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Localizing Modality Compatibility Effects: Evidence From Dual-Task Interference

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Performance is typically superior with modality-compatible stimulus–response sets (e.g., responding vocally to auditory stimuli and manually to visual stimuli) than with modality-incompatible sets (e.g., responding vocally to visual stimuli and manually to auditory stimuli). Here we studied the information-processing stage at which these modality compatibility effects arise. In three experiments using a dual-task setup, we demonstrated that these compatibility effects arose (at least partly) prior to a capacity-limited central stage that is commonly believed to be the origin of dual-task costs. We suggest that demands to employ a specific effector system bias perceptual processing toward effector-compatible stimulus modalities.

Public Significance Statement

Depending on the stimulus modality, some responses are easier to administer than others; for example, responding vocally to auditory stimuli (modality compatible) is faster and less error prone than responding manually (modality incompatible). Here we identify cognitive processes that are in charge of these modality compatibility effects.

Keywords: action control, modality, psychological refractory period

The speed and accuracy of responding to stimuli depend on the mapping of stimuli and responses. Well-known examples are so-called ideomotor-compatible stimulus–response (S-R) mappings. Ideomotor-compatible S-R mappings exist when stimuli match the perceptual effects of stimulus-assigned responses. For example, it is easier to say "A" when hearing "A," and to write "A" when seeing a written "A," than to say "A" when seeing a written "A" and to write "A" when hearing "A" (Greenwald, 1970). Ideomotor-compatibility effects have been explained by assuming that motor patterns are represented by, and generated through, codes of the motor pattern's perceptual effects (Greenwald, 1970; Kunde, 2001; Lien & Proctor, 2002; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014). Therefore, perceiving a certain perceptual effect activates the motor pattern that typically brings this effect about (Kunde, Schmidts, Wirth, & Herbort, 2017). For example, hearing "A" closely resembles, and thus activates, the vocal action that produces the auditory consequence "A" (i.e., the own speech).

Ideomotor compatibility is akin to, but must be distinguished from, modality compatibility. At the empirical level, modality compatibility denotes performance changes as a function of S-R sets. At the theoretical level, modality compatibility refers to the degree of similarity of the perceptual modality of the most salient response effects (e.g., auditory effects for vocal responses such as speaking or singing; visual effects for manual responses such as seeing the moving hands) and the modality of the task stimuli (Stephan & Koch, 2011). For example, the S-R sets are said to be modality compatible when auditory stimuli require vocal responses and when visual stimuli require manual responses, whereas the reversed mapping is (in relative terms[1]) said to be

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[1] Modality compatibility should not be regarded in absolute terms but, rather, as the relative association strength between stimulus modality and effect modality among different S-R mappings. That is, obviously, manual actions can produce visual changes (e.g., pressing the light switch) but also auditory changes (e.g., hitting a drum). Also, vocal actions can produce auditory changes (e.g., speaking) but also visual changes (e.g., "Alexa, turn on the light"). Compatibility therefore refers to the relative degree of similarity between the modality of an action's most salient sensory consequence and the modality of the task stimuli. Speaking almost always produces auditory changes, and moving the hands almost always produces perceivable visual changes. Therefore, these mappings have stronger associations than auditory–manual and visual–vocal, and they are considered *more* compatible, in relative terms, when pitted against each other. It should also be noted that the visual–manual association is probably weaker than the auditory–vocal association (Hoffmann, Pieczykolan, Koch, & Huestegge, 2019).

modality incompatible (Stephan & Koch, 2010). Whereas every ideomotor-compatible mapping is also modality compatible, not every modality-compatible mapping is also ideomotor compatible. For example, responding vocally with “B” to the auditory stimulus “A” is a modality-compatible mapping (i.e., it is a mapping of an auditory stimulus to a vocal response), whereas it is not ideomotor compatible (i.e., the stimulus does not closely resemble the perceptual consequences of the response).

The benefits of modality compatibility primarily occur in situations in which participants have to transiently switch between effector systems, thus when two response modalities are required either concurrently or in quick succession, whereas they are smaller and not always obtained with task setups that only require one response modality (Fintor, Stephan, & Koch, 2018; Lukas, Philipp, & Koch, 2010). Specifically, the costs of mixing response modalities concurrently, or switching between them, are markedly lower with modality-compatible than modality-incompatible mappings. Interestingly, modality compatibility benefits occur even when the S-R mapping at the level of individual stimuli and responses is not ideomotor compatible (Halvorson, Ebner, & Hazeltine, 2013).

Different explanations of modality compatibility effects appear tenable. One explanation might be termed “effector-set priming.” This account holds that modality compatibility is a relaxed version of ideomotor compatibility. Obviously, hearing the letter “A” does not closely resemble the auditory effects of saying “B” (thus, not ideomotor compatible). Still, an auditory stimulus resembles the auditory consequences of a vocal response more than a visual stimulus (see Stephan & Koch, 2011). Consequently, an auditory stimulus conceivably activates the vocal effector system more than other effector systems (e.g., manual), although not a specific motor pattern within that effector system. Such effector-set priming might be particularly helpful (or helpful at all) when there is another potentially relevant, and thus highly activated, effector system, thus in situations that call for multiple response modalities. Conversely, performance might suffer if stimuli tend to prime the already strongly preactivated, but currently not requested effector system. This would be the case when two modality-incompatible mappings are combined (e.g., responding manually to auditory stimuli and responding vocally to visual stimuli).

A related explanation is that when two modality-compatible mappings are required within a setting, they can be separated more easily and produce less “crosstalk” (Halvorson & Hazeltine, 2015; Schacherer & Hazeltine, 2020). This explanation is akin to the hypothesis of effector-set priming, if one assumes that crosstalk emerges from stimulus-induced priming of an effector system that is currently not required but soon to be used.

To better pinpoint the precise explanation for these modality compatibility benefits, in the current line of research, we functionally localized the modality compatibility effect within the information-processing stream. We did so by using a dual-task approach and by employing a tried and tested set of methods to scrutinize the particular stage of processing at which modality incompatibility costs (performance with modality-incompatible as compared to modality-compatible S-R mappings) occur. Typically, this framework assumes three stages of information processing, a precentral stage, followed by a capacity-limited central stage and a postcentral stage (see Figure 1, top). Specifically, participants perform two independent tasks (Task 1 and Task 2) in close temporal succession, and the imperative stimuli of both tasks appear with a varying stimulus-onset asynchrony (SOA). Usually, these setups produce dual-task costs, with longer Task 2 response times (RTs) the more the tasks overlap in time. The common explanation for dual-task costs is that the central stage of information processing cannot run at all, or not with the same efficiency, for two tasks at the same time (labeled a “bottleneck”; Pashler, 1994; Tombu & Jolicoeur, 2003; see Koch, Poljac, Müller, & Kiesel, 2018, for a recent review).

