

Sequential Adaptation to Modality Incompatibility

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Modality-compatible stimulus–response mappings (e.g., responding vocally to an auditory stimulus and manually to a visual stimulus) are often easier to perform than modality-incompatible sets (reversed modality mappings). Here, we investigate sequential, trial-to-trial, modulations of modality compatibility effects. By reanalyzing a previous experiment and conducting two specifically tailored, new experiments, we demonstrate robust within-task sequential modulations. Furthermore, we test for between-task adaptations by intermixing the modality switching task with a Simon task. Results show reliable sequential adaptations within the modality switching task, but no transfer of adaptation between tasks in either direction. We discuss how a combination of prominent theoretical accounts such as conflict adaptation and episodic binding can serve as the cognitive underpinnings of the observed sequential adaptations.

Public Significance Statement

Human agents appear to be more apt to respond to certain modalities of stimulation like vision (or audition) with certain types of responses, like manual (or vocal) responses. This so-called modality compatibility effect presumably results from long-term learning, which links certain stimulus modalities to certain response modalities. Here, we show that performance deficits with modality incompatible mappings are subject to short-term fluctuations as a function of immediately preceding experience. Thus, apparently highly overlearned preferences of responding in certain ways to certain types of stimulation can become adjusted on a short timescale, suggesting a remarkable flexibility of the sensorimotor system.

Keywords: action control, modality compatibility, sequential adaptation, cognitive control, task switching

Humans have manifold possibilities to interact with their environment. In other words, they possess various modalities to perceive (e.g., vision or audition) and act (e.g., manually or verbally). Some combinations of perceiving and responding go along better and are said to be relatively more compatible than other combinations, which are said to be less compatible. Under certain

circumstances, performance is faster and more accurate when responding manually to visual stimulation and vocally to auditory stimulation than with the reversed modality mapping (Hazeltine et al., 2006; Stelzel et al., 2006; Stelzel & Schubert, 2011; Wirth et al., 2020). Performance drops with modality-incompatible mappings are particularly evident when various stimulus and response modalities are encountered either simultaneously (Hazeltine et al., 2006; Stelzel et al., 2006), or in quick succession (Stephan & Koch, 2010; see Fintor et al., 2018, for the prerequisites for modality compatibility effects).

The reasons for such modality compatibility effects are not entirely settled. One approach suggests resource competition as a possible origin (Wickens, 2008). Modality compatible mappings, such as visuo-manual and auditory-vocal mappings, might draw upon distinct processing resources (visuo-spatial and verbal-auditory, respectively), whereby each mapping can operate with a distinct set of resources. In contrast, with modality incompatible mappings, such as visuo-verbal and auditory-manual mappings, similar resources are required (e.g., visuo-spatial resources in both cases), so that a spread of similar resources among these mappings is necessary, whereby performance in each mapping drops (see also Maquestiaux et al., 2018 for the idea of modality-specific cognitive subsystems).

Another position holds that modality compatibility effects reflect some sort of long-term links between perception and action, probably acquired during ontogenesis. For example, verbal communication

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typically requires responding vocally rather than manually to what is heard from an interaction partner, whereas visually perceived objects are typically manipulated manually rather than vocally. A different (but not necessarily mutually exclusive) view proposes that modality compatibility rests on linkages between efferent output and the reafferent feedback that is typically produced by this output. Not only do we respond quite often vocally to auditory stimulation, but we also produce auditory feedback by doing so, we hear ourselves speaking. Likewise, not only do we respond quite often manually to visual stimulation, but the consequences of doing so are also encountered by vision, we see our hands and what they do in eye–hand coordination (Greenwald, 1970; Rosenbaum, 2017). While such modality linkages come with some flexibility, as altering them may not require much practice (cf. Schacherer & Hazeltine, 2021, 2023; Stephan et al., 2022), it is plausible that encountering stimulation in a certain modality tends to automatically activate the response modality to which it is linked through previous experience (Stephan & Koch, 2011; Wirth et al., 2020). This activation is beneficial if responding in the activated response modality is required, but it may create interference with competing mappings if this modality is currently not appropriate. Specifically, in modality-incompatible mappings a visual stimulus must be assigned to a vocal response which produces auditory feedback, whereas an auditory stimulus must be assigned to a manual response which (often) produces visual feedback. If visual stimuli activate (manual) responses which typically produce visual feedback, and auditory stimuli activate (vocal) responses which typically produce auditory feedback, each stimulus would respectively tend to activate a response set that is currently not required. This creates crosstalk and, consequently, interference between mappings (Schacherer & Hazeltine, 2021). Such interference is more likely when there is uncertainty about the stimulus or response modality required at any moment, that is, when all possible stimulus or response modality remains in a high preparatory state as in task switching (e.g., Fintor et al., 2018; Stephan & Koch, 2010) or dual-tasking (Hazeltine et al., 2006).

Interference is supposed to come with all kinds of short-term adaptations of the cognitive system (Botvinick et al., 2001; Braver, 2012; Verguts et al., 2011). One particularly well-documented adaptation is sequential adaptation. In a typical repetitive task, experiencing interference leads to a transient reduction of interference effects in the subsequent trial. There are by and large two camps to explain such sequential adaptations (for reviews, see Braem et al., 2014, 2019; Frings et al., 2020; Schmidt, 2019). The cognitive control camp assumes that experiencing interference prompts more control, such as a stronger focus on task-relevant information or a stronger suppression of task-irrelevant information (Botvinick et al., 2001; Kerns et al., 2004; Kunde & Wühr, 2006; Pfister et al., 2013; Wirth et al., 2019; Wirth, Pfister, Foerster, et al., 2016). The other camp suggests that sequential modulations rest on memory traces of previous trial episodes (cf. Frings et al., 2020; Hommel, 2004; Schmidt, 2019; Wirth & Kunde, 2020). The basic idea is that the repetition of a certain stimulus feature retrieves certain aspects of the previous trial episode to which this feature is still linked, such as the previous response modality. Among other things, full repetitions of stimulus modality and response modality might be particularly helpful, as here the stimulus retrieves the previous response modality, which fortunately is currently required as well. As the type and frequency of such potential retrieval can vary by design between different transitions of compatibility levels (e.g., full repetitions occur

more often when an incompatible trial follows another incompatible rather than compatible trial) the size of compatibility effects varies as well. These accounts are not necessarily exclusive. Empirically it is surprisingly difficult, and perhaps impossible, to disentangle them completely (Braem et al., 2014; Schmidt, 2019), and at a theoretical level they have been combined to jointly account for sequential modulations (Verguts & Notebaert, 2008).

The present article had two goals: First, we investigated whether modality compatibility effects are subject to such transient, sequential modulations in the first place. Observing sequential modulations that are akin to other conflict adaptation effects would lend support to the assumption that incompatible modality mappings do come with conflict, while other accounts are not excluded. To foreshadow the results, we made observations that are in line with conflict adaptation, but also observations that are more in line with memory retrieval. Second, we tested whether the observed sequential modulations of modality compatibility effects generalize to a different type of interference. Finding no generalization would suggest interference-specific modulation processes, whereas generalization would suggest overarching modulations processes. Modulations across different types of interference are rarely observed, but they have occasionally been reported for distinctively different types of interference tasks (Braem et al., 2014; Wirth, Pfister, & Kunde, 2016). To test for such transfer, we chose a Simon task with a highly dissimilar response set, stimulus set, and relevant stimulus features.

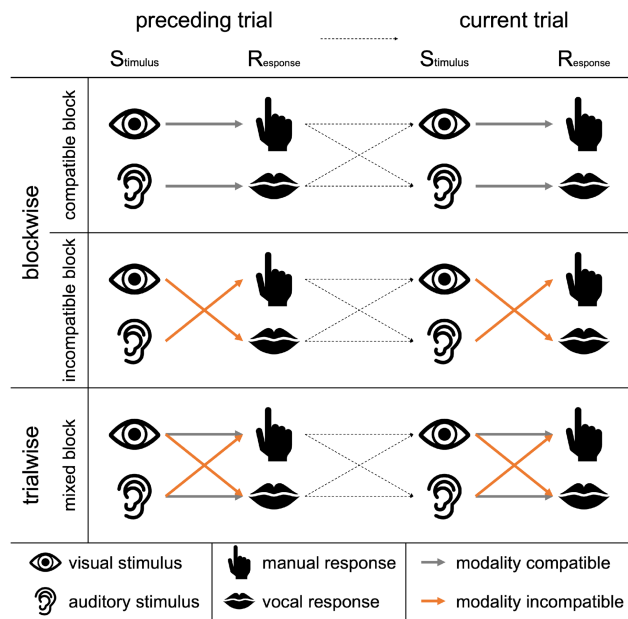
Reanalysis of Existing Data

Introduction

Most previous studies on modality compatibility used a blockwise manipulation, in which participants were instructed to use either a pair of modality-compatible or of modality-incompatible mappings (Stephan & Koch, 2010; see Fintor et al., 2018, for a discussion). Therefore, a modality compatible mapping was always followed by another compatible mapping, and an incompatible mapping was always followed by a modality incompatible mapping (see Figure 1). However, to examine sequential adaptation effects, modality compatibility must be manipulated in a way that the modality compatibility of the stimulus–response (S–R) mappings is not constant within a block but can change from trial to trial. To the best of our knowledge, this has only been done once before (Wirth et al., 2020, Experiment 3). Specifically, in that study, the stimulus modality (visual vs. auditory) varied randomly, but participants were instructed in each individual trial by a response-modality cue (see Philipp & Koch, 2005, 2011), indicating whether the response had to be made vocally or manually. In this study, we nonetheless observed a sizeable modality compatibility effect, which might, in theory, suffice to reveal a sequential adaptation to modality incompatibility, if such a transient reduction of interference exists.

