Decomposing multitasking costs: Reconciling generic and modality-specific accounts in task switching

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Zusammenfassung

Kognitive Kontrolle ist eine notwendige Fähigkeit, um mit den im Alltag zunehmend häufigeren Multitasking-Anforderungen umzugehen. Untersucht wird kognitive Kontrolle unter anderem mit Doppelaufgaben-Paradigmen (Teilnehmende bearbeiten zwei Aufgaben auf demselben Trial, entweder gleichzeitig oder in kurzer Abfolge) oder Aufgabenwechsel-Paradigmen (Teilnehmende bearbeiten zwei Aufgaben innerhalb eines experimentellen Blocks, sodass Aufgaben sich von einem Trial zum nächsten entweder wiederholen oder wechseln). Während kognitive Kontrolle anfänglich als generische und inhaltsfreie Prozesse konzeptualisiert wurde, "zentral" lokalisiert zwischen – und daher unabhängig von – Wahrnehmung und Handlung, wurde diese Denkweise infrage gestellt durch Forschung zur Modalitätskompatibilität.

Multitasking-Kosten werden nachweislich beeinflusst von der Ähnlichkeit der Stimulusmodalität (z.B. visuell oder auditiv) zur Modalität des antizipierten Effektes (visuell oder auditiv) der Reaktion (manuelle Reaktionen produzieren tendenziell sichtbare Effekte, vokale Reaktionen produzieren tendenziell hörbare Effekte). Der häufigste Befund besteht in größeren Multitasking-Kosten mit modalitätsinkompatiblen Mappings (visuell-vokale und auditiv-manuelle Aufgaben) als mit modalitätskompatiblen Mappings (visuell-manuelle und auditiv-vokale Aufgaben). Unter anderem wurde dies auf größeren Crosstalk zwischen den Aufgaben mit modalitätsinkompatiblen Mappings zurückgeführt, da bei diesen der antizipierte Effekt der Reaktion sich immer auf die Stimulusmodalität der entgegengesetzten Aufgabe bezieht, was zu größerer Verwirrung über die auszuführende Aufgabe führt. Während solche Befunde stark nahelegen, dass kognitive Kontrolle nicht mehr als gänzlich amodal betrachtet werden kann, ist es gleichzeitig schwierig, gänzlich auszuschließen, dass generische, inhaltsfreie Komponenten weiterhin zumindest teilweise zu den Gesamt-Multitaskingkosten beitragen könnten.

Diese Dissertation umfasst drei Aufgabenwechsel-Studien (Friedgen, Koch, Poljac, et al., 2022; Friedgen et al., 2021; Friedgen, Koch, & Stephan, 2022), welche untersucht haben, wie der bekannte Modalitätskompatibilitätseffekt weiter moduliert werden kann. Interaktionen des Modalitätskompatibilitätseffekts mit einem anderen Effekt legen nahe, dass beide ähnliche kognitive Prozesse beeinflussen; umgekehrt, wenn Modalitätskompatibilitätseffekte unabhängig von anderen Effekten gefunden werden, legt dies nahe, dass die beiden Faktoren unterschiedliche Prozesse beeinflussen. Ein gebündelter Bericht über die Befunde aller drei Studien bietet Gelegenheit, nicht nur die empirischen Ergebnisse selbst, sondern auch die entgegengesetzten theoretischen Ansätze zu integrieren, die das Thema Modalitätskompatibilität umgeben. Lokalisierung des Crosstalks kann dabei helfen, die Gesamt-Multitaskingkosten zu zerlegen in

modalitätsspezifische und generische Komponenten. Kann gezeigt werden, dass sowohl generische als auch modalitätsspezifische Einflüsse zu den Gesamt-Multitaskingkosten beitragen, würde dies erlauben, amodale Ansätze für Doppelaufgaben und Aufgabenwechsel mit modalitätsspezifischen Ansätzen ergänzend in Einklang zu bringen. Eine Integration der Ansätze würde zugleich einen Bogen spannen von traditionellen Verarbeitungsstufen-Ansätzen zur ideomotorischen Theorie, auf der die meiste Modalitätskompatibilitätsforschung basiert, aufgrund der angenommenen Abhängigkeit von antizipierten Reaktionseffekten.

In Studie I (Friedgen et al., 2021) verstärkte die Verwendung räumlich-verbaler Verarbeitungscodes und zeitlicher Diskriminationsaufgaben, im Vergleich zu räumlich-lokalisierten Verarbeitungscodes / räumlichen Diskriminationsaufgaben, den Modalitätskompatibilitätseffekt auf Mischkosten (und teilweise auch auf Wechselkosten). Diese Modulation des Modalitätskompatibilitätseffekts mag teilweise auf einer zentralen Stufe stattfinden, da räumliche vs. verbale Codes mit allen drei Verarbeitungsstufen – Perzeption, Kognition, und Handlung – in Verbindung gebracht wurden (Wickens, 2008). Studie II (Friedgen, Koch, & Stephan, 2022) zeigte getrennte Effekte von Modalitätskompatibilität und räumlicher Stimulus-Reaktions-(S-R)-Kompatibilität, jedoch keine Interaktion der beiden. Da S-R-Kompatibilität traditionell mit der Reaktionsauswahl assoziiert wird, liegt nahe, dass modalitätsspezifische Effekte zumindest teilweise vor und/oder nach einer zentralen Stufe auftreten (Wirth et al., 2020). Bedeutet dies, dass Aufgabenauswahl und Reaktionsauswahl getrennte Prozesse sind, so mag auch der in Studie III gefundene Bias (Friedgen, Koch, Poljac, et al., 2022), im freiwilligen Aufgabenwechsel einen größeren Anteil modalitätskompatibler als modalitätsinkompatibler Aufgaben auszuführen, getrennt sein von der Reaktionsauswahl. In Studie III fanden wir diesen Bias auf Auswahlraten, der zuerst von Fintor et al. (2020) berichtet wurde, in Abwesenheit eines konsistenten Modalitätskompatibilitätseffekts auf Wechselkosten. Wir entdeckten auch, dass, im Gegensatz zum Aufgaben-Wiederholungs-Bias, der Modalitätskompatibilitätsbias auf die Auswahlraten nicht weiter moduliert wurde von Manipulationen des Reaktions-Stimulus-Intervalls (RSI).

Zusammen legen diese Studien nahe, dass nicht alle modalitätsspezifischen Einflüsse auf Multitaskingkosten zentralen Reaktionsauswahl-Prozessen zugeschrieben werden können. Zugleich spricht die Robustheit von Modalitätskompatibilitätseffekten auf Multitaskingkosten weiterhin gegen die Idee gänzlich amodaler zentraler Prozesse. Zukünftige Forschung sollte sich daher verstärkt darauf konzentrieren, modalitätsspezifische und amodale Komponenten der Gesamt-Multitaskingkosten voneinander zu trennen, anstatt sich gänzlich einem Ansatz mit Vorzug über den anderen zu verschreiben.