A possible explanation of reduced dual-task costs with modality-compatible mappings would thus be that this limited stage is shortened. In the present study we tested, and eventually challenged, this proposal. Specifically, Experiment 1 used effect-propagation logic (see Figure 1) to reveal whether modality compatibility effects emerged from a stage later than the central capacity-limited stage. Experiments 2 and 3 then employed the locus of slack logic (see Figure 4) to reveal whether modality compatibility effects emerged from the precentral or central stage.

Experiment 1: Effect Propagation

Experiment 1 used the effect-propagation method (Schweickert, 1978; Wirth, Janczyk, & Kunde, 2018), in which the manipulation of interest (modality compatibility) is implemented in Task 1 while another task, Task 2, has to be carried out concurrently (see Figure 1).

In the baseline condition (modality compatible), participants were first confronted with the stimulus of Task 1 (S1), which had to be answered manually or vocally (R1). After a short or long delay (SOA), the stimulus for Task 2 (S2) appeared and had to be answered via foot (R2). The model assumes that whereas the precentral and postcentral stages can run in parallel, the central stage presents a cognitive bottleneck, so the central stages of both tasks cannot overlap in time. Hence, with the short SOA, the central stage of Task 2 has to wait until the central stage of Task 1 is completed, creating idle time in Task 2 (cognitive slack). With this setup, we would expect no influence of SOA on Task 1 RTs (unless we assume capacity sharing, Tombu & Jolicoeur, 2003). Task 2 RTs should be faster with the long SOA compared to the short SOA.

When introducing the modality compatibility manipulation in Task 1, the setup differentiated between two models. Model A (see Figure 1) assumes modality incompatibility costs to arise in and thereby lengthen the precentral or central stage (the illustration only depicts the central option, but the predictions for the precentral option are the same). If that were the case, then we should find (a) longer Task 1 RTs for modality-incompatible compared to modality-compatible trials (see Vertical Marker 1 in Figure 1) because the incompatible trials included the modality incompatibility response costs (orange) and (b) longer Task 2 RTs after modality-incompatible compared to modality-compatible trials (effect propagation, at least for the short SOA; see Vertical Markers 2 and 3 in Figure 1) because completing the central stage in Task 1 later than in modality-compatible trials increased the cognitive slack in Task 2. Model B assumes modality incompatibility costs to be located in the postcentral stage. With this model, we would also assume (a) longer Task 1 RTs for modality-incompatible compared to modality-compatible trials (see Vertical Marker 1 in Figure 1) but (b) no influence of modality compati-

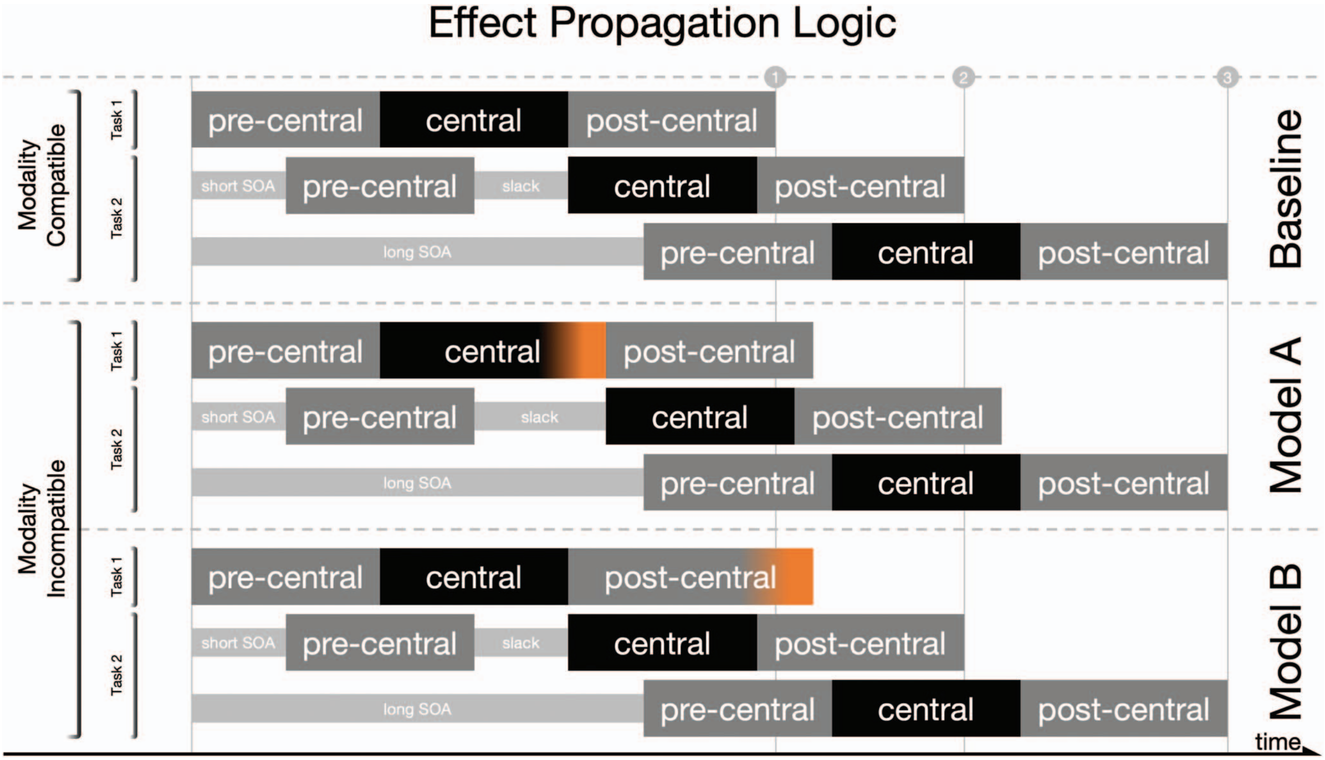

Figure 1. Effect-propagation logic. Modality-compatible trials served as a baseline against which modality-incompatible trials were tested. With the modality compatibility manipulation implemented in Task 1, we differentiated between two models: Model A, which assumes modality incompatibility costs (in orange) to arise in the precentral or central stage (only the latter is depicted here, but predictions for both options are the same), and Model B, which assumes modality incompatibility costs to be located in the postcentral stage. Vertical Markers 1, 2, and 3 indicate performance in the modality-compatible condition and serve to aid visual comparison between the models. See the online article for the color version of this figure.

bility in Task 2 at either SOA (no effect propagation; see Vertical Markers 2 and 3 in Figure 1).

Modality compatibility was varied blockwise in Task 1 by manipulating the mapping instructions prior to the blocks. That is, every block contained both visual and auditory stimuli, which had to be answered via both manual and vocal responses; only the mapping between those stimuli and responses differed between blocks. In modality-compatible blocks, visual stimuli called for manual responses, and auditory stimuli called for vocal responses. In modality-incompatible blocks, visual stimuli called for vocal responses, and auditory stimuli called for manual responses. So with equal stimulus and response events in all blocks, comparing performance in modality-compatible against modality-incompatible blocks allowed us to assess the influence of the S-R mappings free from any stimulus or response contributions.