However, this experiment was not initially designed to examine the assumed sequential adaptations and, hence, might not be ideal to reveal any possible effect. Specifically, we used a psychological refractory period setup in which the modality manipulation was only implemented in the second task. Hence, two subsequent modality switching tasks were always interleaved with (and sometimes overlapped with) a different task. Moreover, we used a variable stimulus

Figure 1
Blockwise Versus Trialwise Manipulation of S–R Modality Compatibility



Note. Participants are confronted with both visual stimuli (eye symbol) and auditory stimuli (ear symbol), which must be answered manually (hand symbol) or vocally (mouth symbol). With a blockwise manipulation, each stimulus modality is constantly mapped to a response modality, and modality compatibility must be manipulated between blocks. In contrast, a trialwise manipulation allows for mixing modality compatible and incompatible mappings within the same block, and the currently relevant response modality (and thereby modality compatibility) must be indicated by an additional cue. In both cases, any response can be followed by any stimulus modality. S = stimulus; R = response. See the online article for the color version of the figure.

onset asynchrony (SOA), which is not ideally suited for carryover effects and may further obscure modality-specific sequential adaptations. With those caveats in mind, we nonetheless decided to first reanalyze the existing data for the assumed sequential adaptations. If such an effect would emerge despite the interim task and the suboptimal timing, this could not only be considered first evidence for the existence of the effect, but it would also let us assess its robustness.

Method

A set of 48 participants performed two tasks: first, a simple S–R task, in which they answered a vibrotactile stimulus on their leg with a corresponding pedal press, and second, a modality switching task in which they responded either manually or vocally to visual or auditory stimuli. For the vibrotactile task, small vibrating motors were attached to the participants' left and right legs, and vibration stimuli had to be answered via left and right pedal responses. For the modality switching task, participants were asked to respond to the direction of either visually presented arrows pointing to the left or right, or to tones that were played on the left or the right side. Arrow position (at the upper or lower half of the screen) and tone pitch (high or low) indicated the response modality (manual or vocal). The tasks were

presented in a dual-task setup with a varying SOA (100 vs. 1,000 ms) between the vibrotactile task and the modality switching task. The modality switching task will be used in the later experiments and will therefore be described in full detail later (for the full Method section, please refer to the original article, Wirth et al., 2020, Experiment 3).

Results

We reanalyzed the data of this study with a focus on sequential adaptations of the modality switching task. For the response time (RT) analysis, we ignored all performance metrics from the vibrotactile task and excluded trials with errors and omissions in the modality switching task (20.1%), trials following errors and omissions in the modality switching task (13.8%), and the first trial of each block (0.3%). The remaining trials were screened for outliers, and we removed trials in which RTs deviated more than 2.5 SDs from the corresponding cell mean (0.7%), computed separately for each participant and each experimental condition (preceding and current modality compatibility). Overall, 35.0% of the trials were removed.

The remaining data were then analyzed via a 2×2 analysis of variance (ANOVA) with preceding modality compatibility (compatible vs. incompatible) and current modality compatibility (compatible vs. incompatible) as within-subject factors (see Figure 2). Planned post hoc analyses tested for the compatibility effect after incompatible and after compatible trials. For all post hoc tests, we computed $d_z = \frac{t}{\sqrt{n}}$. Error rates (percent error, PE) were analyzed accordingly.

RTs

Responses were faster in modality compatible trials (981 ms) than in modality incompatible trials (1,038 ms), $F(1, 47) = 128.46$, $p < .001$, $\eta_p^2 = .73$. There was no main effect of preceding modality compatibility, $F < 1$. Crucially, preceding and current modality interacted, $F(1, 47) = 73.04$, $p < .001$, $\eta_p^2 = .61$, indicating larger compatibility effects after a modality compatible trial, $t(47) = 14.81$, $p < .001$, $d_z = 2.14$, $\Delta = 98$ ms, compared to after a modality incompatible trial, $t(47) = 2.14$, $p = .038$, $d_z = 0.31$, $\Delta = 16$ ms.

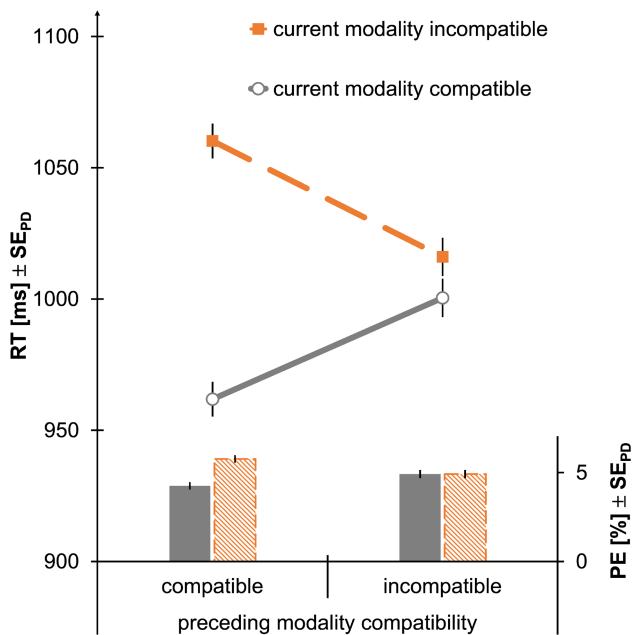
PEs

There were fewer errors in modality compatible trials (4.6%) than in modality incompatible trials (5.3%), $F(1, 47) = 18.46$, $p < .001$, $\eta_p^2 = .28$. There was no main effect of preceding modality compatibility, $F(1, 47) = 1.15$, $p = .289$, $\eta_p^2 = .02$. Crucially, preceding and current modality interacted, $F(1, 47) = 30.32$, $p < .001$, $\eta_p^2 = .39$, indicating larger compatibility effects after a modality compatible trial, $t(47) = 7.06$, $p < .001$, $d_z = 1.02$, $\Delta = 1.5\%$, compared to after a modality incompatible trial, $t(47) = -0.01$, $p = .991$, $|d_z| < 0.01$, $|\Delta| < 0.1\%$.

Discussion

The reanalysis of the existing data revealed that, despite the suboptimal setup for the effect, modality manipulations are indeed subject to sequential modulation. As expected, modality compatibility effects were larger after modality compatible trials than after modality incompatible trials. Notably, this was evident in both RTs and error rates.

Figure 2
Results of the Reanalysis of Wirth et al. (2020, Experiment 3)



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

While it is impressive that the sequential modulation of the modality compatibility effect even seems to subsist an interspersed task (which may affect the observed interaction in ways that we could only speculate on), we do not want to draw any premature conclusions. Therefore, we designed two new studies that allowed us to investigate the aftereffects of modality (in)compatibility more directly.

Experiment 1

Introduction

This experiment adapted the modality switching task from Wirth et al. (2020, Experiment 3), but removed all multitasking¹ demands in the sense that only one response is required in each individual trial. This approach is particularly suited to reveal pure influences of the sequential modulations of modality compatibility effects. Again, participants were confronted with either visual or auditory stimuli, which they had to respond to either manually or vocally. To optimize the preconditions for sequential modulations, we shortened the response-stimulus interval (RSI) as much as possible (cf. Egner et al., 2010).

We expected better performance with modality compatible compared to modality incompatible mappings. Furthermore, we expected adaptation processes, with a larger modality–compatibility effect after a compatible than after an incompatible trial.

Method

Transparency and Openness

All data and analysis code are available at <https://osf.io/wg7p5>. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the experiments. These studies were not preregistered.

Participants

We based our power analysis for the critical interaction between preceding and current modality compatibility on the observed effect size in RTs in the reanalysis of Wirth et al. (2020) as reported above, $\eta_p^2 = .61$. At $\alpha = .05$, 24 participants provide a power of $1 - \beta > .99$ to detect similar effect sizes (Anderson & Kelley, 2020) and allow for counterbalancing. All participants ($M_{age} = 28.9$ years, $SD = 8.1$) provided written informed consent and received monetary compensation. Three participants were replaced because of high error rates (>30%, two participants) or technical issues resulting in incomplete data (one participant).

Apparatus and Stimuli

Visual stimuli were arrows pointing to either the left or right side. They were presented centrally on the upper or lower part of a 24 in. screen in white font against a black background. Auditory stimuli were sinus tones (low: G3, 196 Hz vs. high: G4, 392 Hz) presented on either the left or the right ear via headphones.