Summary

Cognitive control is a necessary ability to deal with increasingly more common multitasking requirements in daily life. Cognitive control is investigated experimentally, among others, using dual-tasking paradigms (participants performing two tasks on the same trial, either simultaneously or in close succession) or task-switching paradigms (participants performing two tasks within an experimental block, so that tasks can either repeat or switch from one trial to the next). While cognitive control was initially conceptualised as generic, content-free processes, localised "centrally" in between – and therefore independent from – perception and action, this notion has been called into question by research on modality compatibility:

Multitasking costs have been shown to be affected by the similarity of the stimulus modality (e.g., visual or auditory) to the modality of the anticipated effect (visual or auditory) of the response (manual responses tend to produce visible effects, vocal responses tend to produce auditory effects). The most common finding consists of larger multitasking costs with modality-incompatible mappings (visual-vocal and auditory-manual tasks) than with modality-compatible mappings (visual-manual and auditory-vocal tasks). Among others, this has been attributed to larger between-task crosstalk with modality-incompatible mappings, since with two of those, the anticipated effect of the response always refers to the stimulus modality of the competing task, leading to greater task confusion. While such findings strongly suggest that cognitive control cannot be considered entirely amodal anymore, at the same time, it is hard to rule out completely that generic, content-free components might still at least be partially contributing to the overall multitasking costs.

The present dissertation encompasses three task-switching studies (Friedgen, Koch, Poljac, et al., 2022; Friedgen et al., 2021; Friedgen, Koch, & Stephan, 2022), which investigated how the known effect of modality compatibility could be further modulated. Interactions of the modality-compatibility effect with another effect suggest that both might affect similar cognitive processes; in turn, whenever modality-compatibility effects are found independently of other effects, this suggests that the two factors affect different processes. A joint report on the findings of all three studies serves as an opportunity to not only integrate the empirical results themselves, but also the opposing theoretical accounts surrounding the topic of modality compatibility. Localising crosstalk can help to decompose the overall multitasking costs into modality-specific and generic components. If both generic and modality-specific influences can be shown to contribute to the overall multitasking costs, this would allow to reconcile amodal accounts of dual tasking and task switching with the modality-specific accounts in a

complementary manner. In the same breath, a reconciliation of the accounts would also bridge the gap between traditional stage accounts and ideomotor theory, on which most modality-compatibility research is based, due to the proposed reliance on anticipated response effects.

In Study I (Friedgen et al., 2021), using spatial-verbal processing codes and temporal-discrimination task demands, in comparison to spatial-location processing codes / spatial-discrimination task demands, increased the modality-compatibility effect on mixing costs (and, to some extent, also on switch costs). This modulation of the modality-compatibility effect may in part occur at a central stage, since spatial vs. verbal processing codes have been assumed to be involved in all three processing stages – perception, cognition, and action (Wickens, 2008). Study II (Friedgen, Koch, & Stephan, 2022) yielded separate effects of modality compatibility and spatial stimulus-response (S-R) compatibility, but no interaction between the two. Since S-R compatibility has traditionally been associated with response selection, this suggests that at least part of the modality-specific effects occur before and/or after a central stage (Wirth et al., 2020). If this means that task selection and response selection are separate processes, then also the bias found in Study III (Friedgen, Koch, Poljac, et al., 2022) in voluntary task switching to perform a higher share of modality-compatible tasks than of modality-incompatible tasks may be distinct from response selection. In Study III, we found this bias on choice rates (first reported by Fintor et al., 2020) in the absence of a consistent modality-compatibility effect on switch costs. We also discovered that, in contrast to the task-repetition bias, the modality-compatibility bias on choice rates was not further modulated by manipulations of the response-stimulus interval (RSI).

Together, these studies suggest that not all modality-specific influences on multitasking costs can be attributed to central processes of response selection. At the same time, the robustness of modality-compatibility effects on multitasking costs also continues to argue against the notion of entirely amodal central processes. Future research should therefore focus more on disentangling modality-specific and amodal components to overall multitasking costs, rather than committing itself entirely to one account over another.

List of scientific publications and submitted manuscripts

Study I

Friedgen, E., Koch, I., & Stephan, D. N. (2021). Modality compatibility in task switching depends on processing codes and task demands. *Psychological Research*, *85*(6), 2346-2363. https://doi.org/10.1007/s00426-020-01412-2

Study II

Friedgen, E., Koch, I., & Stephan, D. N. (2022). Dissociating stimulus-response compatibility and modality compatibility in task switching. *Memory & Cognition*, 1-17, Online First. https://doi.org/10.3758/s13421-022-01276-4

Study III

Friedgen, E., Koch, I., Poljac, E., Liefooghe, B., & Stephan, D. N. (2022). Voluntary Task Switching is affected by modality compatibility, set size, and response-stimulus interval. Manuscript submitted for publication.

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Please note that these articles do not exactly replicate the final version published in *Psychological Research* and *Memory & Cognition.* They are not the versions of record and are therefore not suitable for citation.

Declaration of authorship

I hereby certify that I have composed this cumulative dissertation and that the present thesis is my own original work. I conceptualised the studies, programmed, conducted, and analysed the respective experiments and wrote the included papers and manuscripts. My supervisors Prof. Dr. Iring Koch and Dr. Denise N. Stephan were involved during the conceptualisation of the studies and also assisted in the constitution of the manuscripts. For the paper Friedgen, Koch, Poljac, Liefooghe, & Stephan (2022), I also collaborated with Dr. Edita Poljac and Dr. Baptist Liefooghe in conceptualising the experiments and writing the manuscript.

1 Introduction

Everyday life is rife with both opportunities and requirements for multitasking – despite ongoing "warnings" from the scientific community about its challenges, pitfalls, and even potential dangers. While some of these dangerous multitasking situations, like having a phone call while driving a car, have been discussed at length in the public eye, all the way up to leading to legal changes banning such behaviour in many places, countless other demands to engage in multitasking continue to be imposed on every individual on a daily basis. Added to that, the specific requirements of a given multitasking situations are often overlooked: We tend to be more interested in multitasking as a "generic", context-independent ability – rather than wondering under which circumstances multitasking (either performing two tasks simultaneously or switching between them) can be facilitated for anyone, and under which circumstances it cannot.

For all the danger associated with it, it is worth noting that the commonly discussed phoning-while-driving scenario consists of two tasks that could theoretically proceed independently of each other: Watching the road and responding to the changing input by indicating direction changes and turning the steering wheel (a visual-manual task), while at the same time listening to the person on the phone and responding to them with words of our own (an auditory-vocal task). Compare this to a call at the office, where you might have to read some information from a computer screen or paper document and convey it to the person on the phone (a visual-vocal task), and then switch to writing down what they are telling you over the phone in response (an auditory-manual task). Are these tasks more difficult? If so, are they also more challenging in isolation, or is it the specific combination of these tasks? Is it multitasking performance on the tasks in general (compared to performing each single one of them in isolation) that is negatively affected, and/or is it specifically the challenge of switching back and forth between them? And how is that effort of switching between the tasks in turn influenced by the specific requirements of the tasks at hand?