Visual stimuli were left- and right-pointing arrows; auditory stimuli were sinus tones presented to either the left or right ear. Manual responses were left and right keypresses; vocal responses consisted of saying the words “left” or “right” (see Greenwald & Shulman, 1973). Thus, visual–manual and auditory–vocal pairings were modality compatible but not ideomotor compatible because the visual stimuli did not closely resemble the visual consequences of the manual keypresses, and the auditory stimuli did not closely resemble the auditory consequences of the vocal responses. Task 2 used another set of stimulus and response modalities, namely, tactile stimulation of the left or right thigh, which required a corresponding left or right pedal response.

We expected to find faster responding with modality-compatible than with modality-incompatible S-R mappings in Task 1. Moreover, we expected a psychological refractory period (PRP) effect, that is, slower responding in Task 2 with a short rather than with a long SOA. Of most interest was whether the modality compatibility effect we expected in Task 1 would propagate to Task 2 with a short SOA. If it did so, this would suggest that the modality compatibility effect emerged from processing at, or before, the central stage (see Figure 1, Model A).

Method

Participants. Forty-eight participants were recruited (mean age = 27.5 years, standard deviation [*SD*] = 8.2, 13 male, 5 left-handed) and received monetary compensation. All participants reported normal or corrected-to-normal vision and were naïve concerning the hypotheses of the experiment. The sample size was chosen to provide a power of >.95 at an alpha of .05 for medium effects ($d_z = 0.5$) for the simple comparison of the modality-compatible versus the modality-incompatible mapping. We computed the power analysis based on a medium effect size because this is the smallest that we would find theoretically relevant. All participants provided written informed consent prior to the experiment and were debriefed after the session.

Apparatus and stimuli.

Mixed-Modality task. Visual stimuli were arrows that were presented centrally on the screen and pointed to either the left or the right side. They were presented in white font against a black background on a 17-in. screen. Auditory stimuli were sinus tones of 196 Hz (G3) that were played via headsets to either the left or the right ear for 100 ms. Manual responses were given via two marked buttons on a standard QWERTZ keyboard (*F* for left and *J* for right) with the index fingers of participants' left and right hands. For vocal responses, participants had to speak the German equivalents of left (*links*) and right (*rechts*) into the microphone of their headset, which was then analyzed via specialized voice-recognition software.[2]

Tactile-Pedal task. Stimuli were tactile vibrations that were administered via small vibrating motors (akin to cell-phone vibrations) that were strapped to the participants' left and right upper legs. Responses to these vibrations were given via left and right foot pedals that were fixed to the floor.

Procedure. Every trial started with a blank black screen. After 500 ms, S1 appeared, either as an arrow on the screen or as a tone played via headphones. Depending on the modality compatibility, participants had to respond manually or verbally but always in a spatially compatible manner (answering a left arrow/tone with a left keypress or by saying "left" and answering a right arrow/tone with a right keypress or by saying "right"). Responses could be given within 2,000 ms from S1 onset.

After an SOA of either 100 or 1,000 ms (varied randomly from trial to trial), S2 could be felt as a vibration on either the left or the right leg, and it had to be answered within 2,000 ms with a spatially compatible pedal response. The vibration was constantly on, and it only stopped when either R2 was given or the time limit of 2,000 ms exceeded.

Responses for both tasks could be given in any order. If participants gave a wrong response or if they failed to give any response within the response deadline, they were given feedback. For commission errors, they were shown the message "Mixed-Modality Task: Error!" or "Tactile-Pedal Task: Error!" in red font. For omission errors, they were shown the message "Mixed-Modality Task: Too Slow!" or "Tactile-Pedal Task: Too Slow!" in red font. The feedback stayed on the screen for 1,000 ms. To provide feedback not only in the visual modality, this feedback was further accompanied by a buzzer sound.

Within a block, both visual and auditory stimuli were intermixed randomly, and both manual and vocal responses were required. More specifically, in a modality-compatible block, participants had to respond manually to visual stimuli and respond vocally to auditory stimuli by indicating the direction of the stimulus. In a modality-incompatible block, participants had to respond vocally to visual stimuli and manually to auditory stimuli. Modality compatibility switched after half of the experiment, and block order (first half modality compatible vs. first half modality incompatible) was counterbalanced between participants.

Participants completed 10 blocks, 5 blocks with a modality-compatible mapping in Task 1 and 5 blocks with an incompatible mapping, of 80 trials each, with each combination of S1 (visual left; visual right; auditory left; auditory right), S2 (vibration left; vibration right), and SOA (100 ms; 1,000 ms) presented five times.

Results

RT analysis. The raw data are publicly available at http://osf.io/x2wre. For RT analyses, we excluded trials with errors and omissions (Task 1: 14.7%, Task 2: 4.7%). The remaining trials were screened for outliers, and we removed trials in which RTs for any task deviated more than 2.5 *SD*s from the corresponding cell mean, computed separately for each participant and experimental condition (2.8%). Overall, 20.2% of the trials were removed.

The remaining data were aggregated as the mean RT for each participant and for each combination of modality compatibility (compatible vs. incompatible) and SOA (100 ms vs. 1,000 ms) and for each task. The data were then analyzed via 2 × 2 analyses of variance (ANOVAs) with modality compatibility and SOA as within-subjects factors, separately for each task (see Figure 2). Planned post hoc analyses tested for the modality compatibility effect at each SOA level. For all post hoc tests, we computed $d_z = \frac{t}{\sqrt{n}}$.

Mixed-Modality Task 1. Responses were faster in modality-compatible trials (786 ms) than in modality-incompatible trials (843 ms), $F(1, 47) = 33.12$, $p < .001$, $\eta_p^2 = .41$. Further, we found faster responses for the long SOA (797 ms) than for the short SOA (832 ms), $F(1, 47) = 87.52$, $p < .001$, $\eta_p^2 = .65$. There was no interaction between both factors ($F < 1$), indicating that modality compatibility effects were present with both short SOA, $\Delta = 59$ ms, $t(47) = 6.00$, $p < .001$, $d_z = 0.87$, and long SOA, $\Delta = 55$ms, $t(47) = 5.04$, $p < .001$, $d_z = 0.73$.

