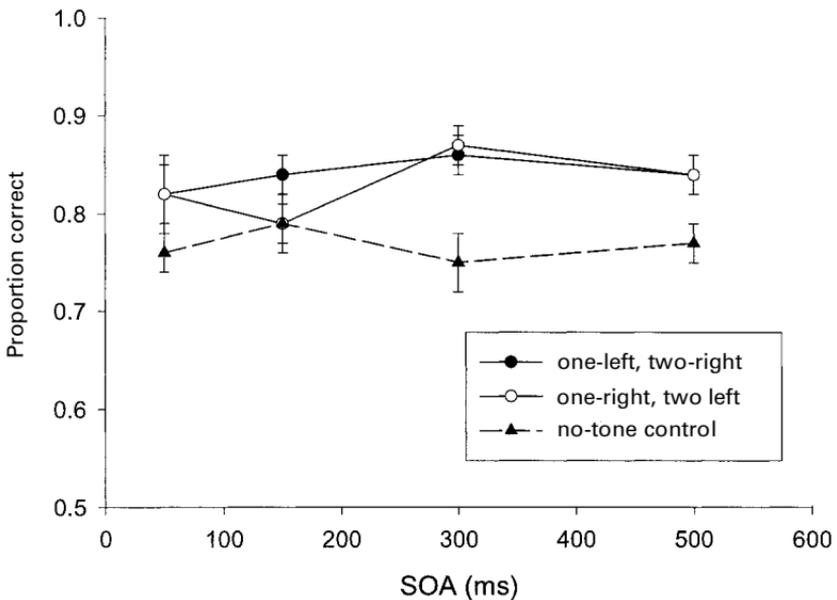
Figure 5. Results from Experiment 4. Mean proportion of correctly identified visual stimuli (with standard errors between participants) as a function of three combinations between the presence or absence of irrelevant tones and the visual stimuli (one long tone/left-pointing arrow and two short tones/right-pointing arrow; one long tone/right-pointing arrow and two short tones/left-pointing arrow; left- and right-pointing arrow without tone), and the tone–arrow SOA. Each data point is based on 360 observations.

warning signal for the occurrence of the visual stimulus, but that participants needed more than 150 ms to effectively use this information (cf., Bertelson, 1967; Bertelson & Tisseyre, 1968). More important, however, neither a main effect of the tone–arrow relationship nor an interaction of this factor with SOA was observed (both $F < 1$). Thus, these results confirmed the prediction that the pure presentation of a long tone or of two short tones can not specifically affect the identification of the arrows.

In the second part of the analysis, the unspecific effects of the presence or absence of a long tone or of two short tones on the identification of a left- or right-pointing arrow were analysed. Therefore, the proportions of correctly identified visual stimuli were computed across all possible combinations of a long tone or two short tones with a left- or right-pointing arrow (the filled and unfilled circles in Figure 5) and compared with the identification rates of visual stimuli when no tone had been presented (the filled triangles in Figure 5). This was done in a two-factorial ANOVA with tone (present or absent) and SOA (50, 150, 300, or 500 ms) as within-participant factors. The main effect of SOA was not significant ($F < 1$), but there was a significant main effect of tone, $F(1, 11) = 28.20$, $p < .001$. The presentation of a tone improved visual identification accuracy ($M = 0.84$), as compared to the performance in the absence of a tone ($M = 0.77$). The two-way interaction between tone and SOA was also significant, $F(3, 33) = 3.12$, $p = .039$. This interaction is due to a significant effect of SOA on identification performance when a tone had been presented (see earlier), whereas the SOA had no effect on identification performance in the absence of a tone, $F(3, 33) = 1.14$, $p = .348$. In other words, the positive effect of tone presentation on visual encoding increases with increasing SOA, as compared to the no-tone condition.

To examine the possibility that the absence of a specific tone–arrow interference in the present experiment would also reduce the unspecific effect as compared to Experiment 3, the identification rates from trials with tone presentation entered into a two-way ANOVA with the factors experiment and SOA. This analysis revealed significant main effects of experiment, $F(1, 22) = 5.76$, $p = .025$, and SOA, $F(3, 66) = 30.82$, $p < .001$, and—more important—a significant interaction between both factors, $F(3, 66) = 22.69$, $p < .001$. For the 50 ms SOA, the identification rate was higher in the present experiment ($M = 0.82$) than in Experiment 3 ($M = 0.60$), whereas the identification rates were very similar for the other SOAs.