In an applied context, the main goal of asking such questions might be to maximise work efficiency (and make said work more profitable as a result), or to reduce the likelihood of mistakes. While reaction speed may be vital in the car-driving scenario, in many other real-life settings, prevention of errors can often be even more important, in terms of ensuring the safety of everyone involved in a given process. In a research setting, meanwhile, both response times (RT) and error rates (sometimes referred to as percentage of errors = PE) are used to make inferences about our cognitive architecture, the strategies we choose to employ to deal with

such multitasking situations, as well as about the ability of our brain to adapt to these demands, through lifelong learning experience and with practice over time. In particular, multitasking is implemented as an experimental paradigm, in form of *dual tasking* and *task switching,* in order to investigate *cognitive control.*

2 Cognitive control

Cognitive control has been referred to by many different names: Norman and Shallice (1986) referred to it as the *supervisory attentional system,* responsible for goal-oriented behaviour (see also Logan, 2003), as opposed to automatic behaviours, which compete to be selected by a *contention scheduling* mechanism, based on their level of activation. Miyake et al. (2000) used the term *executive functions,* which encompass *shifting, updating,* and *inhibition.* While the authors explicitly state that none of these three functions related to dual tasking in their study, *shifting* (between different mental sets) is basically equivalent to the general idea of task switching. *Updating* is the active manipulation of information in working memory, instead of merely storing it passively. This allows for old, no-longer task-relevant information to be substituted by new, now task-relevant information. *Inhibition* in turn describes the (deliberate) suppression of automatic responses, like in the Stroop task (see Macleod, 1991, for a review). These functions were defined by Miyake et al. (2000) as unitary, that is, a reflection of a common mechanism, and therefore generic.

A famous example of amodal cognitive control is the multiple-component working memory model by Baddeley (1992, 2010). At the heart of this model, there is the central executive, responsible for the coordination of the information that is contributed by the two (or three) "slave" systems: The visuo-spatial sketchpad, the phonological loop, and (added later) the episodic buffer. While the slave systems can hold modality-specific information, the central executive itself is one example of a cognitive control process that is considered "generic" or "amodal", that is, content-independent. There is also the idea of conflict monitoring (Botvinick et al., 2001), where on the one hand, proactive *top-down* processes (associated with the prefrontal cortex, Miller & Cohen, 2001) enable goal-driven behaviour through preparation, and on the other hand, reactive *bottom-up* processes attempt to resolve conflict when it is detected. This may be required to select the correct response, and/or to select the correct task set.

A task set is defined as the combination of mental resources required to perform a given cognitive task (Monsell, 2003; Monsell et al., 2003). Most notably, this includes representations of the stimuli, responses, and stimulus-response combinations (S-R mappings) relevant to the task (see Kiesel et al., 2010; Vandierendonck et al., 2010, for reviews) – and as such, a task set

could also include stimulus-response modalities and their respective mappings. Any type of multitasking situation consequently requires several task sets. Therefore, different types of performance costs tend to arise in form of higher response times (RT) and error rates: *dual-task costs, mixing costs,* and *switch costs*.

2.1 Multitasking

2.1.1 Dual-tasking accounts

Dual-task costs arise when two tasks must be performed on the same trial, either simultaneously or with a small delay between the presentation of the first and the second stimulus (the so-called *stimulus onset asynchrony,* SOA for short). This interval is often manipulated in the *psychological refractory period* (PRP) paradigm: The typical finding is that, the shorter the SOA, the worse performance will be on the second task, while performance on task one usually remains unaffected by these SOA manipulations (Logan & Gordon, 2001). Using the *locus-of-slack logic* (Schweickert, 1978) and/or *effect-propagation logic* (Wirth et al., 2015), effects can be localised to different phases of processing (see also Foerster et al., 2019; Janczyk & Kunde, 2020). Information processing theories commonly assume at least three such processing stages: perception, cognition, and action (Donders, 1868/1969; Sanders, 1998; Shannon, 1948; Sternberg, 1969).

The traditional theoretical explanations for these empirical observations can be roughly sorted into two main categories: Either they postulate a *structural* response-selection bottleneck (RSB), due to which processing of the second task has to wait until response selection for the first task has been completed (Pashler, 1994; Telford, 1931; Welford, 1952); or they assume a limited resource or capacity that must be divided up between the two tasks (Kahneman, 1973), with a *strategic* bottleneck-like pattern (Meyer & Kieras, 1997a, 1997b) merely reflecting one specific type of resource allocation (Navon & Miller, 2002; Tombu & Jolicoeur, 2003), that is, an "all-or-none" distribution of this common resource (100% to the first task, 0% to the second, then vice versa after completion of the first task). A *bottleneck* is a processing limitation, due to which processing of one task has to wait until processing of the same stage in another task has been completed. Specifically, the concept of a "central" bottleneck, or "central" capacity sharing, ties these accounts closely to the idea of (distinct, separate, independent) processing stages (Donders, 1868/1969; Sanders, 1998; Shannon, 1948; Sternberg, 1969).

In contrast, ideomotor accounts, like Theory of Event Coding (TEC) (Hommel et al., 2001), assume a *common* basis for perception and action: Actions are represented in form of

their perceived and anticipated events and therefore associated with each other in both directions – not just in sequential order. Perceiving the effects together with the actions that produce them binds them together in an event file, like a small episodic memory containing them both. More recently, the Binding and Retrieval in Action Control (BRAC) account suggested that the binding of action-effect associations and their retrieval from memory at a later point in time are separate processes (Frings et al., 2020). "Hard" versions of ideomotor theory assume that the anticipation of the action effect is necessary to not just initiate, but also to select the action to begin with. Note that some versions of ideomotor theory can still be considered amodal, like mirror-neuron accounts (see Shin et al., 2010, for a review), and also the event codes in TEC are considered modality-free. Ideomotor compatibility however is explicitly about the degree of similarity between stimuli and the anticipated response effects (Greenwald, 1972, 2003; Greenwald & Shulman, 1973; see also Halvorson et al., 2013; Halvorson & Hazeltine, 2015). Hence, modality-compatibility research has historically been more closely tied to ideomotor theory, even though a processing-stage logic has still been used for pragmatic reasons (e.g., Wirth et al., 2020).

Although both response-selection bottleneck models and limited-capacity models are usually considered models of dual tasking in particular, they contain certain assumptions and implications (most notably, the assumption of response selection being a "central", "generic", "amodal" process that is independent of features of the stimuli and responses themselves), which are also relevant for task switching.

2.1.2 Task-switching accounts

In task switching, meanwhile, two types of switch costs can be distinguished: "Global" switch costs (more commonly referred to as *mixing costs*) and "local" switch costs from trial to trial (oftentimes just referred to as *switch costs*). Note that, throughout the present dissertation, whenever the term *switch costs* is used without further specification, as it is common in the literature, this term specifically refers to local switch costs (see Kiesel et al., 2010, for a review).

Mixing costs are calculated as the difference in performance on repetition trials in mixed-task blocks vs. repetition trials in single-task blocks. As such, no shifting of the task set is required on any of those trials; however, in the mixed-task block, it is still necessary to maintain at least two task sets in an activated state in working memory. This additional cognitive load is what mixing costs (that is, worse performance on repetition trials in mixed-task blocks compared to single-task blocks) are therefore commonly assumed to reflect (Kiesel et al., 2010;

Rogers & Monsell, 1995). Alternatively, mixing costs might reflect the mere uncertainty about which task will be required on the upcoming trial (Poljac et al., 2009; Rubin & Meiran, 2005).

In contrast, switch costs describe the difference in performance within mixed-task blocks between switch trials and repetition trials, with performance on switch trials being worse. This performance decrement can arise either from the necessity to reconfigure the task set for the upcoming trial (Rogers & Monsell, 1995), or due to the need to overcome interference from the (other) task set of the preceding trial, in form of persisting activation or *task-set inertia* (Allport et al., 1994), which needs to be inhibited in order to perform the required task. These different explanations are commonly referred to as the *reconfiguration view* and the *interference view* (see Vandierendonck et al., 2010, for a review). With reconfiguration referring to the following trial, as opposed to interference referring to the preceding trial, reconfiguration has thus been associated with (active goal-based) preparation for the upcoming task, that is, with top-down processes; conversely, interference from previous trials can persists passively, and can arise from features of the stimuli and/or responses, which links it to bottom-up processes. However, examining preparation effects experimentally usually requires the use of cues, which are presented some time before the target stimulus.