Tactile-Pedal Task 2. We found faster responses after modality-compatible trials (781 ms) than after modality-incompatible trials (813 ms), $F(1, 47) = 14.26$, $p < .001$, $\eta_p^2 = .23$, indicating propagation of the modality compatibility effect. Responses were overall faster after the long SOA (565 ms) than after the short SOA (1,030 ms), $F(1, 47) = 823.43$, $p < .001$, $\eta_p^2 = .95$. An interaction between both factors, $F(1, 47) = 16.10$, $p < .001$, $\eta_p^2 = .26$, indicated that the forward-propagated modality compatibility effect was significant only for the short SOA, $\Delta = 56$ ms, $t(47) = 4.38$, $p < .001$, $d_z = 0.63$, but not for the long SOA, $\Delta = 8$ms, $t(47) = 1.09$, $p = .28$, $d_z = 0.16$.

Correlation analysis. Finally, to test how the modality incompatibility costs were related in both tasks, we computed mean modality incompatibility costs for each participant in both tasks (as mean $\mathrm{RT}_{\mathrm{incompatible}}$ minus mean $\mathrm{RT}_{\mathrm{compatible}}$; for Task 2, we only used the data of the short SOA condition because the effect did not propagate to Task 2 in trials with the long SOA). We then correlated the modality incompatibility costs of both tasks and found a strong positive correlation, $r(46) = .681$, $p < .001$, indicating that participants' modality incompatibility costs in Task 1 were directly and linearly linked to the slowdown in Task 2 after modality-incompatible trials (see Figure 3), highlighting the direct effect propagation of the Task 1 manipulation onto Task 2.

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[2] Before the experiment started, the software was trained and adjusted to accurately discriminate between left and right vocal responses for each individual participant. The experiment only started if participants achieved at least 95% in terms of accurately categorized responses.

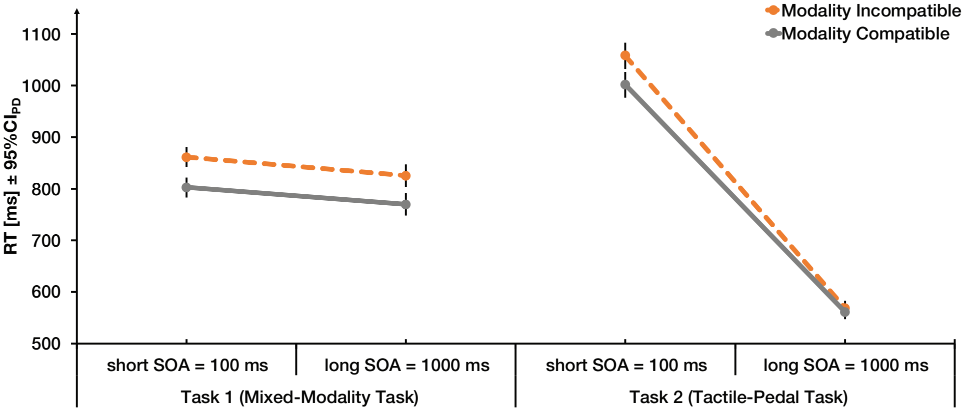

Figure 2. Results of Experiment 1. Response times (RTs) are reported separately for Tasks 1 and 2 and for the short and long stimulus-onset asynchrony (SOA). The lower, dark gray lines represent the modality-compatible trials; the upper, dashed, orange lines represent the modality-incompatible trials. Error bars denote the 95% confidence interval of paired differences, computed separately for each comparison of modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

Error analysis. For the error analysis, we have to differentiate between the different types of errors that were possible within this design. In the Mixed-Modality Task 1, there were *modality errors*, in which participants responded in the incorrect response modality (but in the correct direction). Second, there were *directional errors*, in which participants responded in the correct response modality but pressed the wrong key or indicated the wrong direction with their voices. Also, there are cases in which participants failed in both modality and direction, which we call *combination errors*. Then, with the voice-recognition software, there was a slim chance that neither "left" nor "right" was understood clearly, which we refer to as a *technical error*. And finally, there was the possibility of *response omissions*. In the Tactile-Pedal Task 2, participants could only commit directional errors (by pressing the wrong foot pedal) or response omissions.

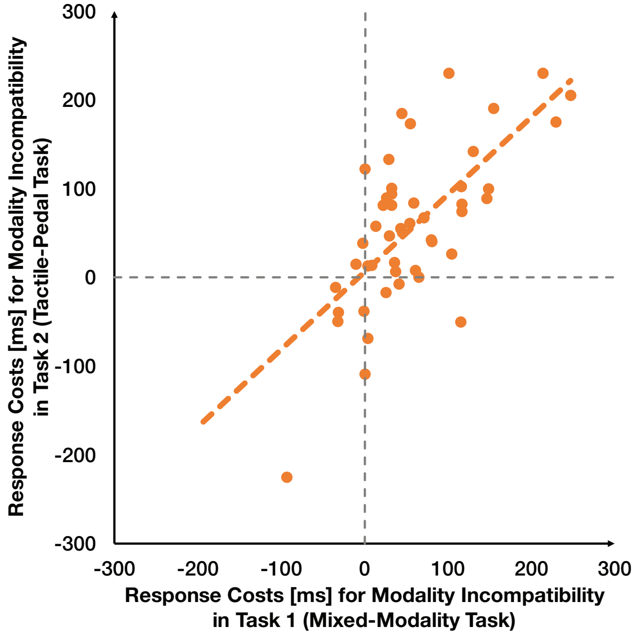

Figure 3. Correlation results of Experiment 1. The *x*-axis shows the net modality incompatibility costs in Task 1 (Mixed-Modality Task); the *y*-axis shows the net propagated modality incompatibility costs in Task 2 (Tactile-Pedal Task). Each data point represents one participant. See the online article for the color version of this figure.

The error data were aggregated as the percentage of errors for each participant and for each combination of modality compatibility (compatible vs. incompatible) and SOA (100 ms vs. 1,000 ms) and for each type of error and were then analyzed, akin to the RT data, via 2 × 2 ANOVAs.

Modality errors in Task 1 were more prominent with the short SOA (4.9%) than with the long SOA (4.4%), $F(1, 47) = 5.06$, $p = .029$, $\eta_p^2 = .10$, but there were no other contributing factors (Fs < 1.24, ps $> .27$). Similarly, directional errors in Task 1 were more prominent with the short SOA (5.6%) than with the long SOA (5.0%), $F(1, 47) = 5.42$, $p = .024$, $\eta_p^2 = .10$, but there were no other contributing factors (Fs < 1). Also, combination errors in Task 1 were more prominent with the short SOA (0.5%) than with the long SOA (0.3%), $F(1, 47) = 7.30$, $p = .010$, $\eta_p^2 = .13$, but there were no other contributing factors (Fs < 2.19, ps $> .15$). Technical errors in Task 1 happened similarly often in all conditions (1.4%; Fs < 1.68, ps $> .20$). Omissions in Task 1 were again more likely with the short SOA (4.1%) than with the long SOA (1.8%), $F(1, 47) = 28.81$, $p < .001$, $\eta_p^2 = .38$, and were also more likely in modality-incompatible trials (3.7%) than in modality-compatible trials (2.3%), $F(1, 47) = 8.72$, $p = .005$, $\eta_p^2 = .16$, but there was no combined influence of both factors, $F(1, 47) = 3.88$, $p = .06$, $\eta_p^2 = .08$.