Discussion

The mere presentation of one long tone or two short tones exerted neither a specific nor an unspecific (negative) effect on the visual encoding of left- or right-pointing arrowheads, even when the tones and the visual stimuli overlapped in time. This result suggests that the early deficit in visual encoding in

Experiment 3 was not due to the concurrent presentation of low or high tones and left- or right-pointing arrowheads. Instead, it suggests that specific associations between these tones and these visual stimuli were also responsible for the unspecific interference effect. These associations are automatically activated by the presentation of a tone (e.g., a low tone), and affect both the encoding of the associated stimulus (left-pointing arrow), as well as the encoding of the non-associated stimulus (right-pointing arrow). A more detailed account is presented in the General Discussion.

The results of Experiment 4 are consistent with the findings of Jolicoeur (1999b), who also observed no (negative) effect from to-be-ignored low or high tones on visual encoding of letters. Together, the findings suggest that there is no unspecific cross-modal interference effect when there are no specific associations between the to-be-ignored tones and the to-be-encoded visual stimuli. We conclude that there are no specific associations between long or short tones with "left" or "right", because no specific interference was observed in the present experiment. In addition, it is very unlikely that there are specific associations between low or high tones and the letters "X" or "Y" (Jolicoeur, 1999b).

The finding that the tones used in the present experiment were unable to specifically affect visual encoding of left- or right-pointing arrowheads was important for the next experiment. In Experiment 5, one long tone and two short tones were used as cues in the response task, in order to demonstrate the blindness effect without modulations through a tone–arrow interference.

EXPERIMENT 5

After the successful demonstration of the tone–arrow interference in the absence of a response task in Experiment 3, the present experiment aimed to isolate the response–arrow interference (i.e., the "original" blindness effect) in the absence of a modulation by a tone–arrow interference. Therefore, the response cues used in Experiments 1 and 2 were replaced by one long tone and two short tones. On the basis of the results of Experiment 4, it was assumed that these response cues do not differ in their relationship to the spatial left/right dimension of the arrows.

Method

Participants. Sixteen paid volunteers (nine females, seven males; aged 19–34 years) took part in the experiment. All participants reported to have normal or corrected-to-normal vision; only one declared to be left handed. None had participated in Experiments 1–4.

Apparatus and stimuli. The apparatus and the visual stimuli were the same as in Experiment 1, except that now a Macintosh Quadra was used to control the

experiment. The major difference between the present experiment and Experiment 1 was that the low-pitched and the high-pitched tone, used as auditory stimuli in Experiment 1, were replaced by one long tone presented for 150 ms and two short tones presented for 50 ms each with an inter-stimulus interval of 50 ms. These tones had an equal pitch of 600 Hz and were again presented concurrently to both ears via headphones.

Procedure and design.   The procedure of Experiment 5 was identical to the procedure of Experiment 1, except that one half of the participants had to press the left key to one long tone and the right key to the short tones. For the other half of the participants, the mapping rule was inverted. As in Experiment 1, the compatibility between the responses and the visual stimuli, as well as the SOA between the tones and the visual stimuli, were varied within participants, whereas the mapping between tones and responses was varied between participants. Thus, the present experiment was based on a $2 \times 2 \times 5$ mixed design.
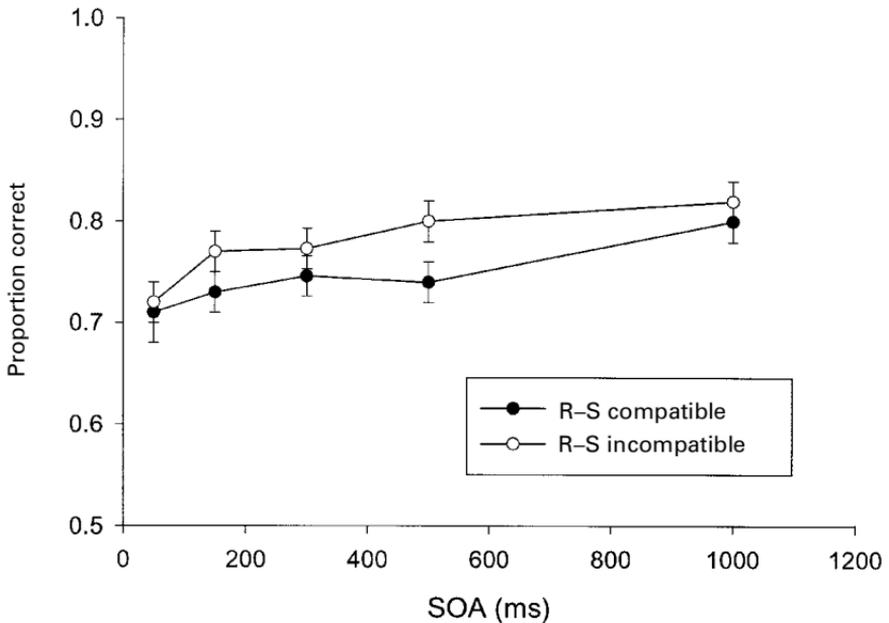
Results