In the task-cuing paradigm, the CSI, that is, the duration between the cue indicating the task to be performed and the target stimulus, can be manipulated. While switch costs tend to decrease with longer CSIs, usually some residual switch costs remain (Mayr & Kliegl, 2000; Rogers & Monsell, 1995). Two-stage models of preparation (see Kiesel et al., 2010, for a review) explain these residual costs by assuming that completely preparing for a task switch is impossible (Rubinstein et al., 2001): A first step of preparation can occur right after the response to the previous trial, in form of allowing the previously activated task set to decay (endogenous component of task-set reconfiguration). Consequently, this decay can already occur between the response on the previous trial and the presentation of either the next trial's stimulus (response-stimulus interval, RSI) or next trial's cue (response-cue interval, RCI). The second step of preparing for a switch, meanwhile, relies on the information present in the stimulus, and can therefore only take place after stimulus presentation on the subsequent trial (exogenous component of task-set reconfiguration).

The Voluntary Task Switching (VTS) paradigm (Arrington & Logan, 2004, 2005; see Kiesel et al., 2010; Vandierendonck et al., 2010, for reviews) was developed to study task switching and endogenous cognitive control in the *absence* of cues. Participants are presented with bivalent stimuli (that is, stimuli which are relevant to both tasks), and are free to choose

which task to perform. Usually, limitations on this freedom include the instruction to try and perform both tasks equally often, but without resorting to any kind of regularity (like A-A-B-B). Instead, the original instruction by (Arrington & Logan, 2004) tells the subjects to imagine a coin toss, so that the task is determined randomly on every single trial. Typically, participants in VTS studies tend to repeat the task they have just performed – a phenomenon known as the *task-repetition bias* (see also Mittelstädt et al., 2018). This bias can be increased after a short response-stimulus interval (RSI), whether RSI is manipulated by trial (Arrington & Logan, 2005) or by block (Arrington & Logan, 2004). Another way to increase the task-repetition bias is by adding working-memory load (Demanet et al., 2010). It is therefore assumed that the task-repetition bias results from bottom-up processes picking the most active task representation from working memory – which is usually the representation of the task that has just been performed (Orr et al., 2012). Top-down processes should consequently be required to overcome this tendency. By preoccupying these top-down processes with another task, like maintaining a letter sequence that the participant has to recall after the experimental block, the influence of bottom-up processes would then be increased, resulting in a stronger task-repetition bias.

2.1.3 Linking dual-tasking and task-switching research

Dual-task research and task-switching research have been progressing largely independently of each other for a long time. In this tradition, the present dissertation focuses on task switching, since all three studies included in it were task-switching studies. However, it should be noted that dual tasking and task switching are nowadays more often examined through a shared lens, in a common, overarching framework: A recent review by Koch et al. (2018) integrated these two fields of research, by sorting the various findings along three dimensions: structure, flexibility, and plasticity.

The *structural* perspective is concerned with questions about cognitive architecture, such as whether there are distinct processing stages (like perception, "central" processes / response selection, and motor execution), and/or whether any of these stages have structural bottlenecks that limit information processing. The *flexibility* perspective refers to the human ability to adapt behaviour, but within the confines of these structural limitations. Finally, the *plasticity* perspective refers to how learning and practice can change both structural cognitive architecture and flexible, adaptive strategies over time.

In both dual tasking and task switching, the notion of central processes being amodal by definition (Kahneman, 1973; Pashler, 1994), with their locus being *between* perception and action, has been called into question for at least the past twenty years (Schumacher et al., 2001).

In particular, a multitude of studies have shown that all three types of multitasking costs were smaller with so-called *modality-compatible* stimulus-response (S-R) modality mappings (for example, visual-manual and auditory-vocal) compared to *modality-incompatible* mappings (for example, visual-vocal and auditory-manual).

There have been several different attempts at explaining these findings – in terms of generally preferred S-R modality mappings based on different neuronal processing pathways (Ruthruff et al., 2006; Stelzel et al., 2006), or in terms of different working-memory subsystems involved in compatible vs. incompatible modality mappings (Maquestiaux et al., 2018), or in terms of increased between-task crosstalk with incompatible modality mappings due to lifelong ideomotor learning (Schacherer & Hazeltine, 2020, 2021; Stephan & Koch, 2010, 2011). Yet, what is still missing is at least a rudimentary model – ideally, one that can be applied to both dual-tasking and task-switching research – that explains where (on set- or element level, Kornblum et al., 1990; Wang & Proctor, 1996) and/or when (at which processing stage, Sanders, 1998; Shannon, 1948) in the action-selection process these modality-specific effects occur.

In the present dissertation, using these questions of the level (element level vs. set level) and "stage" (stimulus perception, response selection, response initiation, response execution) modality-specific effects occur, I am going to attempt to integrate dual-task and task-switching research (the latter including the Studies I – III) on modality compatibility. In the end, I want to raise the question of whether modality-specific accounts of multitasking costs, such as cross-talk, and the traditional notion of generic / content-free response-selection processes, necessarily have to be mutually exclusive – or whether instead, there may be both modality-specific and amodal components to multitasking costs. If the latter is the case, future research might focus on determining the respective share of these modality-specific and generic components to the overall costs, rather than trying to pit one account against another.

2.2 Central processes

2.2.1 Generic (amodal) accounts

As briefly touched on in the previous section, whenever cognitive-control or response-selection processes are referred to as "central" processes, this means they occur between perception (of the stimuli) and action / motor execution (of the response). Embedded in the word "central" is thus the assumption that information processing follows discrete stages for perception, cognition, and action in sequential order (Sanders, 1998; Shannon, 1948), assuming these

stages to be independent from one another (Donders, 1868/1969; Sternberg, 1969). This idea of distinct separate stages stands in contrast to ideomotor theory (see Shin et al., 2010, for a review). According to the ideomotor principle (James, 1890), actions are selected and initiated based on goals / expected outcomes, so that performing an action requires perceptual codes. A strict separation of perception and action stages therefore does not make sense in an ideomotor framework. Instead, ideomotor theory assumes certain response thresholds, which activation of a perceptual code needs to overcome in order for the action that produces this effect to be initiated (see Janczyk & Kunde, 2020, for a review contrasting stage and ideomotor theory).

In traditional stage logic, any of the stages can contain bottlenecks; they have been suggested at the perceptual level (Broadbent, 1958) and at the motor level (Keele, 1973). Some accounts also postulate an additional stage called *response initiation,* after *response selection* but preceding overt *response execution* (Kunde et al., 2004), so that bottlenecks could occur in this response-initiation stage, too (De Jong, 1993). However, the specific idea of a central Response-Selection Bottleneck (RSB) (Telford, 1931; Welford, 1952) has traditionally been associated with dual tasking (Pashler, 1994). This *structural* account assumes that, from the three postulated stages of perception, response selection, and response execution, the first and the last can take place concurrently, but the "central" process in the middle, response selection, cannot: It needs to be completed for task one first before response selection for task two can take place.