Directional errors in Task 2 happened similarly often in all conditions (2.9%; Fs < 2.18, ps $> .15$). Omission errors in Task 2 were more prominent with the short SOA (2.5%) than with the long SOA (1.0%), $F(1, 47) = 49.57$, $p < .001$, $\eta_p^2 = .51$, but there were no other contributing factors (Fs < 1.37, ps $> .25$).

Overall, the error results suggest that there was no systematic speed–accuracy trade-off.

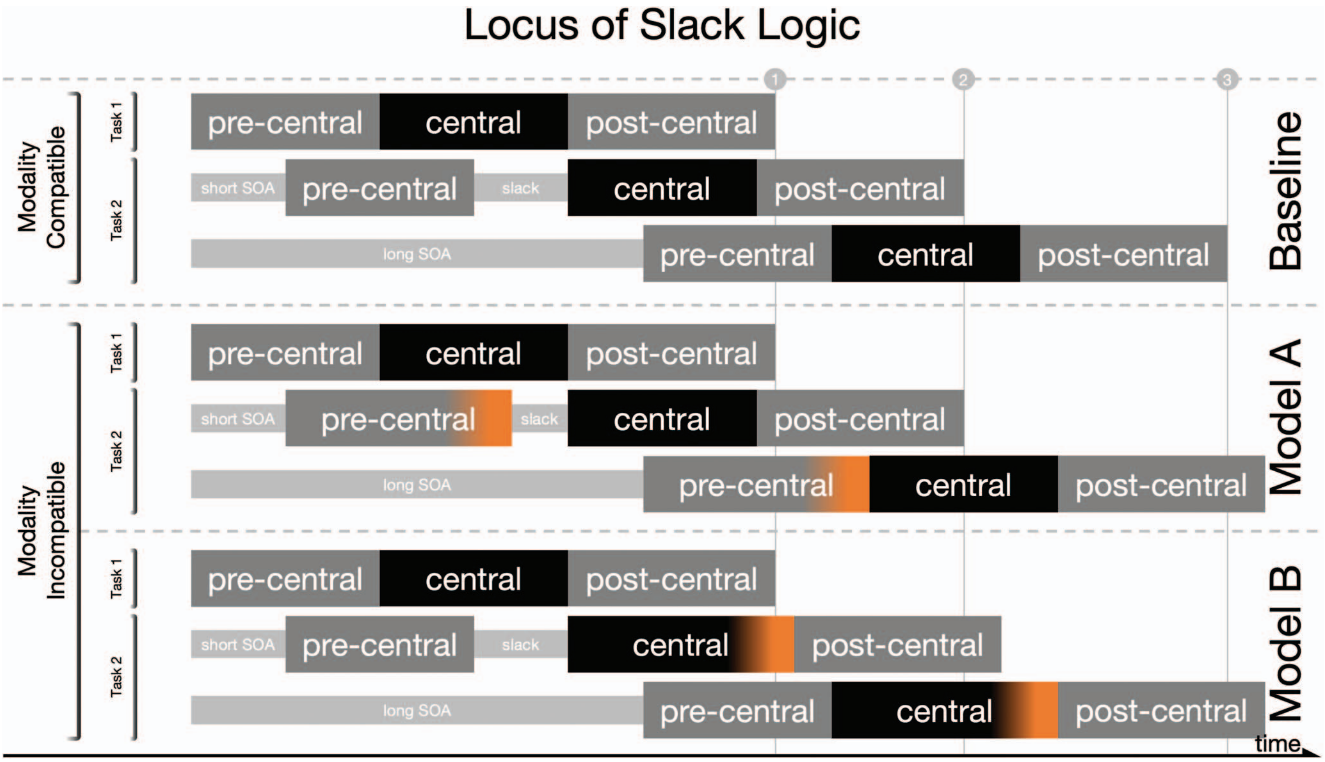

Figure 4. Locus of slack logic. Modality-compatible trials served as a baseline against which modality-incompatible trials were tested. With the modality compatibility manipulation implemented in Task 2, we differentiated between two models: Model A, which assumes modality incompatibility costs (in orange) to arise in the precentral stage, and Model B, which assumes modality incompatibility costs to be located in the central or postcentral stage (only the former is depicted here, but predictions for both options are the same). Vertical Markers 1, 2, and 3 indicate performance in the modality-compatible condition and serve to aid visual comparison between the models. See the online article for the color version of this figure.

Discussion

Experiment 1 revealed a robust modality compatibility effect in Task 1. Moreover, it revealed a sizable PRP effect for Task 2, suggesting the involvement of capacity limitations in both tasks. Interestingly, SOA also had an impact on Task 1, which was incompatible with the predictions of the strictly serial model proposed in Figure 1. This effect can be explained by assuming capacity sharing, such that limited cognitive resources are shared between central stages (Tombu & Jolicoeur, 2003). Instead of cognitive slack, this model would assume that both central stages run in parallel, but neither does so at full capacity, lengthening the central stages of both tasks. If we assume the central stage not to run at full capacity with the short SOA, this can explain why even Task 1 RTs were slightly slower in this condition. Crucially, the predictions that serial processing and capacity sharing make for the effect-propagation logic (and the locus of slack logic; see Experiments 2 and 3) are identical. Also, with a closer look at the absolute RTs, we see that R1 was usually given within 1,000 ms, that is, usually before S2 onset, in the case of the long SOA. This means that although the two tasks always overlapped in time with the short SOA, they were almost always temporally separate with the long SOA. Therefore, the factor SOA also implies with versus without temporal task overlap and may consequently reflect other influences, such as simultaneous versus sequential processing (which, again, speak against a strictly serial model). Still, we opted for the serial model for illustration purposes (Figures 1 and 4) because this can be grasped more easily.

Most importantly, the modality compatibility effect in Task 1 fully propagated to Task 2 at a short SOA. Notably, the size of the effect in Task 1 (57 ms across the two SOA conditions) was numerically almost identical to the carryover effect in Task 2 for the short SOA (56 ms). Plus, this was not only true for the overall group but also for each individual participant; the size of the individual modality incompatibility costs in Task 1 correlated strongly with the forward-propagated size of the modality incompatibility costs in Task 2. Altogether, these results show that the modality compatibility effect had its origin before or at the central stage of information processing but not at a postcentral stage.

Experiment 2: Locus of Slack

Having ruled out a postcentral locus of the modality compatibility effect in Experiment 1, we aimed to scrutinize the precise locus, precentral or central, in Experiment 2.