Response task.   Across all conditions and participants, less than 4% of the reaction times exceeded the criterion of 1000 ms. The error percentage had a grand mean of 5.3% (SD = 2.8). The error percentages were analysed in an ANOVA with the between-participants factor mapping (two levels), the within-participant factors compatibility (two levels), and SOA (five levels). As in Experiment 1, the only significant effect was the main effect of SOA, $F(4, 56) = 2.95$, $p = .028$, according to which the percentage of false responses increased with decreasing SOA.

The mean correct reaction time across all conditions was 491 ms (SD = 79). A corresponding ANOVA revealed no significant effect.

Identification task.   The mean presentation time for the visual stimuli was 44 ms in the group with the tone–response mapping "one tone–left" and "two tones–right"; and it was 34 ms in the group with the mapping "one tone–right" and "two tones–left". The difference of 10 ms was not significant, $t(14) = 1.37$, $p > .10$ (two-tailed). Across all conditions, the proportion of correctly identified visual stimuli was 0.76 (SD = 0.05). Figure 6 depicts these proportions as a function of all possible combinations of the different levels of the factors compatibility and SOA.

The proportions of correctly identified visual stimuli were analysed in an ANOVA with the between-participant factor mapping (two levels), the within-participant factors compatibility (two levels), and SOA (five levels). This ANOVA revealed the same pattern of main effects as did the ANOVA in Experiment 1. The main effect of mapping was not significant, $F(1, 14) = 2.96$, $p = .108$. However, the main effects of SOA, $F(4, 56) = 7.37$, $p < .001$, and of

Figure 6. Results from the visual encoding task in Experiment 5. Mean proportion of correctly identified visual stimuli (with standard errors between participants) as a function of the response–arrow compatibility (compatible vs incompatible), and the tone–arrow SOA. Each data point is based on about 950 observations.

compatibility, $F(1, 14) = 8.79$, $p = .010$, were significant. The effect of SOA reflects the observation that identification accuracy increased when the SOA increased: There was a difference of 0.10 between the identification accuracy for the shortest SOA of 50 ms ($M = 0.71$) and the identification accuracy for the longest SOA of 1000 ms ($M = 0.81$). The effect of compatibility was due to the fact that response-compatible stimuli ($M = 0.75$) were identified less accurately than response-incompatible stimuli ($M = 0.78$). Importantly, and in contrast to the results of Experiment 1, none of the interactions between the factors mapping, compatibility, and SOA was significant (all $F < 1$).

Discussion

In line with our original expectations, the blindness to response-compatible stimuli was observed in the present experiment in the absence of the modulation by the tone–arrow interference in Experiments 1 and 2. Therefore, the present finding is highly similar to the response–arrow interference already observed with previous—non PRP—tasks (e.g., Müsseler & Hommel, 1997a). However, in contrast to the previous studies, the present finding demonstrates

that the blindness effect is not restricted to situations in which the response has to be withheld before or during stimulus encoding.