An alternative explanation is the notion of limited capacity: Either in form of a general limitation of cognitive resources (Kahneman, 1973), or a limitation specific to the central stage of processing (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). This is a more *flexible* account, since such a resource could be divided between different tasks: In that case, dual-task costs would arise from a flexible, strategic change, rather than from an inherent structural limitation (Meyer & Kieras, 1997a, 1997b). A bottleneck would therefore represent just one of many possible ways to share this central capacity: A rather "extreme" version, in which all of this common resource is devoted to only one task first, and none to the second task, until processing of the first task has been completed. Hence, such a bottleneck would not be structural and engrained in cognitive architecture; the bottleneck would be set up flexibly, according to a certain processing strategy.

All of these accounts have in common, though, that the limitations and resources in question are assumed to be "generic", that is, they are content-independent, not modality-specific. As such, they cannot explain a growing number of findings in both dual tasking and task

switching that demonstrated modality-specific influences in multitasking (e.g., Fintor et al., 2020; Fintor et al., 2018, 2019; Göthe et al., 2016; Hazeltine et al., 2006; Ruthruff et al., 2006; Schäffner et al., 2018; Schumacher et al., 2001; Stelzel & Schubert, 2011; Stelzel et al., 2006; Stephan & Koch, 2010, 2011, 2015, 2016; Stephan et al., 2013).

2.2.2 Modality-specific accounts

The notion of modality compatibility (Stephan & Koch, 2010, 2011) is a more abstract, generalised version of ideomotor compatibility, which was defined by Greenwald (1972) as the degree to which a stimulus resembles the sensory feedback resulting from the appropriate response. Since according to the ideomotor principle (James, 1890), actions are *selected* and/or *initiated* based on their anticipated effects, the representation of this effect gets integrated into response selection and/or initiation. The distinction between response selection and response initiation will become crucial later on; Kunde et al. (2004) define response selection as the earliest phases of the production of a movement, and response initiation as the processes directly preceding overt motor execution of the response.

An influential model of multitasking that takes modality-specific influences into account is the Multiple Resource Theory (Navon & Gopher, 1979; Wickens, 1984, 2008; Wickens et al., 1983; Wickens et al., 1984). For the sake of brevity, we will focus on Wickens's version of the account here: Like the central bottleneck account, it presumes three processing stages (perception, cognition, and responding), and like the capacity-sharing models, it assumes a limitation of resources. However, rather than there just being a single, generic resource, as the name of the model implies, there are multiple resources: This is commonly represented in the shape of a cube, with separate subsections for different stimulus modalities (visual and auditory), responses (manual and vocal), different processing codes (spatial and verbal), and a further distinction within visual processing (focal and ambient).

The model predicts better time sharing between two tasks, the more that they rely on different, separate resources. Applying this to a modality-compatible multitasking condition, time sharing should be better because one task uses the specific resources for visual stimuli and manual responses, whereas the other task uses the specific resources for auditory stimuli and vocal responses. However, by itself, the same would be true for modality-incompatible conditions: One task would use the separate resources for visual stimuli and vocal responses, the other task the resources for auditory stimuli and manual responses. Only when the modalities of the anticipated response effects are added in, it becomes clear how modality-incompatible tasks would use more resources and, crucially, partly overlapping resources, compared to

modality-compatible tasks: Since vocal responses have auditory effects, and manual responses tend to have (among others) visible effects, a visual-vocal task would still use resources for auditory processing, too, to process the anticipated effect of the vocal response; and likewise, an auditory-manual task would still use resources for visual processing, too, to process the anticipated effect of the manual response. With modality-compatible mappings, meanwhile, the anticipated response effect in a visual-manual task would still only require visual resources, and the anticipated response effect in an auditory-vocal task would still only require auditory resources. Hence, time sharing with modality-incompatible tasks should be worse.

Note that this would be a modification of the Multiple Resource account, making it more comparable to our own crosstalk account (see below): In Wickens's model (2008), the modalities dimension is restricted to perception, and does not extend to the cognition or responding stage. However, the processing codes dimension (spatial vs. verbal) does extend from perception to cognition, and also to action, with manual responses using the same resources as spatial processing, and vocal responses using the same resources as verbal processing. Thus, if interactions can be found between a manipulation of spatial vs. verbal processing codes and modality-compatibility effects, by extension this would entail the possibility of the modalities dimension at least partially affecting the central stage of cognition, too. Indeed, such interactions of modality-compatibility effects with manipulations of the spatial vs. verbal processing codes were found in Study I (see also Göthe et al., 2016; Schäffner et al., 2018).

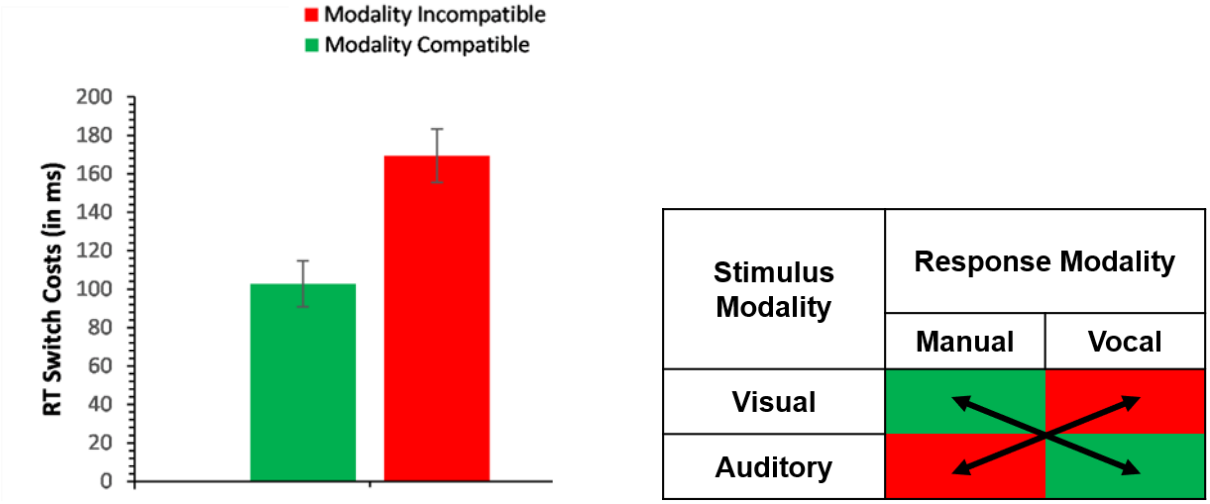
In a similar manner to Multiple-Resource Theory, modality-compatibility effects on multitasking costs can be explained in terms of the multiple-component working-memory model by Baddeley (1992, 2010). I will address this line of thought later with regards to Study I, where we discussed it in detail (and, again, slightly modified it, in order to integrate it with the crosstalk account). Working-memory accounts have special relevance for modality-compatibility effects on mixing costs, since mixing costs are assumed to reflect the higher workload of maintaining two task sets in an activated state in a multitasking setting, rather than just one, in a single-task setting. The main restriction of working-memory accounts is that they can explain the modality-compatibility effects themselves, but not where the cognitive architecture that causes them comes from.

The *crosstalk* account is the explanation which currently seems to explain the biggest share of findings on modality compatibility (e.g., Fintor et al., 2018; Schacherer & Hazeltine, 2021; Stephan & Koch, 2010, 2011). Crosstalk is a term to describe any case in which the processing requirements of one task overlap and interfere with the processing requirements of

another task (Navon & Miller, 1987). Thus, rather than attributing modality-compatibility effects to a general preference for certain stimulus-response modality mappings (e.g., Ruthruff et al., 2006), the crosstalk account attributes them to interference between the representations involved in the central processes (Schacherer & Hazeltine, 2021).