With the locus of slack logic (Foerster, Wirth, Berghoefer, Kunde, & Pfister, 2019; Schweickert, 1978), we again differentiated between two models by implementing the modality compatibility manipulation in Task 2. Model A (see Figure 4) assumes modality incompatibility costs to arise in and thereby lengthen the precentral stage. If that were the case, then we should find (a) no effect of modality incompatibility in Task 1 (see Vertical Marker 1 in Figure 4) and (b) longer Task 2 RTs for modality-incompatible compared to modality-compatible trials for the long SOA, but modality incompatibility costs should be reduced or even absent with the short SOA (see Vertical Markers 2 and 3 in Figure 4) because these costs can (partly) be compensated for by stretching into the cognitive slack. Model B assumes modality incompatibility costs to be located in the central or postcentral stage (the illustration only depicts the central option, but the predictions for the postcentral option are the same). With this model, we would again assume (a) no effect of modality incompatibility in Task 1 (see Vertical Marker 1 in Figure 4) but (b) modality incompatibility costs of equal size for both the short and long SOA (see Vertical Markers 2 and 3 in Figure 4).

Method

A new set of 48 participants was recruited (mean age = 26.4 years, *SD* = 7.4, 14 male, 6 left-handed) and received monetary compensation.[3] They fulfilled the same criteria as in Experiment 1.

Stimuli, apparatus, and the overall trial structure were identical to Experiment 1; only the order of the tasks was switched, with the Tactile-Pedal Task now serving as Task 1 and the Mixed-Modality Task serving as Task 2. That is, after a blank screen of 500 ms, participants now first felt a vibration on the leg (S1) that had to be answered via a foot pedal (R1). After an SOA of either 100 or 1,000 ms, S2 appeared, either as a visual arrow on the screen pointing leftward or rightward or as a tone played to the left or right ear, which had to be answered either manually or vocally (R2). Counterbalancing, response deadlines, and feedback stayed the same.

Again, participants completed 10 blocks, 5 blocks with a modality-compatible mapping in Task 2 and 5 blocks with an incompatible mapping, of 80 trials each, with each combination of S1 (vibration left; vibration right), S2 (visual left; visual right; auditory left; auditory right), and SOA (100 ms; 1,000 ms) presented five times.

Results

RT analysis. The raw data are publicly available at http://osf.io/x2wre. RT data were handled as in Experiment 1. We excluded trials with errors and omissions (Task 1: 4.6%, Task 2: 15.7%) and removed outliers (3.0%). Overall, 21.3% of the trials were removed. The remaining data were analyzed exactly as in Experiment 1 (see Figure 5).

Tactile-Pedal Task 1. Responses were faster with the long SOA (555 ms) than with the short SOA (664 ms), $F(1, 47) = 47.61$, $p < .001$, $\eta_p^2 = .53$. There was neither a main effect of modality compatibility nor interaction between both factors (Fs < 1).

Mixed-Modality Task 2. Responses were faster in modality-compatible trials (781 ms) than in modality-incompatible trials (813 ms), $F(1, 47) = 41.05$, $p < .001$, $\eta_p^2 = .47$. Again, we found faster responses after the long SOA (565 ms) than after the short SOA (1,030 ms), $F(1, 47) = 583.70$, $p < .001$, $\eta_p^2 = .93$. An interaction between both factors, $F(1, 47) = 4.91$, $p = .032$, $\eta_p^2 = .10$, indicated that modality compatibility effects were significantly smaller for the short SOA, $\Delta = 42$ ms, $t(47) = 5.03$, $p < .001$, $d_z = 0.73$, than for the long SOA, $\Delta = 63$ ms, $t(47) = 6.01$, $p < .001$, $d_z = 0.87$.

Error analysis. Error data analysis was conducted as in Experiment 1.

Directional errors in Task 1 were more prominent with the short SOA (4.8%) than with the long SOA (0.4%), $F(1, 47) = 98.23$, $p < .001$, $\eta_p^2 = .68$, but there were no other contributing factors (Fs < 1.98, ps $> .17$). Omission errors in Task 1 happened similarly often in all conditions (1.9%; Fs < 1.39, ps $> .24$).

Modality errors in Task 2 were more prominent with the long SOA (6.5%) than with the short SOA (5.1%), $F(1, 47) = 20.58$, $p < .001$, $\eta_p^2 = .30$, and also more likely in modality-incompatible trials (6.6%) than in modality-compatible trials (5.0%), $F(1, 47) = 4.05$, $p = .050$, $\eta_p^2 = .08$. A significant interaction, $F(1, 47) = 4.12$, $p = .048$, $\eta_p^2 = .08$, further indicated smaller effects of modality incompatibility with the short SOA ($\Delta = 1.0\%$) than with the long SOA ($\Delta = 2.3\%$). Directional errors in Task 2 happened similarly often in all conditions (5.3%; Fs < 3.42, ps $> .08$). Combination errors in Task 2 were more prominent with the short SOA (0.8%) than with the long SOA (0.5%), $F(1, 47) = 11.44$, $p = .001$, $\eta_p^2 = .20$, but there was no main effect of modality compatibility ($F < 1$). A significant interaction, $F(1, 47) = 5.48$, $p = .024$, $\eta_p^2 = .10$, further indicated larger effects of modality incompatibility with the long SOA ($\Delta = 0.2\%$) than with the short SOA ($\Delta = -0.2\%$). Technical errors in Task 2 happened similarly often in all conditions (1.2%; Fs < 2.93, ps $> .09$). Omissions in Task 2 were again more likely with the short SOA (4.4%) than with the long SOA (1.1%), $F(1, 47) = 67.65$, $p < .001$, $\eta_p^2 = .59$, but there were no other contributing factors (Fs < 1.12, ps $> .30$).

Again, the error results suggest that there was no systematic speed–accuracy trade-off.

Discussion

The results of Experiment 2 again revealed a modality compatibility effect, now in Task 2, which was of similar size as in Experiment 1. Again, there was also a sizable PRP effect. And again, we found an influence of SOA in Task 1, indicating capacity sharing. Most importantly, the effect of modality compatibility was significantly smaller at the short SOA than at the long SOA. This clearly suggests that the modality compatibility effect (at least partly) arises in the precentral stage. Still, we cannot completely exclude the central stage because this would require the modality compatibility effect to be completely eliminated with the short SOA.

Although significant, the interaction of modality compatibility and SOA in the Task 2 RTs was modest in size. Therefore, we aimed to replicate this underadditive interaction in Experiment 3 with a theoretically important modification.

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[3] With three participants, an unforeseen technical error occurred during data collection such that a fraction of the trials was not recorded, resulting in missing 2.8%, 2.0%, and 0.1% of their data. We still decided to keep the data of these three participants because the amount of missing data was negligible, especially when considering that a larger amount of data was discarded anyway as errors or outliers.