Moreover, Experiments 3 and 5 provide indirect evidence for our interpretation of why the blindness effect occurred only for one of the two alternative tone–response mappings in Experiments 1 and 2. The assumption was that in these experiments two different kinds of interference had converged in the low–left and high–right tone–response mapping, but had nullified each other in the low–right and high–left mapping. Experiments 3 and 5 demonstrated the tone–arrow interference and the response–arrow interference independently from each other; thus, these two interferences could have interacted in Experiments 1 and 2. We present an account for these interference effects in the General Discussion.

Finally, Experiment 5 revealed evidence for an unspecific response–arrow interference effect: The greater the temporal overlap between the speeded response task and the visual encoding task, the worse was overall performance in the encoding task. We found a performance decrement of 6% between the SOAs of 50 and 500 ms, which is very similar to the performance decrement that Jolicoeur (1999a, Exp. 2) has observed (about 5% between the SOAs of 50 and 600 ms). But because there was no neutral condition in Experiment 5, it is not for sure that this unspecific effect actually represents costs. Experiment 4 showed that the presentation of short or long tones can improve performance in a concurrent visual encoding task, compared to visual encoding in the absence of a tone, and that this improvement increased with the SOA. Our interpretation of this result was that the tone served as a warning signal for the occurrence of the visual stimulus. It is unlikely, however, that the tones could be used as warning signals in Experiment 5, when the participants had to respond as quickly as possible to the tones. Moreover, Experiment 4 showed no evidence that the mere presentation of short or long tones can impair concurrent visual encoding. Thus, the decrease in visual performance with decreasing SOA in the present experiment is most likely a cost at short SOAs that is caused by the concurrent preparation of a motor response.

GENERAL DISCUSSION

The major aim of the present study was to investigate the conditions under which processing in a motor (response) task specifically interferes with concurrent processing in a visual encoding (identification) task. From such studies it may be possible to learn more about the representations and/or processes in which response preparation and perception overlap.

Such previous studies have demonstrated unspecific impairment of visual encoding when the participants were simultaneously engaged in a speeded choice–response task (e.g., Jolicoeur, 1999a; De Jong & Sweet, 1994). From

these studies, however, it remained unclear to which degree the inability to fully prepare for two tasks at the same time has contributed to the observed unspecific impairment. Instead of an interference at the visual encoding phase, the impairment could also have originated from a procedural interference, due to some limited multi-purpose capacity.

Other studies have demonstrated specific impairment of visual encoding when the participants were simultaneously engaged in an unspeeded choice–response task. The finding was that the preparedness to execute a left or right keypress or the execution itself impaired the concurrent encoding of a response-compatible visual stimulus. In these studies, however, the execution of the response had to be postponed (suppressed) either until a neutral response had been performed (e.g., Müsseler & Hommel, 1997a) or until a "go" signal had occurred (e.g., Wühr & Müsseler, 2001). Thus, it was unclear whether the blindness effect originated from the preparation of the response, or from the withholding of the response. In order to test this issue in the present experiments, the participants performed keypresses to a tone as quickly as possible and identified left- or right-pointing arrowheads presented in between. In addition to the compatibility between the response and the visual stimulus, the SOA between the tone and the visual stimulus was systematically varied in order to investigate when—if at all—the blindness effect emerges in respect to the processing in the response task.

There were four major findings. The first finding was that speeded left or right keypresses unspecifically interfered with the encoding of briefly presented visual stimuli (Experiments 1, 2, and 5). The identification of stimuli presented during the preparation and execution of the responses was worse compared to the identification of stimuli after the execution of the responses, irrespective of the compatibility between responses and visual stimuli. This unspecific response–stimulus interference was even observed at SOAs between tones and visual stimuli, at which possible (direct) stimulus–stimulus interferences were unlikely to play a role (SOAs ≥ 150 ms). This finding replicates the earlier findings reported by De Jong and Sweet (1994) and Jolicoeur (1999a).

Second, a speeded left or right keypress did also specifically interfere with the encoding of the briefly presented visual stimuli (Experiments 1, 2, and 5). The speeded preparation and execution of responses caused inferior identification performance for response-compatible stimuli compared to response-incompatible stimuli. This finding shows that the blindness effect is not restricted to situations in which the response has to be withheld before or during stimulus encoding. In the present experiments, in which the response had to be performed as quickly as possible to the tones, the blindness effect seemed to grow during the processing of the response task and to peak around response execution. Thus, neither an abrupt onset of the blindness effect was observed nor was the blindness effect preceded by a brief period of superior

identification of response-compatible stimuli. However, superior identification could be expected under certain assumptions, which are discussed later.