Participants responded manually or vocally: Manual responses consisted of keypresses on the left (F) or the right (J) side via two marked keys of a QWERTZ keyboard. Vocal responses were the German words for left (“links”) or right (“rechts”), which were analyzed by a custom voice-recognition software.²

Participants were instructed to always respond in a spatially compatible manner: Left pointing arrows and tones on the left ear had to be answered with a left manual or vocal response, and right pointing arrows and tones on the right ear had to be answered with a right manual or vocal response. Tone pitch and arrow position on the screen determined the modality of the response. Half of the participants were instructed to respond vocally to high tones and arrows in the upper part of the screen, and to respond manually to low tones and arrows in the lower part of the screen. The other half of participants was instructed with the reverse modality mapping for counterbalancing.

That way, trials could be modality compatible (visual-manual and auditory-vocal) or modality incompatible (visual-vocal and auditory-manual), and modality mappings could change from trial to trial.

¹ Note that “multitasking” is difficult to define, an issue that we will come back to in the General Discussion section. Yet, multitasking is considered a definite prerequisite for modality compatibility effects to emerge in the sense that several stimulus and response modalities (and thereby S–R mappings) within the same task can potentially occur (see Fintor et al., 2018). This is different from how we used the term so far, that is, to describe task demands in which distinctly instructed tasks must be performed at the same time or in fast succession. While we removed the vibro-tactile task and thereby the requirement to switch between tasks, Experiment 1 still confronts participants with multiple stimulus and response modalities.

² Prior to the experiment, the software was adjusted to accurately discriminate between the two possible vocal responses for each individual participant. The experiment only proceeded when at least 95% of the vocal responses were properly categorized.

Procedure

Participants performed 10 blocks, each consisting of 160 trials of the modality switching task with short breaks after each block (see Figure 3). A blank screen marked the beginning of a trial. After 500 ms, the imperative stimulus was presented for 100 ms (auditory stimulus) or until response detection (visual stimulus). The next trial started immediately after the participants response. If no response was detected within 2,000 ms after stimulus presentation, the trial counted as an omission. In case of an omission or commission error, feedback was provided for 1,000 ms in both modalities. It encompassed a visual error message “Zu Langsam” (German for “too slow”; omission error) or “Fehler” (German for “error”; commission error) and an accompanying buzzer sound.

Results

Data were handled as in the reanalysis described above. We excluded trials with errors and omissions (17.4%), trials following errors and omissions (12.5%), the first trial of each block (0.4%), and outliers (0.9%). Overall, 31.2% of the trials were removed. The remaining data were analyzed exactly as in the reanalysis described above (see Figure 4).

RTs

Responses were faster in modality compatible trials (797 ms) than in modality incompatible trials (843 ms), $F(1, 23) = 85.95, p < .001, \eta_p^2 = .79$. Moreover, responses were slightly faster after modality incompatible trials (811 ms) compared to after modality compatible trials (830 ms), $F(1, 23) = 16.06, p < .001, \eta_p^2 = .41$. Crucially, preceding and current modality compatibility interacted, $F(1, 23) = 169.17, p < .001, \eta_p^2 = .88$, indicating a large modality compatibility effect after a modality compatible trial, $t(23) = 14.90, p < .001, d_z = 3.04, \Delta = 140$ ms, and a reversed modality compatibility effect after a modality incompatible trial, $t(23) = -5.86, p < .001, d_z = -1.20, \Delta = -47$ ms.

PEs

There were fewer errors in modality compatible trials (4.0%) than in modality incompatible trials (4.7%), $F(1, 23) = 15.26, p < .001, \eta_p^2 = .40$. Moreover, there were fewer errors after modality incompatible trials (4.2%) compared to after modality compatible trials (4.5%), $F(1, 23) = 11.54, p = .002, \eta_p^2 = .33$. Crucially, preceding and current modality compatibility interacted, $F(1, 23) = 36.38, p < .001, \eta_p^2 = .61$, indicating a large modality compatibility effect after a modality compatible trial, $t(23) = 7.63, p < .001, d_z = 1.56, \Delta = 1.8\%$, but no significant difference after a modality incompatible trial, $t(23) = -1.75, p = .094, d_z = -0.36, \Delta = -0.5\%$.

Discussion

In Experiment 1, we tested whether a modality incompatible episode would trigger adaptation processes that could reduce the impact of future modality incompatible episodes. First, we found a robust modality compatibility effect, with slower RTs for modality incompatible mappings compared to modality compatible mappings, even in a trialwise setting that had all concurrent response demands removed. This is not trivial because modality compatibility effects are sometimes said to only surface in “multitasking” setups (see

Footnote 1), but not when single tasking (e.g., Stephan & Koch, 2010³), an observation on which we will elaborate on in the General Discussion section.

Next, we found that while responding in an incompatible manner comes with considerable RT costs, this episode can diminish the RTs of subsequent modality incompatible episodes, indicating that participants adapted to modality incompatible mappings, showing reduced performance deficits in a trial sequence of two subsequent incompatible trials. The first theoretical account that comes to mind when trying to explain such a pattern of results is conflict adaptation (Botvinick et al., 2001; Gratton et al., 1992). Experiencing conflict (in our case, a modality incompatible episode) is said to trigger some sort of conflict adaptation signal, which in turn adjusts the cognitive system (i.e., attentional focus, weighted processing, response thresholds) so that a subsequent conflicting episode can be handled better and is less detrimental towards performance. However, there are two things that indicate that conflict adaptation may not be the only cause of the observed interaction.

First, conflict adaptation would assume a speedup of incompatible trials after incompatible trials (compared to incompatible trials after compatible trials; see Figure 4, orange line), while there is no straightforward prediction of the observed slowdown of compatible trials after incompatible trials (compared to compatible trials after compatible trials; see Figure 4, gray line). The theory assumes that compatible trials do not come with considerable conflict, so compatible trials should not induce adaptation, whereas previous incompatible (i.e., conflicting) trials should. Still, we are not the first authors to report that such adaptations can be, at least partly, driven by compatible trials as well (Verguts et al., 2011), and it is not implausible to

³ Additionally, Stephan and Koch (2010) focus on switch costs in a blocked design in which they employed either only compatible or only incompatible modality mappings, and they report larger switch costs in incompatible → incompatible sequences compared to compatible → compatible sequences. With our design, we can also test for this effect by pitting full repetitions against full alternations (i.e., repeating the S–R mapping vs. switching the S–R mapping, see Table 1), separately for each modality sequence. Full repetitions made up 52.6% of all compatible → compatible sequences, and 52.0% of all incompatible → incompatible sequences.

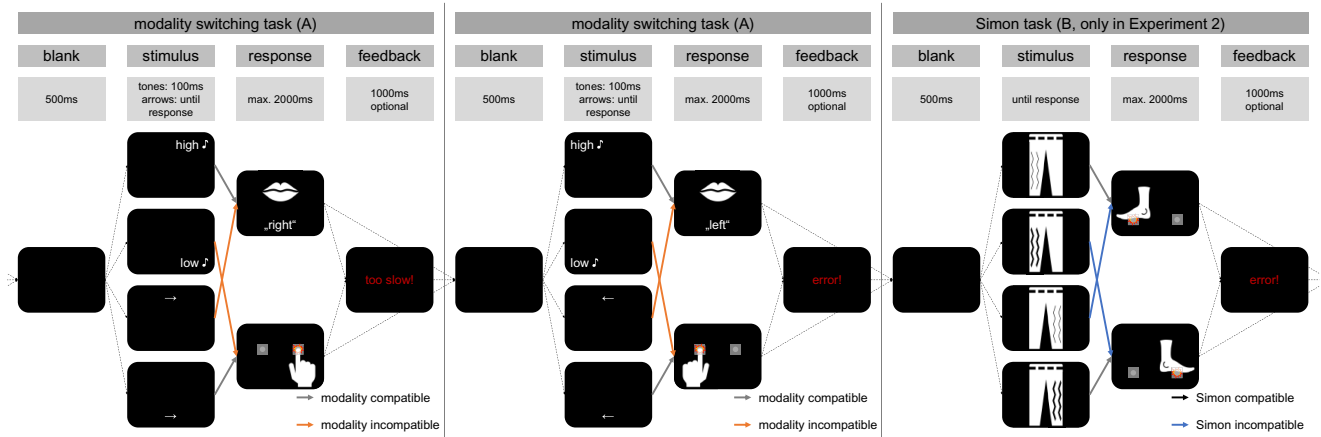
The data were analyzed via a 2 × 2 ANOVA with binding sequence (full repetitions vs. full alternations) and modality compatibility sequence (compatible vs. incompatible) as within-subjects factors.

Indeed, we observed larger RTs for full alternations (893 ms) compared to full repetitions (666 ms), $F(1, 23) = 178.87, p < .001, \eta_p^2 = .89$, and overall faster responses for the modality compatible sequences (766 ms) compared to the modality incompatible sequences (794 ms), $F(1, 23) = 19.93, p < .001, \eta_p^2 = .46$, and a significant interaction, $F(1, 23) = 12.28, p = .002, \eta_p^2 = .35$, indicating larger switch costs in incompatible sequences, $t(23) = 13.43, p < .001, d_z = 2.74, \Delta = 252$ ms, compared to compatible sequences, $t(23) = 11.32, p < .001, d_z = 2.31, \Delta = 203$ ms.