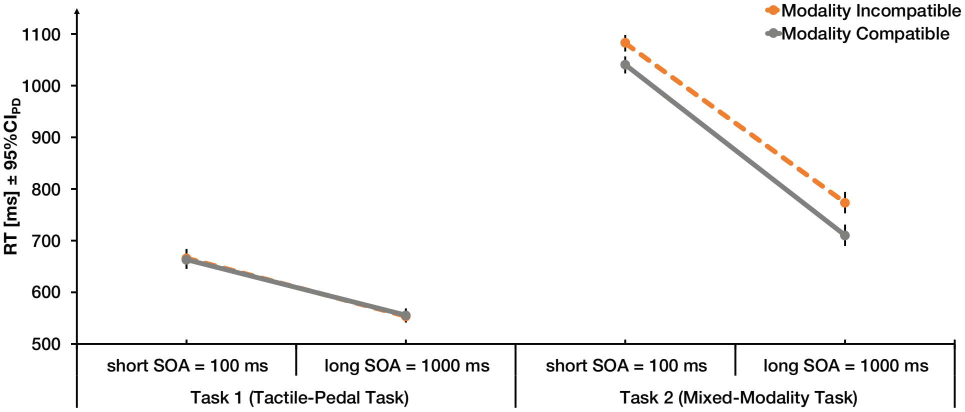

Figure 5. Results of Experiment 2. Response times (RTs) are reported separately for Tasks 1 and 2 and for the short and long stimulus-onset asynchrony (SOA). The lower, dark gray lines represent the modality-compatible trials; the upper, dashed, orange lines represent the modality-incompatible trials. Error bars denote the 95% confidence interval of paired differences, computed separately for each comparison of modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

Experiment 3: Locus of Slack, Trialwise

The results of Experiment 2 suggest that modality compatibility effects emerged, at least partly, prior to the central stage. We discuss possible candidates for cognitive processes taking place during the precentral stage in the General Discussion section. Yet, whatever these processes may be, we observed the crucial interaction of SOA and modality compatibility while modality compatibility was manipulated blockwise. Blockwise manipulations might invoke strategic adaptations, such as response preparation (Schubert, 1999), trade-offs such as slower responses due to a heightened response threshold, or overall lower motivation in more difficult blocks (e.g., Wirth, Pfister, Janczyk, & Kunde, 2015). In other words, even though the upcoming stimulus modality itself was not predictable, the S-R modality mapping for the upcoming Task 2 stimulus was perfectly predictable, and participants might have adjusted processing strategies accordingly. For example, in a modality-compatible block, they might have intentionally processed stimuli to a lesser extent as compared to a modality-incompatible block because they knew that the effector system activated by preliminary evidence of the stimulus was always the correct one. Such strategies are countermanded when the modality compatibility varies trialwise. Thus, we added another dimension to the stimuli in both modalities (visual and auditory) that would inform participants on how to respond: High tones and arrows in the upper half of the screen were to be answered vocally, whereas low tones and arrows in the lower half of the screen were to be answered manually. By randomly intermixing all S-R combinations within a block, it was unpredictable whether the next trial would be modality compatible or modality incompatible. Any strategic preparation for a modality (in)compatible trial was thus pointless.

Method

A new set of 48 participants was recruited (mean age = 23.8 years, *SD* = 2.9, 11 male, 6 left-handed)[4] and received monetary compensation. They fulfilled the same criteria as in Experiments 1 and 2.

The setup of Experiment 3 was similar to that of Experiment 2, except that instead of having blocks that consisted of only modality-compatible or modality-incompatible trials, both modality relations were now randomly intermixed within blocks. To do so, we had to announce the modality compatibility in each trial so that participants knew with which effector to respond. We did so by adding two higher sinus tones of 392 Hz (G4) that were played via headsets to either the left or the right ear for 100 ms to our set of auditory stimuli and by presenting the arrows either in the upper or lower half of the screen. Participants were instructed that if they were confronted with a high tone or if an arrow appeared in the upper half of the screen, they were to respond vocally, and if they heard a low tone or if an arrow appeared in the lower half of the screen, they were to respond manually.

Participants now completed five blocks of 160 trials each, with each combination of S1 (vibration left; vibration right), S2 (visual left; visual right; auditory left; auditory right), modality compatibility (compatible; incompatible), and SOA (100 ms; 1,000 ms) presented five times.

Results

RT analysis. The raw data are publicly available at http://osf.io/x2wre. RT data were handled as in the previous experiments. We excluded trials with errors and omissions (Task 1: 4.7%, Task 2: 20.1%) and removed outliers (2.6%). Overall, 25.4% of the trials were removed. The remaining data were analyzed exactly as in Experiment 1 (see Figure 6).

Tactile-Pedal Task 1. Responses were faster with the long SOA (593 ms) than with the short SOA (650 ms), *F*(1, 47) =

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[4] Again, with two participants, a technical error occurred during data collection such that some trials were not recorded, resulting in missing 4.9% and 2.9% of their data. Two other participants were removed from the sample because of high error rates (> 40%) and were replaced.

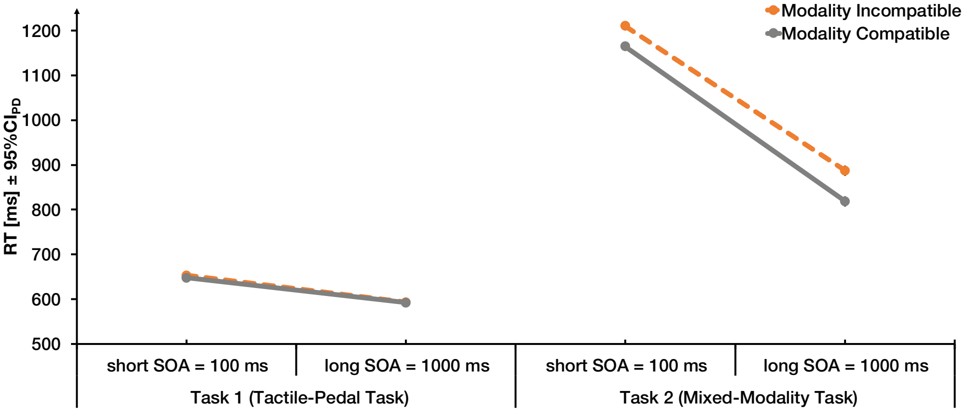

Figure 6. Results of Experiment 3. Response times (RTs) are reported separately for Tasks 1 and 2 and for the short and long stimulus-onset asynchrony (SOA). The lower, dark gray lines represent the modality-compatible trials; the upper, dashed, orange lines represent the modality-incompatible trials. Error bars denote the 95% confidence interval of paired differences, computed separately for each comparison of modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

47.11, $p < .001$, $\eta_p^2 = .50$. There was neither a main effect of modality compatibility nor interaction between both factors (*F*s < 2.14, *p*s > .15).