Third, a particular set of auditory stimuli was able to specifically interfere with the encoding of briefly presented visual stimuli (Experiment 3). In particular, the encoding of a left-pointing arrow was inferior when it followed a low-pitched tone than when it followed a high-pitched tone, whereas the encoding of a right-pointing arrow was inferior when it followed a high-pitched tone than when it followed a low-pitched tone. In contrast to this specific tone–arrow interference, the identification of a left- or right-pointing arrow was not differentially affected by the presentation of a long tone or two short tones, with equal pitch (Experiment 4).

Fourth, the specific tone–arow interference modulated the specific response–arrow interference when the task allowed both interferences to occur simultaneously (Experiments 1 and 2). That is, a (response-compatible) left-pointing arrow was identified less well than a (response-incompatible) right-pointing arrow when a left key was pressed to a low-pitched tone, but not when the left key was pressed to a high-pitched tone. Correspondingly, a (response-compatible) right-pointing arrow was identified less well than a (response-incompatible) left-pointing arrow when a right key was pressed to a high-pitched tone, but not when the right key was pressed to a low-pitched tone.

Before we turn to our explanation of these findings, a few comments on the time course of the blindness effect observed in the present experiments seem to be appropriate. Of course, these comments are only based on qualitative observations because we never found a significant two-way interaction between compatibility and SOA, and—therefore—did not perform post hoc comparisons on the data. However, it may be interesting to note that in all of the present dual-task experiments, the blindness effect was numerically greatest for the SOA of 500 ms, when the visual stimulus was presented most closely to response execution (mean reaction times of the Experiments 1, 2, and 5 were 466 ms, 474 ms, and 491 ms, respectively). This observation suggests that the better prepared the response the stronger the blindness to response-compatible stimuli. This suggestion is supported by the results of more recent experiments, in which the participants identified left- and right-pointing arrows while they performed a compatible or an incompatible response, or while they performed one of two neutral responses. We observed a significant disadvantage to identifying response-compatible stimuli compared to the neutral conditions only for the medium SOA of 400 ms, which again was closest to response execution (Müsseler & Wühr, 2001). Thus, the preparation and execution of a speeded response produces costs in the encoding of compatible stimuli that peak around response execution. By contrast, the blindness effect was clearly diminished at the 1000 ms SOA in two out of three of the present dual-task experiments. Only in Experiment 1, the blindness effect seemed to be still large for the 1000 ms

SOA. However, this might be due to the possible additivity of the two specific interference effects, the tone–arrow and the response–arrow interference, in this experiment.

In the following section, it is discussed how well the two-stage model of action planning, proposed by Stoet and Hommel (1999; see also Hommel et al., in press; Müsseler, 1999), is able to account for the different findings of the present study.

The two-stage account of action planning

The two-stage model of action planning (Stoet & Hommel, 1999) has been proposed to explain specific interference effects between different sets of concurrently performed tasks. The model rests on two basic assumptions. The first assumption is that features of to-be-perceived stimuli and features of to-be-performed responses are represented by the same cognitive codes (cf., Hommel, 1997; MacKay, 1987; Müsseler & Prinz, 1996). For example, the identity of a to-be-perceived left-pointing arrow and the position of a to-be-performed left keypress are represented by accessing the same cognitive LEFT code. This common-coding assumption (Prinz, 1990, 1997) allows the model not only to account for specific interference effects between the processing of two different stimuli or between the processing of two different responses (Stoet & Hommel, 1999), but also to account for specific interference effects between the processing of a response and the processing of a stimulus. Any of these interference effects is interpreted as a crosstalk due to structural overlap.