Similarly, we observed higher error rates for full alternations (1.5%) compared to full repetitions (0.9%), $F(1, 23) = 54.70, p < .001, \eta_p^2 = .70$, but the main effect of modality compatibility sequence as well as the interaction was not significant, $F_s < 1$.

This shows that even with a modality manipulation that can change from trial to trial, we were able to replicate the increased switch costs with incompatible modality mappings (Stephan & Koch, 2010). Future research should further test how blockwise and trialwise modality compatibility manipulations may differently affect performance.

Figure 3
Procedure of Experiments 1 and 2



Note. In the modality task (A), a blank screen was followed by either a visual stimulus (arrow pointing left or right, displayed in the upper or lower half of the screen) or an auditory stimulus (tone played to the left or right ear, in high or low pitch) had to be answered manually (left or right button) or vocally (speaking “left” or “right” into a microphone). In the current example, high tones and arrows in the upper half of the screen had to be answered vocally, and low tones and arrows in the lower half of the screen had to be answered manually. In case of errors, feedback was displayed. The Simon task (B) was only interspersed in Experiment 2. Here, vibration stimuli (to the left or right leg, with high or low intensity) had to be answered via pedal responses (left or right foot buttons). In Experiment 2, all blank screens were presented for 1,000 ms (instead of 500 ms). See the online article for the color version of the figure.

assume that global shifts in attention, processing, and response thresholds could also affect how the responses of compatible trials are enacted.

Second, conflict adaptation would not predict that the modality compatibility effect reverses after an incompatible trial. Even though the discussed parameter shifts of the cognitive system can evidently increase performance for subsequent incompatible trials (even if it is at the cost of compatible trials following incompatible trials), conflict adaptation theory would not ascribe the cognitive system the flexibility to instantiate parameters that favor the processing of conflicting episodes. While conflict adaptation is thought to operate on a relatively high level, more low-level cognitive mechanisms may help to explain this result, namely episodic binding (Frings et al., 2020; Hommel, 2004).

When stimuli and responses (or more precisely: features of stimuli and responses, such as their modality) are experienced together in an episode, they are thought to be bound together in an event file. Repeating the full event (full repetitions) is therefore assumed to come with performance benefits, as the features of the repeat episode are already bound together. Similarly, subsequent events that do not share any of the features of the previous episode (full alternations) are thought to be easily enacted, as none of the previously bound features are required. Performance decrements are expected if an episode repeats some, but not all previously bound features (partial repetitions), as it is assumed that the repeated and therefore already bound features must first be released from their previous event file to be accessible for the current episode. Dissecting the possible sequences in Experiment 1 (see Table 1) demonstrates a systematic influence of episodic binding: Those sequences that come with better performance (compatible → compatible; incompatible → incompatible) represent full repetitions and full alternations, while the sequences that come with worse performance consist of partial repetitions.

One might be tempted to dissect the current setup to further address the contribution of episodic binding by selecting some of those sequences that are assumed to be least affected by any binding processes and analyzing them in isolation. However, such an approach will inherently introduce additional confounds. For example, if we were to select only those sequences in which the stimulus modality switches (removing all full repetitions and stimulus modality repetitions, all white lines in Table 1), to control for modality repetition benefits, we are left with only those sequences in which the response modality switches in compatible → compatible and incompatible → incompatible sequences, and only response modality repetitions in the others (see also Experiment 2 alpha in Appendix B). Episodic binding of stimulus modality to response modality is an inherent part of the design of the experiment and cannot be eliminated completely when testing for aftereffects of a task onto itself. Before discussing the possible models for the observed adaptation further in the General Discussion section, Experiment 2 will first provide additional evidence for the sequential adaptation to modality incompatibility.

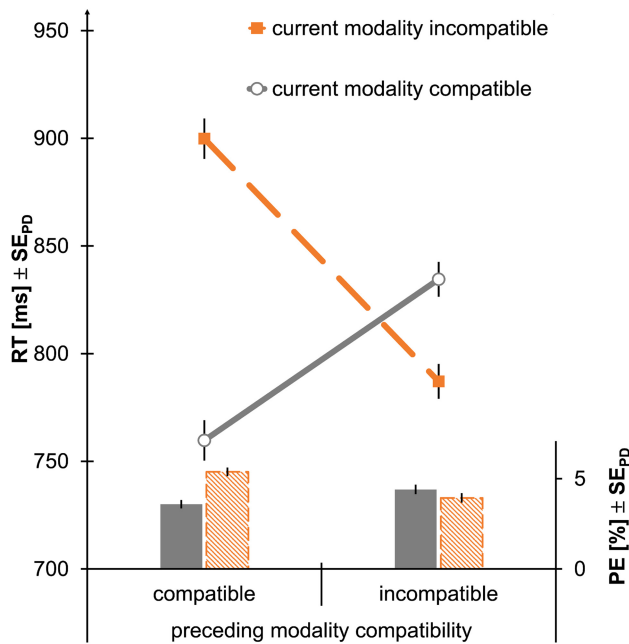
Experiment 2

Introduction

Experiment 1 was helpful in demonstrating sequential modulations of modality compatibility effects as well as possible constraints regarding their interpretation. Experiment 2 aimed to conform the robustness of the phenomenon under optimized conditions, as well as testing the scope of changes that modality incompatible events might prompt. Specifically, we first exercised more control over which trial sequences participants were presented with. In Experiment 1, the sequences were completely random, so that every sequence was possible, but not every sequence was encountered equally often. Therefore, we implemented a fixed

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Figure 4
Results of Experiment 1



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

task structure, in which we could control the task sequence more easily. Second, we wanted to test the specificity of the adaptation to modality incompatibility, meaning whether this adaptation can transfer to another conflict task and vice versa. Therefore, we added a Simon task in which we manipulated spatial compatibility: Participants responded to the type of vibrotactile stimulation (high vs. low intensity) at their left or right leg (stimulus location irrelevant) with a left or right pedal response. Again, trials could be Simon compatible, when the vibration was administered to the leg that had to produce the response, or Simon incompatible, when the vibration was administered to the opposite leg. Participants now had to alternate between the modality switching task and the Simon task in a fixed AAB–AAB sequence, with two subsequent modality switching tasks (to replicate the within task adaptations) followed by one Simon task (to test for between-task adaptations in the AB and the BA dyads).

Apart from replicating our previous results, we expected a Simon effect with faster responses for compatible trials compared to incompatible trials. Finding that modality-incompatible trials attenuate the Simon effect in subsequent trials (and vice versa) would be rather strong evidence for an overarching interference adaptation process (Braem et al., 2014), though not finding such transfer would not ultimately exclude the possibility of global adaptation operations (Egner, 2008).

Method

Participants

Based on the power analysis of Experiment 1, new set of 24 participants was recruited. All participants ($M_{age} = 23.7$ years, $SD = 3.0$) provided written informed consent and received monetary compensation. Four participants were replaced because of high error rates (>30%).

Apparatus, Stimuli, and Procedure

The setup was identical to Experiment 1 with the following changes: Participants had to switch between the modality switching task from Experiment 1 and a Simon task. The tasks were displayed in a fixed sequence, in which two modality switching tasks were always followed by one Simon task (AAB–AAB). In case of errors or omissions, the same feedback as in Experiment 1 was displayed, again for 1,000 ms. After a correct response, the next task started after 500 ms.

For the modality switching task, we now controlled for the frequency of sequences (see Table A1 in Appendix A). For the Simon task, stimuli were vibrations administered to the left or right leg in high or low intensity, presented until response detection. Responses were pedal presses with the left or right foot. This way, we made sure that there was no overlap between the stimulus modalities and the required response effectors of the two tasks. Participants had to respond to the intensity of the vibration, whereas the spatial location of the tactile stimulus was irrelevant. Hence, trials could be Simon compatible (response required at the vibrating leg) or Simon incompatible (response required at the other leg). The S–R mapping of vibration intensity (high vs. low) and required pedal response (left vs. right) was counterbalanced across participants.

Participants performed two blocks, each consisting of 256 AAB trial triplets (making 768 trials), with short breaks after each 64th triplet (after each 192nd trial).

Results

Experiment 2 employed a fixed task sequence (AAB–AAB), which can be further broken down into three trial dyads. This allows us not only to replicate sequential adaptations within the modality switching task under more controlled conditions (AA sequence), but also to analyze the possible adaptation that the modality switching task causes in the Simon task (AB sequence) and vice versa (BA sequence). Accordingly, the three dyads were analyzed separately.

Modality Switching Task → Modality Switching Task Sequences (AA)

This analysis investigates the second response in the AAB sequence. We excluded errors and omissions (13.8%), responses following errors and omissions (11.3%), the first triplet of each block (1.0%),⁴ and outliers (2.2%). Overall, 28.3% of the trials were

⁴As Experiment 2 employed a fixed AAB–AAB task structure, the first triplet of each block (consisting of two modality switching tasks and one Simon task) would not necessarily have to be discarded completely (only for the analysis of the very first modality switching task of a block). Still, we decided to remove the first triplet in all analyses for consistency.