Mixed-Modality Task 2. Responses were faster in modality-compatible trials (992 ms) than in modality-incompatible trials (1,049 ms), $F(1, 47) = 146.49$, $p < .001$, $\eta_p^2 = .76$. Again, we found faster responses after the long SOA (853 ms) than after the short SOA (1,187 ms), $F(1, 47) = 429.61$, $p < .001$, $\eta_p^2 = .90$. An interaction between both factors, $F(1, 47) = 17.63$, $p < .001$, $\eta_p^2 = .27$, indicated that modality compatibility effects were significantly smaller for the short SOA, $\Delta = 45$ ms, $t(47) = 9.09$, $p < .001$, $d_z = 1.31$, than for the long SOA, $\Delta = 69$ ms, $t(47) = 11.64$, $p < .001$, $d_z = 1.68$.

Error analysis. Error data analysis was conducted as in the previous experiments.

Directional errors in Task 1 were more prominent with the short SOA (5.8%) than with the long SOA (0.7%), $F(1, 47) = 72.21$, $p < .001$, $\eta_p^2 = .61$, and also more likely in modality-compatible trials (3.5%) than in modality-incompatible trials (3.1%), $F(1, 47) = 4.62$, $p = .037$, $\eta_p^2 = .09$. A significant interaction, $F(1, 47) = 6.11$, $p = .017$, $\eta_p^2 = .12$, further indicated larger effects of modality incompatibility with the long SOA ($\Delta = 0.0\%$) than with the short SOA ($\Delta = -0.8\%$).

Omission errors in Task 1 were more likely with the long SOA (1.6%) than with the short SOA (1.2%), $F(1, 47) = 5.83$, $p = .020$, $\eta_p^2 = .11$, but there were no other contributing factors (*F*s < 2.85, *p*s > .10).

Modality errors in Task 2 were more prominent with the long SOA (8.1%) than with the short SOA (6.0%), $F(1, 47) = 31.31$, $p < .001$, $\eta_p^2 = .40$, and also more likely in modality-incompatible trials (8.6%) than in modality-compatible trials (5.5%), $F(1, 47) = 20.20$, $p < .001$, $\eta_p^2 = .30$. A significant interaction, $F(1, 47) = 17.51$, $p < .001$, $\eta_p^2 = .27$, further indicated smaller effects of modality incompatibility with the short SOA ($\Delta = 1.7\%$) than with the long SOA ($\Delta = 4.5\%$). Directional errors in Task 2 happened similarly often in all conditions (6.5%; *F*s < 3.85, *p*s > .06). Combination errors in Task 2 were more prominent with the short SOA (1.0%) than with the long SOA (0.7%), $F(1, 47) = 9.97$, $p = .003$, $\eta_p^2 = .18$, and also more likely in modality-incompatible trials (1.0%) than in modality-compatible trials (0.7%), $F(1, 47) = 4.92$, $p = .032$, $\eta_p^2 = .10$. A significant interaction, $F(1, 47) = 6.67$, $p = .013$, $\eta_p^2 = .12$, further indicated larger effects of modality incompatibility with the long SOA ($\Delta = 0.5\%$) than with the short SOA ($\Delta = 0.1\%$). Technical errors in Task 2 happened similarly often in all conditions (1.3%; *F*s < 1).

Omissions in Task 2 were again more likely with the short SOA (6.9%) than with the long SOA (1.8%), $F(1, 47) = 178.22$, $p < .001$, $\eta_p^2 = .79$, but there were no other contributing factors (*F*s < 1).

Again, the error results suggest that there was no systematic speed–accuracy trade-off.

Discussion

The results of Experiment 3 clearly replicated those of Experiment 2 while also ruling out strategic preparation processes for the upcoming level of modality compatibility. Again, we cannot clearly exclude the central stage as a possible locus for modality compatibility effects to arise. This would only be possible if the effect was completely eliminated at the short SOA, but it would also depend on the specific duration of several cognitive processes and the timing of the experiment. But crucially, we again saw that there must have been some precentral processes involved when translating stimuli into modality (in)compatible responses.

General Discussion

Why does responding with modality-compatible S-R mappings speed up compared to modality-incompatible mappings? It seems natural to assume that this is due to a speeding up of the capacity-limited stage that is usually held responsible for response selection, that is, translating perceptual stimulus information into response codes. However, although the present observations do not falsify this hypothesis, they very consistently show that this is unlikely to be the only mechanism at work. Rather these modality compatibility effects seem to (partly) arise at a stage earlier than the central capacity-limited stage. Therefore, we will discuss some precentral process candidates that might be involved in modality compatibility.

Effector-Set Priming

First, effector-set priming might play a role. As discussed in the introduction, the confrontation with a stimulus might automatically preactivate a whole associated effector set, even if stimulus identity, and thus response identity, is not yet known. Especially when participants have to switch between effector systems, a preactivated effector system would lead to performance benefits with modality-compatible mappings (when a response of the associated effector system is ultimately required) and to performance decrements with incompatible mappings (when a response of another, not-yet-activated effector system is required). Response activation is a process that has been shown to take place during the precentral phases of information processing, and it could be a driving force in modality compatibility effects (Hommel, 1998; Lien & Proctor, 2002).

Stimulus-Uptake Facilitation

From another perspective, the reverse relationship between stimuli and responses proposes another possibility. Instead of perceived stimulus modality priming response sets, we might also assume that a known response modality facilitates stimulus uptake for response-compatible stimulus modalities. That is, vocal response sets facilitate information uptake of auditory stimulation, and/or manual response sets facilitate uptake of visual information (for a related idea, see Stephan & Koch, 2016). Once the response modality is known, the system is biased toward modality-compatible stimuli. With a constant mapping of S-R modalities (as in Experiments 1 and 2), the response modality is known once the stimulus modality is known. Conceivably, stimulus modality (i.e., is this a visual or auditory stimulus?) is available long before stimulus processing (including stimulus identification) is completed, which would leave time for the proposed biasing effect to take place. If this were the case, then this biasing must be able to adapt transiently because we found the same pattern of results with a varying mapping of S-R modalities (Experiment 3). Even here, the required response modality was known with stimulus onset (via the location of the arrow and the pitch of the tone), which may have sufficed to (a) inform about the required response set and (b) bias perceptual processes toward modality-compatibly stimulus processing. The finding that action demands can prime the processing of stimulus dimensions related to these action demands is not a new observation. For example, Fagioli, Hommel, and Schubotz (2007) observed that demanding reaching actions facilitated processing of the visual location, whereas demanding grasping actions facilitated processing of the visual size. We suggest that this proposal holds across different input channels (i.e., stimulus modalities) as well.

Finally, the two possible mechanisms presented here (effector-set priming and stimulus-uptake facilitation) are neither an exhaustive list of possible mechanisms nor mutually exclusive options. However, we believe that the present research represents an important step forward to pinpointing the causes of the intriguing modality compatibility phenomenon.

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