The second basic assumption of the two-stage model is that the formation of any cognitive representation of a stimulus or of a response takes place in two successive steps. During the first stage, the features of a perceived stimulus or of a to-be-performed response are *activated*. However, if more than one stimulus is simultaneously present or if more than one response is to be performed, the activation of feature codes does not allow to distinguish between different stimuli and/or responses. This fact is known as the "binding problem" (cf., Treisman, 1996). Therefore, the already activated feature codes that belong to one and the same stimulus or response are *bound* together, that is, during the second stage of processing, these codes are integrated into an event file. Stoet and Hommel (1999) claimed that if the contents of two tasks, which have to be processed in parallel, overlap in at least one of their features, the performance in the second task critically depends on the temporal relationship between the processing in both tasks. If the overlapping feature code is just activated by the processing in the first task, then processing (of that feature) in the second task should be facilitated. If, however, the overlapping feature code is already bound by the processing in the first task, then processing (of that feature) in the second task should be hampered.

Originally, the two-stage model was applied to account for specific response–response interference effects (cf., Stoet, 1998; Stoet & Hommel, 1999). However, this model can also be applied to account for the blindness effect, a case of specific response–stimulus interference. The explanation is, for example, that when the LEFT feature code is already bound into the plan for a left response, this feature code is not available for the encoding and representation of a left stimulus (cf., Hommel et al., in press; Müsseler, 1999; Stoet & Hommel, 1999). Correspondingly, the blindness effect should emerge as soon as the preparation of the response has begun and should continue until this response is finally executed.

A very similar explanation can account for the specific tone–arrow interference, as it was observed in Experiment 3. Because there is no direct feature overlap between a low-pitched tone and a left response, or between a high-pitched tone and a right response, it has to be assumed that the feature codes of LOW and LEFT, as well as the feature codes of HIGH and RIGHT, are more strongly *associated* than the feature codes of LOW and RIGHT, or the feature codes of HIGH and LEFT. This assumption is supported by observations of corresponding spatial stereotypes associated with the pitch of tones (Mudd, 1963), and by observations of orthogonal stimulus–response compatibility effects between visual stimuli that varied in their vertical positions (up vs down) and left or right keypresses (e.g., Lippa, 1996a, b; Weeks & Proctor, 1990). If, for example, a low-pitched tone is presented, the LOW code and the associated LEFT code are both activated and—at least sometimes—are bound together automatically. As a consequence, the encoding and representation of a left stimulus, presented after the low-pitched tone, is impaired because the LEFT feature code is already bound into a representation of the tone. This explanation implies that not only the feature codes of physical properties of a stimulus are bound into its representation (an event file), but also the feature codes of *semantic* properties of that particular stimulus.

Now, let us turn to the interaction between the specific tone–arrow interference and the specific response–arrow interference, as observed in Experiments 1 and 2. In these experiments, the participants performed a left or right response to the low-pitched or the high-pitched tone, while a visual stimulus had to be identified. In such a situation, one can assume that the low-pitched or the high-pitched tone is processed on two different routes, one route being automatic and (mainly) instruction-independent, and the other route being controlled and instruction-dependent (cf., De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Kornblum, Hasbroucq, & Osman, 1990).

The consequences for the mapping "low tone–left response vs high tone–right response" are the following. When, for example, a low tone is presented, the feature code LOW activates the feature code for LEFT automatically, because LOW and LEFT are associated (see earlier), but simultaneously the code LEFT is activated on a second, controlled route, because the instruction

demands for a left response. Thus, in this case, the activation via two (parallel) routes converges on the same (LEFT) code, which results in a fast and strong binding of this code into the representation of the response, which means that the encoding of the response-compatible (left) stimulus is impaired, whereas the encoding of the response-incompatible (right) stimulus is not affected. As a result, a strong blindness effect can be observed.

A different situation emerges for the mapping "low tone–right response vs high tone–left response". When, for example, a low tone is presented, the feature code LOW again activates the associated feature code for LEFT automatically, but now—according to the instruction—the code RIGHT is activated on the second, controlled route. The result of this divergent activation of both the LEFT and the RIGHT code is that the LEFT code is—at least sometimes—integrated (bound) into a representation of the tone and that the RIGHT code is always integrated (bound) into a representation of the response. The consequence is that this tone–response mapping leads not only to an impairment of encoding the response-compatible (right) stimulus but also to an impairment of encoding the response-incompatible—but tone-associated—(left) stimulus. As a result, the blindness effect is diminished.