Table 1
Modality Sequence Combinations of Stimuli (S) and Responses (R) in Experiment 1

Modality sequence	Preceding trial		Current trial		Binding sequence
	S	R	S	R	
Compatible → compatible	Visual	Manual	Visual	Manual	Full repetition
	Visual	Manual	Auditory	Vocal	Full alternation
	Auditory	Vocal	Auditory	Vocal	Full repetition
	Auditory	Vocal	Visual	Manual	Full alternation
Compatible → incompatible	Visual	Manual	Visual	Vocal	Stimulus modality repetition
	Visual	Manual	Auditory	Manual	Response modality repetition
	Auditory	Vocal	Auditory	Manual	Stimulus modality repetition
	Auditory	Vocal	Visual	Vocal	Response modality repetition
Incompatible → compatible	Visual	Vocal	Visual	Manual	Stimulus modality repetition
	Visual	Vocal	Auditory	Vocal	Response modality repetition
	Auditory	Manual	Auditory	Vocal	Stimulus modality repetition
	Auditory	Manual	Visual	Manual	Response modality repetition
Incompatible → incompatible	Visual	Vocal	Visual	Vocal	Full repetition
	Visual	Vocal	Auditory	Manual	Full alternation
	Auditory	Manual	Auditory	Manual	Full repetition
	Auditory	Manual	Visual	Vocal	Full alternation

Note. While those trial sequences that repeat modalities consist of full repetitions and full alternations, which are thought to come with performance benefits, those trial sequences that switch modalities consist of partial repetitions, which are thought to come with performance deficits. For brevity, we omitted the response direction (left vs. right) in both tasks. The full table with all sequences can be found in the [Appendix \(Table A1\)](#). S = stimulus; R = response.

removed. The remaining data were analyzed exactly as in the previous experiments (see [Figure 5](#)).

RTs. Responses were faster in modality compatible trials (890 ms) than in modality incompatible trials (923 ms), $F(1, 23) = 13.44, p = .001, \eta_p^2 = .37$. Moreover, responses were faster after modality incompatible trials (888 ms) compared to after modality compatible trials (925 ms), $F(1, 23) = 19.13, p < .001, \eta_p^2 = .45$. Crucially, preceding and current modality compatibility interacted, $F(1, 23) = 74.69, p < .001, \eta_p^2 = .77$, indicating a large modality compatibility effect after a modality compatible trial, $t(23) = 8.54, p < .001, d_z = 1.74, \Delta = 92$ ms, and a reversed modality compatibility effect after a modality incompatible trial, $t(23) = -2.11, p = .046, d_z = -0.43, \Delta = -25$ ms.

PEs. There was no main effect of current modality compatibility, $F < 1$, but more errors occurred after a modality compatible trial (3.6%) compared to after a modality incompatible trial (3.3%), $F(1, 23) = 5.50, p = .028, \eta_p^2 = .19$. Preceding and current modality compatibility interacted, $F(1, 23) = 16.55, p < .001, \eta_p^2 = .42$, but neither of the planned post hoc tests revealed any significant contribution on their own, $|t|s < 1.63, ps > .118$.

Modality Switching Task → Simon Task Sequences (AB)

This analysis investigates the third response in the AAB sequence. We excluded errors and omissions (16.6%), responses following errors and omissions (9.8%), the first triplet of each block (1.0%), and outliers (3.0%). Overall, 30.4% of the trials were removed. The remaining data were then analyzed via a 2 × 2 ANOVA with preceding modality compatibility (compatible vs. incompatible)

and current Simon compatibility (compatible vs. incompatible) as within-subject factors (see [Figure 6](#)).

RTs. Responses were faster in Simon compatible trials (971 ms) than in Simon incompatible trials (1,022 ms), $F(1, 23) = 15.01, p < .001, \eta_p^2 = .40$. Neither the main effect of preceding modality compatibility nor the interaction were significant, $Fs < 1$.

PEs. There were less errors in Simon compatible trials (3.0%) than in Simon incompatible trials (5.1%), $F(1, 23) = 5.45, p = .029, \eta_p^2 = .19$. Neither the main effect of preceding modality compatibility, $F(1, 23) = 2.13, p = .158, \eta_p^2 = .09$, nor the interaction, $F < 1$, were significant.

Simon Task → Modality Switching Task Sequences (BA)

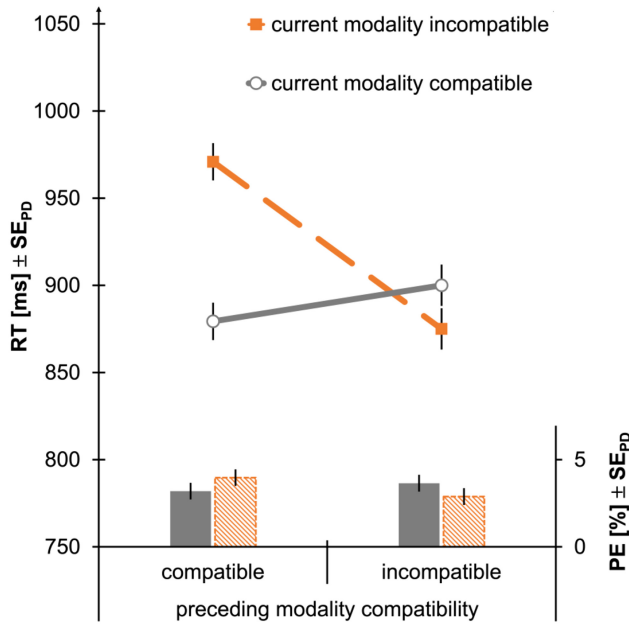
This analysis investigates the first response in the AAB sequence. We excluded errors and omissions (15.1%), responses following errors and omissions (12.3%), the first triplet of each block (1.0%), and outliers (2.9%). Overall, 31.3% of the trials were removed. The remaining data were then analyzed via a 2 × 2 ANOVA with preceding Simon compatibility (compatible vs. incompatible) and current modality compatibility (compatible vs. incompatible) as within-subject factors (see [Figure 7](#)).

RTs. Responses were faster in modality compatible trials (923 ms) than in modality incompatible trials (990 ms), $F(1, 23) = 24.91, p < .001, \eta_p^2 = .52$. Moreover, responses were slightly faster after a Simon compatible trial (951 ms) than after a Simon incompatible trial (963 ms), $F(1, 23) = 4.32, p = .049, \eta_p^2 = .16$. The interaction was not significant, $F < 1$.

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Figure 5

Results of Experiment 2: Modality Switching Task → Modality Switching Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

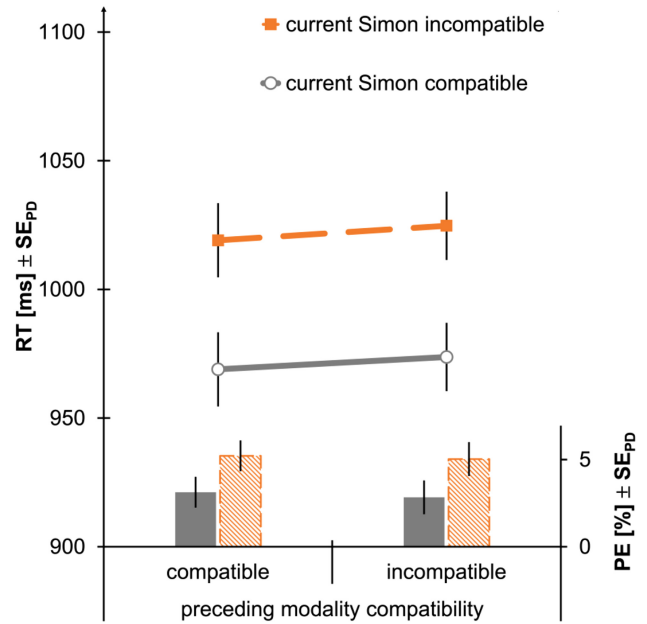
PEs. Neither the main effects, $F_s < 1$, nor the interaction, $F(1, 23) = 4.26, p = .051, \eta_p^2 = .16$, were significant.