Figure 1

The typical finding of larger switch costs (left) when switching between modality-incompatible stimulus-response mappings (red) compared to switching between modality-compatible mappings (green). This can be explained by the logic of crosstalk (right). RT = response time; error bars represent the standard error of the mean. Data taken from Study II, Experiment 1.



If there were a general preference for, e.g., a compatible visual-manual modality mapping over an incompatible visual-vocal mapping, effects of modality compatibility should also be found a) when comparing single-task blocks with those respective mappings, and b) in mixed-task blocks featuring one compatible and one incompatible modality mapping. However, neither seems to be the case: Effects of modality compatibility in single-task blocks are usually not found (Fintor et al., 2019; Stephan & Koch, 2010, 2015, 2016), and when they are, they sometimes also point in the opposite direction, with worse performance on the modality-compatible single-task than on the modality-incompatible single task (Fintor et al., 2019; Stephan & Koch, 2011)[1].

The crosstalk account now posits that the main reason why multitasking costs tend to be larger with two incompatible modality mappings, compared to two compatible modality

[1] The study by Fintor et al. (2019) found no single-task difference between modality-compatibility conditions in Experiment 1, found them in Experiment 2, but this effect was only significant in error rates; the numerical trend in RT went in the opposite direction, hence the authors suggested a speed-accuracy trade-off.

mappings, is rooted in the modalities of the anticipated response effects: Throughout our lives, we have had the experience that manual actions tend to lead to tactile (Stephan & Koch, 2015) and visible changes in the environment (as do pedal actions, since walking takes us into a different visual environment, Stephan et al., 2021), whereas vocal actions have auditory effects (hearing the sound of our own voice). In a modality-compatible multitasking setting, the visual-manual task thus has an anticipated response effect in the same modality as the stimulus (visual), and the auditory-vocal task also has an anticipated response effect in the same modality as the stimulus (auditory). In modality-incompatible multitasking contexts, meanwhile, with the visual-vocal task, the anticipated effect of the vocal response is still in the auditory modality, therefore refers to the competing auditory-manual task; in turn, with the auditory-manual task, the anticipated effect of the manual response is still in the visual modality, therefore refers to the competing visual-vocal task. This leads to greater *between-task crosstalk,* or between-task confusion, with incompatible modality mappings, compared to compatible modality mappings. On an empirical level, this can be observed in form of larger dual-task costs, mixing costs, and/or switch costs, respectively, with incompatible modality mappings – but, as just mentioned, usually without any modality-compatibility effects on single-task performance.

One notable exception is the study by Fintor et al. (2018), in which modality-compatibility effects in the expected direction (=better performance on modality-compatible tasks) indeed also appeared in single-task blocks. However, this particular study supports the crosstalk account (or rather: rules out the alternative "preferred-mappings" account) in another way: The authors systematically varied transitions of stimulus modality and response modality. In one experiment, both stimulus and response modality switched. In a second experiment, response modality was varied (manual or vocal), while stimulus modality remained constant within a given block (visual or auditory, in counterbalanced order). In a third experiment, stimulus modality was varied (visual or auditory), while response modality remained constant within a given block (manual or vocal, in counterbalanced order). Significantly larger switch costs were only found when participants had to switch between *two* incompatible modality mappings, compared to switching between *two* compatible modality mappings – not when they had to switch between one incompatible and one compatible modality mapping.

This fits the predictions of the crosstalk account: Only when two task sets have to be maintained in an activated state in working memory can the representations of their anticipated effects interfere with each other. More recently, Schacherer and Hazeltine (2020) further strengthened this account in dual tasking, by using induced action effects, rather than merely

the natural consequences of manual actions (visible effects) and vocal actions (auditory effects): As expected, action effects that were modality-compatible with the respective stimuli elicited smaller dual-task costs than modality-incompatible pairings of stimulus and induced action effect. The incorporation of effect anticipation into "central" processes (which may include both response selection and response initiation) is also suggested by research on response-effect compatibility (e.g., Földes et al., 2017; Keller & Koch, 2008; Kunde, 2001): In such paradigms, the effects following a response have been shown to influence speed and accuracy on a given task, even though these effects only occur *after* the response has already been executed. Ideomotor compatibility by itself is a stricter concept than modality compatibility (Stephan & Koch, 2011).

As a more applied example, if somebody is sworn into an office for which they are required to take an oath, they are usually asked to repeat the verbatim of the oath word for word after somebody else. As such, the anticipated effect of the sworn-in person's vocal response is not only identical with the stimulus in terms of both being in the auditory modality, but also in terms of stimulus and response identity. Hence, such a situation would be both ideomotor-compatible and modality-compatible. Meanwhile, hearing a word from a memorised list, and then responding by saying "yes" to confirm that this word was indeed part of the list, would still be modality-compatible, since both the stimulus and the anticipated response effect are in the auditory modality. However, it would not be considered ideomotor-compatible, since stimulus identity differs much more from response identity.

Note that such distinctions are always relative, not absolute. Meaning, one is modality-compatible to a greater degree than another. For example, relatively speaking, tactile stimuli have been shown to be even more modality-compatible with manual responses, compared to visual stimuli (Stephan & Koch, 2015). On a related note, the modality-compatibility effect on switch costs can also be replicated when replacing manual responses with pedal responses (Stephan et al., 2021). The following section will provide a more detailed overview of the findings on modality-specific influences in both dual tasking and task switching.

2.3 Previous research on modality compatibility

2.3.1 Modality-specific influences in dual tasking

In the wake of findings of perfect time sharing of two simultaneous tasks if they were ideomotor compatible (Greenwald, 1972, 2003; Greenwald & Shulman, 1973), the first dual-tasking studies on modality compatibility (before the term was even being used) were practice

studies, and would therefore be classified as most relevant to the *plasticity* aspect of multitasking (Koch et al., 2018). Famously, Schumacher et al. (2001) found that, with a visual-manual and an auditory-vocal task, perfect time sharing could be achieved after extensive practice – that is, dual-task costs vanished completely with what we now refer to as modality-compatible mappings. Hazeltine et al. (2002) reported similar findings, and suggested that after practice, the visual-manual and auditory-vocal task no longer shared a bottleneck. Note that in these experiments, stimuli for both tasks were presented at the same time, and participants were instructed to prioritise both tasks equally. Hazeltine et al. (2006) then suggested that dual-task costs in their study were not caused by a bottleneck for central processes, but by their content. Ruthruff et al. (2006) proposed that binding manual responses to visual stimuli and binding vocal responses to auditory stimuli might represent a natural tendency, based on common real-world experience. Stelzel et al. (2006) supported this view, and linked it to neuroscientific evidence for dedicated processing pathways for a visuo-spatial system (Milner & Goodale, 1995) and an auditory-vocal system (Liberman & Mattingly, 1989). Additionally, Stelzel et al. (2006) reported increased activation of the inferior frontal sulcus (IFS) with the higher dual-task costs due to incompatible modality mappings. Furthermore, Göthe et al. (2016) demonstrated that dual-task costs could be eliminated when vocal responses were paired up with verbal stimuli, given the tight ideomotor binding between speech and verbal material.