Finally, the two-stage model is also able to account for the effects of unspecific response–stimulus interference (e.g., Experiment 5; Jolicoeur, 1999a). The explanation would be that the process of binding feature codes in one task unspecifically interferes with the concurrent binding of different feature codes in a second task. That is, the preparation of a left response, for example, would also interfere with the encoding of a right stimulus, because in both tasks binding processes have to take place which unspecifically interfere with each other. This explanation is in accordance with the observation that not only the preparation of responses impaired the encoding of visual stimuli, but also the other way round, that is, the encoding of stimuli also impaired the preparation of responses. This was indicated by the increasing error rates in the response task with decreasing SOA, a finding also reported by Jolicoeur (1999a). The present explanation of unspecific response–stimulus interference is similar to that proposed by Jolicoeur (1999a), because both accounts claim that some process of consolidation of visual stimulus information is impaired by concurrent processing. However, the present account is more precise in localizing the source of that interference. This source is seen in the binding of feature codes in the course of preparing a response, whereas Jolicoeur (1999a, p. 608) localizes this source in "central processing requiring to perform Task$_1$, perhaps response selection".

However, there is one feature of the present data, which is—at first glance— at odds with the predictions of the two-stage model. The two-stage model predicts that during the first stage of processing, that is the activation of feature codes, the processing in a concurrent task should benefit, if there is feature overlap between the contents of both tasks. Accordingly, the observed

impairment in the identification of response-compatible stimuli at intermediate SOAs should have been preceded by an early facilitation in the identification of response-compatible stimuli at short SOAs. This, however, was never observed, even not in Experiment 5, in which early tone–arrow interference should not have played a role.

There is one possible explanation for this failure to find early facilitation in the identification of response-compatible stimuli, as predicted by the two-stage model. This explanation localizes the source of this failure in the fact that only auditory stimuli were used as response cues in the response task. It is well known, however, that auditory stimuli are processed significantly faster than visual stimuli (cf., Welch & Warren, 1986, for an overview on this topic). This means that the actual tone–arrow SOAs in the present experiments rather underestimate the lead in the processing of tones compared to the processing of visual stimuli. As a consequence, even for an SOA of 50 ms between tones and visual stimuli, binding could already have begun in the response task when the processing of the visual stimulus is starting. One implication of this post hoc explanation is that early facilitation in the identification of response-compatible stimuli should be observed in a situation, in which the processing of the response cues is slowed down, for example by using visual response cues. In a recent series of experiments, we obtained evidence for this hypothesis to be correct (Müsseler & Wühr, in press).

The present findings and the relationship between perception and action

The findings of the present study suggest not only that perception and action might (partially) operate on common cognitive representations but also that some similarities might exist between perceptual encoding and response preparation. It was not only found that the preparation of a (manual) response can affect the visual encoding of a response-compatible stimulus in a specific way, but also that the processing of an auditory stimulus can affect the visual encoding of a tone-associated visual stimulus in a similar way. In addition, it was observed that the processing of a tone and the preparation of a response interacted in their specific influence on the encoding of a visual stimulus. That is, the impairment in encoding a tone-associated visual stimulus and the impairment in encoding a response-compatible stimulus could either amplify or nullify each other, depending on the tone–response mapping in the response task that had to be performed simultaneously with the visual encoding task.

In particular, the interaction between the specific tone–arrow interference effect and the specific response–arrow interference effect supports the notion of a cognitive domain in which the features of stimuli and the features of responses are represented in a supramodal format (cf., MacKay, 1987; Prinz, 1990). Moreover, the similarity between the ways in which the processing of a

tone can affect the encoding of a tone-associated visual stimulus and in which the preparation of a response can affect the encoding of a response-compatible visual stimulus suggests that similar processes might be involved in perception and in response preparation. In particular, it was assumed that the processes of activating and binding cognitive representations (feature codes) were involved in stimulus encoding and in response preparation (cf., Hommel et al., in press; Stoet & Hommel, 1999). The binding of feature codes associated with a tone and the binding of a feature codes associated with a response both lead to similar impairments in encoding a visual stimulus that possesses a feature, whose code is already bound. Thus, perception and action might have more in common than has often been assumed.

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