Discussion

In Experiment 2, we set out not only to replicate the sequential adaptation to modality incompatibility under more controlled conditions within the modality switching task, but also to test for the possible transfer between tasks. Even with the more controlled setup, we again found that modality incompatible trials benefited from preceding modality incompatible episodes. In line with conflict adaptation theory (Botvinick et al., 2001), this benefit is limited to incompatible trials, while compatible trials are not subject of reliable modulation.⁵ We cannot rule out low-level binding processes entirely from our design, but conflict adaptation and episodic binding are not necessarily mutually exclusive. In fact, the current results suggest that both types of processes do not fully capture all aspects of the data on their own, as the reversal of the compatibility effect after an incompatible task is not well in line with conflict adaptation, while the lack of a performance change in compatible tasks as a function of previous compatibility is not well in line with binding accounts. Rather, they probably both contribute to how participants performed in the experiments. In line with the emerging consensus that such sequential modulations are

Figure 6

Results of Experiment 2: Modality Switching Task → Simon Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current Simon compatible trials, and the dashed orange line/bars represent current Simon incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

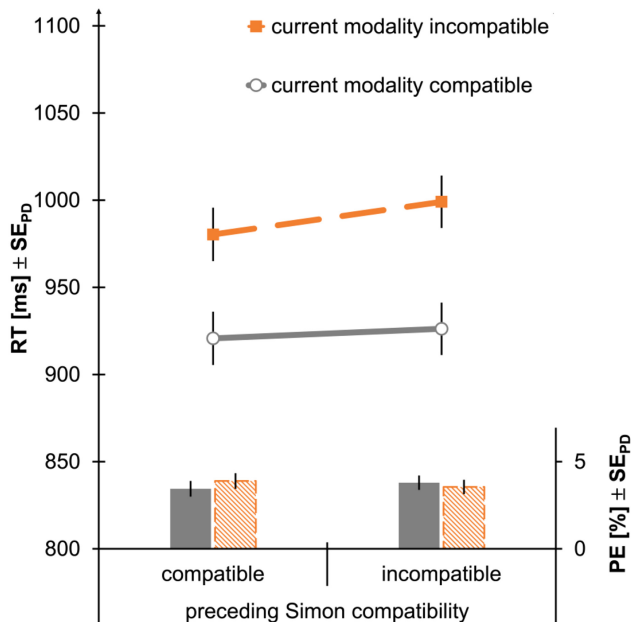
determined by more than one cause (e.g., Egner, 2014), it appears unrealistic, and was not intended, to provide a decisive test between the theories.

Furthermore, we found a Simon effect with our vibrotactile-pedal task setup. However, there was no transfer between the Simon and the modality switching task—neither did previous modality incompatibility improve performance in subsequent Simon incompatible trials, nor did previous Simon incompatibility improve performance in subsequent modality incompatible trials.⁶ This speaks against an overarching interference adaptation process. The preconditions for such a transfer are usually described as either maximally similar or

⁵ Repetition benefit for incompatible → incompatible (relative to compatible → incompatible): $t(23) = 10.22, p < .001, d_z = 2.09, \Delta = 96$ ms (Figure 5, orange line); repetition benefit for compatible → compatible (relative to incompatible → compatible): $t(23) = 1.73, p = .097, d_z = 0.35, \Delta = 20$ ms (Figure 5, gray line).

⁶ Error rates did indeed show a marginally significant interaction in the expected direction, suggesting that we might just lack statistical power to reveal between-task adaptations. The power analysis was in fact only based on the within-task adaptation, so assuming that between-task adaptations might be smaller, we cannot exclude that accuracy in the modality switching task might indeed be modulated by previous Simon (in)compatibility. While the PE results alone do not paint a very clear picture, together with the RT results (interaction $F < 1$) and the results of Experiment 2 alpha (see Appendix B, both RT and PE interaction, $F < 1$), data suggest that the overall evidence rather speaks against between-task adaptation.

Figure 7
Results of Experiment 2: Simon Task → Modality Switching Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following Simon compatible and Simon incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{pd}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

distinctly different congruency tasks (Braem et al., 2014). While we took care to design both tasks so that neither stimulus nor response modality would overlap, both tasks required a response on a left/right dimension, which may have located our tasks somewhere below maximal dissimilarity, thereby lowering the chances to find transfer, while admittedly that maximum seems hard to be determined anyway.

General Discussion

The present study explored whether modality compatibility effects are subject to sequential modulations akin to those reported for many other interference effects (Braem et al., 2019). We found robust modality compatibility effects in two experiments where the modality compatibility mapping varied trialwise. This is noteworthy for at least two reasons.

First, our results are noteworthy because previous reports of modality compatibility effects rested almost exclusively on blocked manipulations (but see Wirth et al., 2020). While a blockwise manipulation maps each stimulus modality unambiguously and constantly to a certain response modality, a trialwise manipulation introduces uncertainty regarding the response modality currently required to respond to stimuli in a certain modality. In other words, a trialwise manipulation of S–R modalities requires a certain flexibility and openness of participants to respond to possible

stimulus modalities with more than one response modality. How the trialwise manipulation of modality compatibility compares to the established blockwise manipulation is an open question at this moment (see Footnote 3), so future research might directly compare how these manipulations relate to each other.

Second, our results are noteworthy because modality compatibility effects have been reported to be weak or unreliable in single or pure task conditions (Stephan & Koch, 2010; but see Footnote 1). As the question of what qualifies as a task is controversial (Künzell et al., 2018), one could argue that participants in our setup performed a single task consisting of four randomly changing modality mappings, or similarly, that they switched between four different tasks. While the appropriate vocabulary to describe how participants conceptualized the modality switching task is debatable, it seems unequivocal that for modality incompatibility costs to arise, participants must be confronted with multiple stimulus modalities that have to be answered via multiple response modalities within a single setup (Fintor et al., 2018). What previously has been described as single task settings that hinder the emergence of modality compatibility effects are in fact those setups in which participants are confronted with only one stimulus modality and/or one response modality (Stephan & Koch, 2010). Whether mixing stimulus and response modalities already qualifies as task switching, and thereby multitasking, is argumentative, and depends on how you define multitasking. A more appropriate description of the precondition for modality compatibility effects seems to be the mixing of stimulus and response modalities within a setup rather than “multitasking” per se. Keeping several stimulus and response modalities active in working memory, as they may become relevant at any time in a constantly switching setup, may increase crosstalk between these active representations, which might be a driving force for modality compatibility effects in the first place (Schacherer & Hazeltine, 2021; Stephan & Koch, 2010). At any rate, this highlights that terms such as single tasking, multitasking, or even task per se are not necessarily helpful in describing the cognitive underpinnings involved in modality compatibility effects and should be replaced by more definite descriptions.

Furthermore, we consistently observed sequential modulations of modality compatibility effects, improving performance in repeated modality incompatible episodes compared to single instances. As demonstrated in the reanalysis of existing data (Wirth et al., 2020), it is remarkable that the sequential modulation of the modality compatibility is robust in that the effect even seems to subsist an interspersed task⁷ (see also Experiment 2 alpha in Appendix B). While we find it important to demonstrate that such sequential modulations occur in a robust manner, we can currently only speculate on what

⁷ As a follow-up exploratory analysis to Experiment 2, we also tested for a possible n-2 sequential adaptation between the modality switching task prior to and following the Simon task. Generally, this setup is suboptimal to produce any sequential effects, as there is not only a longer temporal gap between the trials of interest, but they are also interspersed with a Simon task (but see the reanalysis of Wirth et al., 2020 for a successful application of a similar approach). The analysis produced both main effects of preceding, $F(1, 23) = 5.16, p = .033, \eta_p^2 = .18$, and current modality compatibility, $F(1, 23) = 20.62, p < .001, \eta_p^2 = .47$. The interaction was marginally significant, $F(1, 23) = 3.14, p = .090, \eta_p^2 = .12$, and revealed significant repetition benefits for incompatible trials, $t(23) = 3.19, p = .004, d_z = 0.65, \Delta = 28$ ms, but no repetition benefit for compatible trials, $t(23) = 0.36, p = .720, d_z = 0.07, \Delta = 4$ ms.

cognitive processes drive this sequential modulation. Neither conflict adaptation nor episodic binding seem to explain the pattern of results reported here alone, which is in line with the idea that such sequential modulations are often determined by more than one cause (e.g., Egner, 2014). Oftentimes, sequential modulations of interference effects are attributed to a downregulation of processing irrelevant information (e.g., Botvinick et al., 2001) or upregulation of processing relevant information (Egner & Hirsch, 2005). Such increases of processing selectivity after modality incompatible events might account for the present sequential modulations as well. For example, after having encountered a modality incompatible trial, the system may focus more on the relevant stimulus information alone (here: whether the stimulus conveyed a left or right information) and disregard the stimulus modality that conveys that information.

Finally, our results showed that the level of modality (in)compatibility did not affect subsequent Simon interference, nor did the level of Simon (in)compatibility affect subsequent modality interference. This suggests that, whatever the processes behind modality compatibility sequence effects are, they operate at a local, modality-specific rather than at a global, unspecific level (for further evidence on task specific conflict adaptation, see Kiesel et al., 2006; Kunde & Stöcker, 2002). Although several reasons for a lack of transfer are conceivable, this could readily be explained by potentially different loci of the two compatibility effects investigated here: While the currently emerging consensus holds that modality compatibility effects are not, or at least not exclusively, arising from the central stage of information processing (Friedgen et al., 2022; Wirth et al., 2020), there is considerable evidence that the Simon effect resides in this central stage (McCann & Johnston, 1992). If adaptations to these types of interference had the same locus as the interferences themselves, this would consequently make across-task adaptations rather unlikely.

At any rate, the trialwise manipulation in our experimental setting and the sequential adaptation of modality incompatibility demonstrate that stimulus and response features (here: their direction and modality) are independently and adaptively weighted based on participants' previous experience of conflict. A downregulation of stimulus modality after conflict might be a candidate mechanism for the observed transient adaptation. This seem to be a promising next step in modality compatibility research that offers plenty of new and innovative research questions. Pursuing this route might ultimately provide us with a better understanding of how stimuli are translated into actions by our cognitive system.