Yet, even in multitasking contexts featuring different modality mappings, not all practice is modality-specific: Liepelt, Strobach, et al. (2011) had one group of participants practice single tasks, and had the other group of participants practice single tasks and dual tasks. They found that the latter, hybrid approach yielded the strongest reduction in dual task costs. The authors suggested that hybrid practice allowed participants to acquire an intertask coordination (ITC) skill, which consequently had to be at least in part generic – not specific to the tasks involved. Conversely, Liepelt, Fischer, et al. (2011) examined whether time sharing as reported in the study by Schumacher et al. (2001) would generalise to a visual-manual task and an auditory-pedal task, but found no evidence of such a generalisation. Note though that a recent study in task-switching suggested that pedal responses might be more modality-compatible with visual stimuli than with auditory stimuli (Stephan et al., 2021). Therefore, perhaps a generalisation of time sharing would have been possible by combining a visual-pedal task with an auditory-vocal task instead.

Other findings include Stelzel and Schubert (2011), who showed that modality-compatibility effects on dual-task costs can be replicated even with highly S-R compatible mappings

(which have been used much more frequently in related task-switching studies, as we will discuss in the next section). Stelzel et al. (2017) discovered an interaction of modality compatibility with postural control in older adults; since postural control is assumed to require attention (e.g. Stephan et al., 2018; see Woollacott & Shumway-Cook, 2002, for a review), this finding adds further credibility to working-memory accounts for modality compatibility (of which the crosstalk account, Stephan & Koch, 2010; 2011, is essentially a more specific version, as we shall see later).

Finally, Wirth and colleagues conducted studies attempting to localise where influences of effect anticipation, including modality-compatibility effects, take place in dual tasking. Wirth et al. (2015) reported evidence for effect anticipation occurring during the central bottleneck. Later, Wirth et al. (2020) first ruled out that the that the modality-compatibility effect in their study occurred in the post-central stage in their Experiment 1 – that is, they concluded it must have occurred either in the central stage or the pre-central stage. Experiment 2 and 3 then provided support for the modality-compatibility effect occurring in the pre-central stage. However, the authors noted they still could not completely rule out an at least partial contribution of the central stage to the overall modality-compatibility effect.

2.3.2 Modality-specific influences in task switching

Inspired by the multitude of findings about modality-specific effects in dual-task research, Stephan and Koch performed a series of task-switching studies, in which they repeatedly found modality-specific effects on switch costs (Stephan & Koch, 2010, 2011, 2015, 2016): Specifically, in blocks in which participants had to switch between a visual-manual task and an auditory-vocal task (termed a *modality-compatible* condition), switch costs for RT and error rates were lower than for blocks in which participants had to switch between a visual-vocal task and an auditory-manual task (termed a *modality-incompatible* condition). Note that Stephan and Koch (2015) also extended this pattern to a setup in which visual stimuli were replaced with tactile stimuli (that is, participants switched between modality-compatible tactile-manual and auditory-vocal tasks, or they switched between modality-incompatible tactile-vocal and auditory-manual tasks): For the group using tactile stimuli, this modality-compatibility effect on switch costs was in fact even larger than for the group using visual stimuli. Meanwhile, another study by Stephan et al. (2013) demonstrated that oculomotor responses were in fact *not* more compatible with visual stimuli, as one might suspect; rather, eye movements in particular seem to be supra-modal, that is, equally modality-compatible with both visual and auditory stimuli. This might be, among others, for evolutionary purposes, since both visual and auditory

stimuli can equally require fast visual orientation, e.g., in order to detect potentially approaching predators. More recently, Stephan et al. (2021) extended this field even further, by replicating the modality-compatibility effect on switch costs with pedal responses instead of manual responses. All of these findings primarily concern the *structural* aspect of multitasking (Koch et al., 2018).

Based on the proposition from dual-task research that modality-compatible mappings represent a general preference to bind certain stimulus and response modalities together – visual-manual rather than visual-vocal, and auditory-vocal rather than auditory-manual – one might expect that switching from a modality-compatible task to a modality-incompatible task should be harder than switching from a modality-incompatible task to a modality-compatible task. However, as touched on before, Fintor et al. (2018) demonstrated that, in order for the modality-compatibility effect on switch costs to occur, there must be variability of modality at both the stimulus level and the response level: Only then, a block featuring switches between *two* modality-compatible mappings will feature lower switch costs than a block featuring switches between *two* modality-incompatible mappings. These findings suggest that the *combination* of stimulus- and response *mappings* seems to be the crucial factor, rather than arbitrary differences between individual combinations of stimulus- and response modality.

The role of modality compatibility for the *flexibility* aspect of multitasking has been investigated in two main paradigms: the task-cuing paradigm (Fintor et al., 2019) and Voluntary Task Switching (Fintor et al., 2020). In the task-cuing paradigm, the influence of modality compatibility on switch costs vanished after a long cue-stimulus interval (CSI); in voluntary task switching, when participants were free to choose whether to respond manually or vocally to visual and auditory stimuli, they formed a greater share of modality-compatible mappings than of modality-incompatible mappings. This is a finding that we have been able to replicate in two experiments in Study III. Fintor et al. (2019) showed that residual switch costs can vanish, both with unimodal cues (compatible with the stimulus modality) and with bimodal abstract cues. As a consequence, with no switch costs left, the modality-compatibility effect on switch costs disappeared at long CSIs, too – that is, the decrease in switch costs at long CSIs was not further modulated by modality compatibility. The authors therefore suggested that preparation and modality compatibility might be associated with separate mechanisms.

In the VTS paradigm (Arrington & Logan, 2004, 2005), when allowing participants to freely choose whether to respond manually or vocally to visual and auditory stimuli, Fintor et al. (2020) did not only find that participants tended to form a higher share of modality-

compatible mappings (visual-manual and auditory-vocal) than of modality-incompatible mappings (visual-vocal and auditory-manual); but also, the finding of larger switch costs with modality-incompatible mappings was still present. So far, this modality-compatibility bias on task choice rates was only reported in this single study, consisting of only one experiment. Hence, in our own Study III, we both replicated and extended this finding.

Note that Fintor et al. (2020) used the same spatial-discrimination task as Stephan and Koch (2010), meaning that there was a high degree of dimensional overlap (Kornblum et al., 1990) between stimuli and responses – they all referred to the locations left or right. Stephan and Koch (2011) replicated the modality-compatibility effect on switch costs, even without such dimensional overlap. However, Schacherer and Hazeltine (2019) then proceeded to also eliminate conceptual overlap between stimuli and responses – by ensuring that no combination of stimuli and responses would both feature, for example, alphanumeric characters at the same time – and demonstrated that without such conceptual overlap, the modality-compatibility effect on switch costs could be eliminated. Meanwhile the modality-compatibility effect on mixing costs (larger mixing costs with incompatible modality mappings) remained robust, even without conceptual overlap. Another way to eliminate the costs of switching between different modality mappings – and to thereby eliminate the modality-compatibility effect on such switch costs as a result – has been to use cues (unimodal or bimodal), and a sufficiently long cue-stimulus interval (CSI), as demonstrated by (Fintor et al., 2019).

Finally, with regards to the *plasticity* dimension, Stephan et al. (2022) showed that the switch costs in modality-incompatible conditions could also be reduced by having participants practice the individual component tasks (visual-vocal and auditory-manual), even if only for a short period of time. The authors suggested that these novel modality-incompatible S-R associations can override the previously established modality-compatible associations in the short-term.