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(Appendices follow)

Appendix A

Table A1

Possible Sequences of Experiment 1

Modality sequence	Preceding trial			Current trial			Binding sequence
	S	R	D	S	R	D	
Compatible → compatible	Visual	Manual	Left	Visual	Manual	Left	Full repetition
	Visual	Manual	Left	Auditory	Vocal	Left	Direction repetition
	Auditory	Vocal	Left	Auditory	Vocal	Left	Full repetition
	Auditory	Vocal	Left	Visual	Manual	Left	Direction repetition
	Visual	Manual	Left	Visual	Manual	Right	S + R modality repetition
	Visual	Manual	Left	Auditory	Vocal	Right	Full alternation
	Auditory	Vocal	Left	Auditory	Vocal	Right	S + R modality repetition
	Auditory	Vocal	Left	Visual	Manual	Right	Full alternation
	Visual	Manual	Right	Visual	Manual	Left	S + R modality repetition
	Visual	Manual	Right	Auditory	Vocal	Left	Full alternation
	Auditory	Vocal	Right	Auditory	Vocal	Left	S + R modality repetition
	Auditory	Vocal	Right	Visual	Manual	Left	Full alternation
	Visual	Manual	Right	Visual	Manual	Right	Full repetition
	Visual	Manual	Right	Auditory	Vocal	Right	Direction repetition
	Auditory	Vocal	Right	Auditory	Vocal	Right	Full repetition
Auditory	Vocal	Right	Visual	Manual	Right	Direction repetition	
Compatible → incompatible	Visual	Manual	Left	Visual	Vocal	Left	S modality + direction repetition
	Visual	Manual	Left	Auditory	Manual	Left	R modality + direction repetition
	Auditory	Vocal	Left	Auditory	Manual	Left	S modality + direction repetition
	Auditory	Vocal	Left	Visual	Vocal	Left	R modality + direction repetition
	Visual	Manual	Left	Visual	Vocal	Right	S modality repetition
	Visual	Manual	Left	Auditory	Manual	Right	R modality repetition
	Auditory	Vocal	Left	Auditory	Manual	Right	S modality repetition
	Auditory	Vocal	Left	Visual	Vocal	Right	R modality repetition
	Visual	Manual	Right	Visual	Vocal	Left	S modality repetition
	Visual	Manual	Right	Auditory	Manual	Left	R modality repetition
	Auditory	Vocal	Right	Auditory	Manual	Left	S modality repetition
	Auditory	Vocal	Right	Visual	Vocal	Left	R modality repetition
	Visual	Manual	Right	Visual	Vocal	Right	S modality + direction repetition
	Visual	Manual	Right	Auditory	Manual	Right	R modality + direction repetition
	Auditory	Vocal	Right	Auditory	Manual	Right	S modality + direction repetition
Auditory	Vocal	Right	Visual	Vocal	Right	R modality + direction repetition	
Incompatible → compatible	Visual	Vocal	Left	Visual	Manual	Left	S modality + direction repetition
	Visual	Vocal	Left	Auditory	Vocal	Left	R modality + direction repetition
	Auditory	Manual	Left	Auditory	Vocal	Left	S modality + direction repetition
	Auditory	Manual	Left	Visual	Manual	Left	R modality + direction repetition
	Visual	Vocal	Left	Visual	Manual	Right	S modality repetition
	Visual	Vocal	Left	Auditory	Vocal	Right	R modality repetition
	Auditory	Manual	Left	Auditory	Vocal	Right	S modality repetition
	Auditory	Manual	Left	Visual	Manual	Right	R modality repetition
	Visual	Vocal	Right	Visual	Manual	Left	S modality repetition
	Visual	Vocal	Right	Auditory	Vocal	Left	R modality repetition
	Auditory	Manual	Right	Auditory	Vocal	Left	S modality repetition
	Auditory	Manual	Right	Visual	Manual	Left	R modality repetition
	Visual	Vocal	Right	Visual	Manual	Right	S modality + direction repetition
	Visual	Vocal	Right	Auditory	Vocal	Right	R modality + direction repetition
	Auditory	Manual	Right	Auditory	Vocal	Right	S modality + direction repetition
Auditory	Manual	Right	Visual	Manual	Right	R modality + direction repetition	

(table continues)

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Table A1 (continued)

Modality sequence	Preceding trial			Current trial			Binding sequence
	S	R	D	S	R	D	
Incompatible → incompatible	Visual	Vocal	Left	Visual	Vocal	Left	Full repetition
	Visual	Vocal	Left	Auditory	Manual	Left	Direction repetition
	Auditory	Manual	Left	Auditory	Manual	Left	Full repetition
	Auditory	Manual	Left	Visual	Vocal	Left	Direction repetition
	Visual	Vocal	Left	Visual	Vocal	Right	S + R modality repetition
	Visual	Vocal	Left	Auditory	Manual	Right	Full alternation
	Auditory	Manual	Left	Auditory	Manual	Right	S + R modality repetition
	Auditory	Manual	Left	Visual	Vocal	Right	Full alternation
	Visual	Vocal	Right	Visual	Vocal	Left	S + R modality repetition
	Visual	Vocal	Right	Auditory	Manual	Left	Full alternation
	Auditory	Manual	Right	Auditory	Manual	Left	S + R modality repetition
	Auditory	Manual	Right	Visual	Vocal	Left	Full alternation
	Visual	Vocal	Right	Visual	Vocal	Right	Full repetition
	Visual	Vocal	Right	Auditory	Manual	Right	Direction repetition
	Auditory	Manual	Right	Auditory	Manual	Right	Full repetition
Auditory	Manual	Right	Visual	Vocal	Right	Direction repetition	

Note. All combinations of task-relevant features (S, R, and D) in the preceding and current trial. As Experiment 1 employed a completely random design, sequences were displayed only approximately equally often (i.e., represented in unequal frequencies), and with different frequencies for each participant. In contrast, Experiment 2 presented each sequence exactly 12 times. Sequences that were excluded in Experiment 2 alpha are marked in gray. S = stimulus modality; R = response modality; D = direction.

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Appendix B

Introduction

Before conducting Experiment 2 as reported in the main text, we ran a full sample of an alpha version of Experiment 2 that was programmed in a way that any stimulus repetitions in the AA sequences were not possible (all gray lines in Table A1 were not possible). This selection of trial sequences introduces a possible confound (as described in the discussion of Experiment 1), namely that modality repetition sequences consist of more response modality switches (two-thirds switches, one-third repetitions), and modality switch sequences now consist of more response modality repetitions (two-thirds repetitions, one-third switches).

We report these results for two reasons: First, the selection of sequences does not affect the AB and BA sequences, so the results for the transfer between the modality switching task and the Simon task are still informative. Second, this trial selection would actively counteract any modality compatibility effect and its modulation, as modality switch sequences (which produced the longest response times) benefit most from the high frequency of response modality repetitions, and modality repetition sequences (fast response times) are hindered most by the high frequency of response modality switches. Therefore, a possible main effect of modality compatibility and its sequential modulation under these conditions would speak for the robustness of the sequential adaptation effect.

Method

Participants

A new set of 24 participants was recruited. All participants ($M_{\text{age}} = 27.3$ years, $SD = 9.8$) provided written informed consent and received monetary compensation. Six participants were replaced because of high error rates (>30%, five participants) or technical issues resulting in incomplete data (one participant).

Apparatus, Stimuli, and Procedure

The setup was identical to Experiment 2, but the AA sequences excluded all stimulus repetitions (see Table A1 for a detailed overview of all excluded sequences). This affects full repetitions and stimulus modality repetitions alike. Hence, each condition still consisted of equal numbers of trials presenting visual and auditory stimuli, equal numbers of trials requiring manual and vocal responses, and an equal number of modality repetitions and modality switches, but it produced an imbalance in the ratio of response modality repetitions. Moreover, the RSI after the Simon task (BA sequence) consisted of 1,000 ms (instead of 500 ms). The AA and AB sequences still employed a 500 ms RSI.

Participants performed three blocks, each consisting of 192 AAB triplets (making 576 trials), with short breaks after each 48th triplet (after each 144th trial).

Results

Modality Switching Task → Modality Switching Task Sequences (AA)

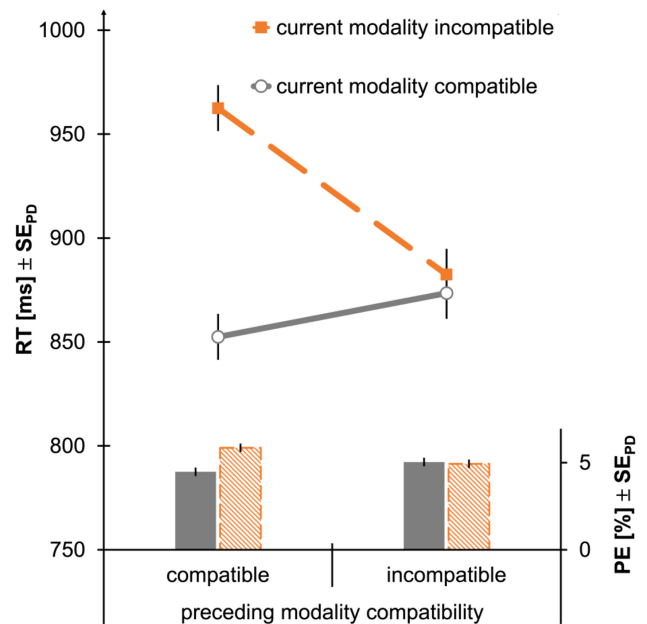
We excluded errors and omissions (20.8%), responses following errors and omissions (16.2%), the first triplet of each block (1.2%), and outliers (1.6%). Overall, 39.9% of the trials were removed. The remaining data were analyzed exactly as in the previous experiments (see Figure B1).

RTs

Responses were faster in modality compatible trials (863 ms) than in modality incompatible trials (922 ms), $F(1, 23) = 63.35$, $p < .001$, $\eta_p^2 = .73$. Moreover, responses were slightly faster after modality incompatible trials (878 ms) compared to after modality compatible trials (908 ms), $F(1, 23) = 10.69$, $p = .003$, $\eta_p^2 = .32$. Crucially, preceding and current modality compatibility interacted, $F(1, 23) = 31.19$, $p < .001$, $\eta_p^2 = .58$, indicating a large

Figure B1

Results of Experiment 2 Alpha: Modality Switching Task → Modality Switching Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{pd}), computed separately for each comparison of preceding modality compatibility (Pfister & Janczyk, 2013). See the online article for the color version of the figure.

compatibility effect after a modality compatible trial, $t(23) = 9.95$, $p < .001$, $d_z = 2.03$, $\Delta = 110$ ms, and no compatibility effect after a modality incompatible trial, $t(23) = 0.72$, $p = .478$, $d_z = 0.15$, $\Delta = 9$ ms.

PEs

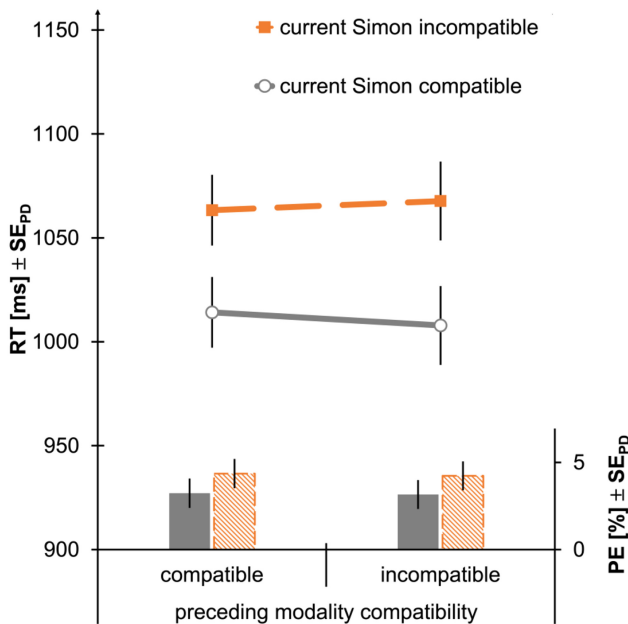
There were fewer errors in modality compatible trials (4.8%) than in modality incompatible trials (5.4%), $F(1, 23) = 10.99$, $p = .003$, $\eta_p^2 = .32$. There was no main effect of preceding modality compatibility, $F(1, 23) = 1.29$, $p = .268$, $\eta_p^2 = .05$. Crucially, preceding and current modality compatibility interacted, $F(1, 23) = 24.35$, $p < .001$, $\eta_p^2 = .51$, indicating a large compatibility effect after a modality compatible trial, $t(23) = 5.70$, $p < .001$, $d_z = 1.16$, $\Delta = 1.4\%$, but no significant difference after a modality incompatible trial, $t(23) = -0.41$, $p = .684$, $d_z = -0.08$, $\Delta = -0.1\%$.

Modality Switching Task → Simon Task Sequences (AB)

We excluded errors and omissions (15.4%), responses following errors and omissions (15.9%), the first triplet of each block (1.4%), and outliers (2.8%). Overall, 35.4% of the trials were removed. The remaining data were then analyzed via a 2×2 ANOVA with preceding modality compatibility (compatible vs. incompatible) and current Simon compatibility (compatible vs. incompatible) as within-subject factors (see Figure B2).

Figure B2

Results of Experiment 2 Alpha: Modality Switching Task → Simon Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following modality compatible and modality incompatible trials. The solid gray line/bars represent the current Simon compatible trials, and the dashed orange line/bars represent current Simon incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfiester & Janczyk, 2013). See the online article for the color version of the figure.

RTs

Responses were faster in Simon compatible trials (1,011 ms) than in incompatible trials (1,066 ms), $F(1, 23) = 9.45$, $p = .005$, $\eta_p^2 = .29$. Neither the main effect of preceding modality compatibility, $F < 1$, nor the interaction, $F(1, 23) = 2.66$, $p = .117$, $\eta_p^2 = .10$, were significant.

PEs

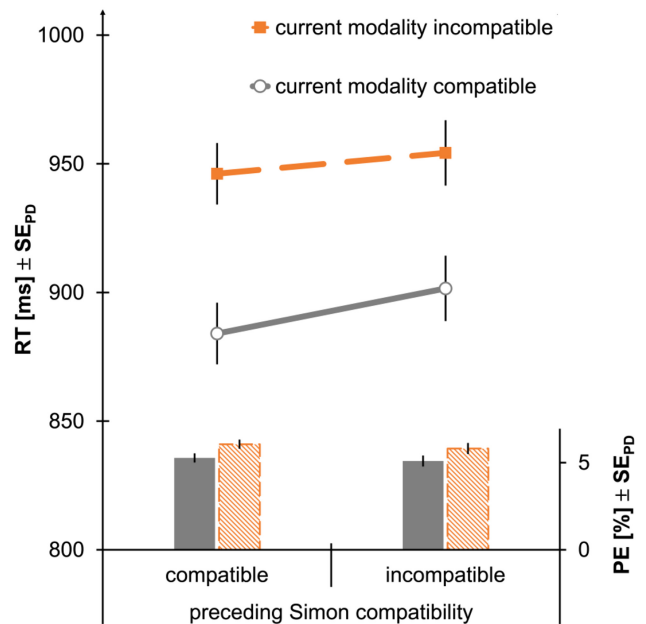
Neither the main effect of current Simon compatibility, $F(1, 23) = 1.77$, $p = .197$, $\eta_p^2 = .07$, nor any of the other effects, $F_s < 1$, were significant.

Simon Task → Modality Switching Task Sequences (BA)

We excluded errors and omissions (22.8%), responses following errors and omissions (10.9%), the first triplet of each block (1.4%), and outliers (2.6%). Overall, 37.7% of the trials were removed. The remaining data were then analyzed via a 2×2 ANOVA with preceding Simon compatibility (compatible vs. incompatible) from the previous trial and current modality compatibility (compatible vs. incompatible) as within-subject factors (see Figure B3).

Figure B3

Results of Experiment 2 Alpha: Simon Task → Modality Switching Task Sequences



Note. Response times (RTs, lines) and error rates (PEs, bars) for trials following Simon compatible and Simon incompatible trials. The solid gray line/bars represent the current modality compatible trials, and the dashed orange line/bars represent current modality incompatible trials. Error bars denote the standard error of paired differences (SE_{PD}), computed separately for each comparison of preceding modality compatibility (Pfiester & Janczyk, 2013). See the online article for the color version of the figure.

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RTs

Responses were faster in modality compatible trials (893 ms) than in modality incompatible trials (950 ms), $F(1, 23) = 29.78$, $p < .001$, $\eta_p^2 = .56$. Neither the main effect of preceding Simon compatibility, $F(1, 23) = 4.19$, $p = .052$, $\eta_p^2 = .15$, nor the interaction, $F < 1$, was significant.

PEs

There were fewer errors in modality compatible trials (5.2%) than in modality incompatible trials (5.9%), $F(1, 23) = 10.80$, $p = .003$, $\eta_p^2 = .32$. Neither the main effect of preceding Simon compatibility, $F(1, 23) = 2.71$, $p = .113$, $\eta_p^2 = .11$, nor the interaction, $F < 1$, was significant.

Discussion

Even with all stimulus repetitions removed from the AA sequences, the alpha version of Experiment 2 still produced the same results as the final version reported in the main text. This is

remarkable, considering that the trial sequences that were employed here should actively counteract any modality compatibility effect and its sequential modulation. This result therefore lets us estimate the robustness of the effect under suboptimal conditions. In contrast to Experiment 2, the modality compatibility effect does not reverse after modality incompatible trials here. We do not want to overinterpret this result, but the lack of full repetitions may have lessened the influence of episodic binding in this setup. This is of course highly speculative, and as described in the main text, the contribution of conflict adaptation and episodic binding can hardly be disentangled.

Moreover, replicating the results of the main Experiment 2, we find no transfer between the modality switching task and the Simon task in any direction. This again would suggest that these adaptation processes operate at a local, modality-specific rather than global level.

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