2.3.3 The role of the anticipation of induced response effects

In a series of five experiments, Schacherer and Hazeltine (2020) directly tested the idea that modality-compatibility effects are based on the anticipation of response effects. For this purpose, the authors used experimentally induced response effects (for example, a dog's bark as an auditory stimulus, and the spoken word "dog" as an induced auditory response effect, but the vocal response was a different, unrelated word), in addition to the unmanipulated natural consequences of manual and vocal responses (since it is difficult to disable the natural feedback of hearing the sound of one's own voice when speaking). Schacherer and Hazeltine (2020)

found smaller dual-task costs when stimuli and induced action effects were modality-compatible – irrespective of whether responses for both tasks were just manual (Experiment 3), or modality-compatible (visual-manual and auditory-vocal, Experiment 1). Conversely, when stimulus-response mappings were modality-incompatible (visual-vocal and auditory-manual, Experiment 2), dual-task costs were similar for modality-compatible and modality-incompatible induced action effects, suggesting that both the natural, unmanipulated response effects and the induced, manipulated response effects had an impact on dual-task costs. The authors replicated the finding of smaller dual-task costs with modality-compatible pairings of stimulus and induced effects, both with reduced physical resemblance between stimulus and response-effect codes (using images of roads and ponds as visual stimuli, a dog's bark and a cat's meow as auditory stimuli, Experiment 4) and with reduced conceptual overlap (for example, pairing the dog's bark with an unrelated sound, Experiment 5). The latter is important, since a previous study of the same authors (Schacherer & Hazeltine, 2019) showed that reducing conceptual overlap can make the modality-compatibility effect on switch costs disappear. In a later study, the authors concluded that crosstalk, based on effect anticipation, is indeed the currently more likely explanation for multitasking costs than resource competition (Schacherer & Hazeltine, 2021).

Effect anticipation has been associated with both response selection and response initiation (Kunde et al., 2004; Wirth et al., 2015). For example, Hommel (1993a) demonstrated that the Simon effect – a spatial S-R compatibility effect (Fitts & Deininger, 1954; Fitts & Seeger, 1953), and therefore assumed to occur at response selection (Proctor & Vu, 2006) – can be inverted through the use of effect anticipation, by telling participants to make one of two lamps light up that were connected to the spatial response on the opposite side (left or right). If we conceptualise response selection as a central process, but response initiation as a post-central process, the importance of this distinction becomes apparent. This is why, in order to determine to which degree central processes are modality specific vs. generic, we need to localise where in the response-production process modality-specific crosstalk might be occurring. The Studies I – III in the present dissertation can provide further insight into this debate.

3. Findings of the present dissertation

3.1 Summary of empirical findings

In three studies, we examined novel manipulations of the known effects of modality compatibility in task switching. Study I demonstrated that the influence of modality compatibility on mixing costs (and, to a lesser extent, switch costs) can be further modulated by the

processing codes (spatial-location stimuli vs. spatial-verbal stimuli) and the task demands (spatial discrimination vs. temporal discrimination) involved. Study II replicated effects of modality compatibility on switch costs and main effects of spatial S-R compatibility, but suggested that these two different types of compatibility did not interact, with moderate but consistent evidence for this null hypothesis. Study III replicated the bias for participants to form a greater share of modality-compatible mappings than of modality-incompatible mappings in voluntary task switching – a bias which had only been found in one previous study so far. Additionally, we manipulated the RSI (short or long). On trials following short RSIs, the task-repetition biases were stronger, as expected (that is, participants were more likely to not only repeat the response modality, manual or vocal, but to also repeat the entire S-R modality mapping, e.g., visual-manual, visual-manual). However, the share of modality-compatible mappings formed was not larger after short RSIs than after long RSIs. For a more detailed overview of the results, see the following table.

Table 1

Overview of findings from the studies Friedgen, Koch, & Stephan (2020, 2022) and Friedgen, Koch, Poljac, Liefooghe, & Stephan (2022)

Study	Main Findings	Stimuli
Friedgen, Koch, & Stephan (2021)	- Larger modality-compatibility effect on mixing costs with spatial-verbal processing codes and temporal-discrimination task demands compared to spatial-location processing codes / task demands - Speed-accuracy trade-off for modality-compatibility effect on switch costs (specifically for spatial-location processing codes / task demands)	- central written or binaural spoken words “left” and “right” (spatial-verbal task, Experiment 1) - central white diamonds or binaural sinus tones for 100 ms vs. 500 ms (temporal-discrimination task, Experiment 2) - left or right white diamonds or sinus tones (spatial-location / spatial-discrimination task, Experiment 1 and 2)
Friedgen, Koch, & Stephan (2022)	- No interaction between modality compatibility and S-R compatibility on switch costs - Larger switch costs in the modality-incompatible condition than in the	- left or right colour words “blue” and “red”; left and right responses to colour meaning, stimulus location task-irrelevant (Simon task, Experiment 1)

	modality-compatible condition in Experiment 1 (Simon task) - Speed-accuracy trade-off for modality compatibility effect on switch costs in Experiment 2 (spatial-discrimination task)	- left or right white diamonds or sinus tones; left and right responses to stimulus location, stimulus location task-relevant (spatial S-R compatibility task, Experiment 2)
Friedgen, Koch, Poljac, Liefooghe, & Stephan (2022)	- Voluntary Task Switching: participants chose to form a greater share of modality-compatible mappings than modality-incompatible mappings - Bias to repeat the response modality and repeat the entire mapping - Both repetition biases increased after short response-stimulus intervals (RSI), whereas the bias to form more modality-compatible mappings did not increase after short RSIs	- central written or binaural spoken number words "one", "two", "three", "four"; responses one of four horizontal keypresses or spoken letters "A", "B", "C", "D" (free task choice)

3.2 Extending the crosstalk account

Between-task crosstalk can be further modulated in various ways. For example, Schäffner et al. (2018) found that the modality-compatibility effect on switch costs was enlarged with verbal input processing codes compared to non-verbal input processing codes (see Göthe et al., 2016 for related findings in dual-task research). The authors attributed this to stronger ideomotor linkages with verbal stimuli, since the effects of vocal responses are not only in the auditory modality, but also usually verbal in nature. In Study I, we aimed at investigating this finding further. Note that the task in the study by Schäffner et al. (2018) required semantic categorisation of the stimuli into "living" and "non-living", but with spatial responses (left or right keypresses or saying the words "left" and "right"). In contrast, Experiment 1 of Study I featured spatial discrimination throughout, either with spatial-verbal stimuli (the written or spoken words "left" and "right", presented centrally on screen / binaurally via headphones), or with spatial-non-verbal, that is, spatial-location stimuli (white diamond shapes presented left and right on screen, or beep tones presented on the left or right ear via headphones). Responses were the same in both conditions, that is, left or right keypresses or saying the words "left" and "right". This means that in the block with spatial-verbal stimuli, vocal responses were ideomotor compatible with auditory stimuli (Greenwald, 1972). Furthermore, Experiment 1 of Study I

as a whole featured more dimensional overlap (Kornblum et al., 1990) than in the study by Schäffner et al. (2018), since all stimuli and responses referred to the spatial domain (left or right).

Dimensional overlap refers to element-level compatibility, like in spatial S-R compatibility tasks (Fitts & Deininger, 1954; Fitts & Seeger, 1953). Traditionally, these S-R compatibility effects have been associated with response selection (an issue I will address later with regards to Study II). Meanwhile, there is also the issue of conceptual overlap, which occurs at the set level. The effect of modality compatibility on switch costs has been replicated without dimensional overlap between stimuli and responses: Stephan and Koch (2011) had participants say "A" or "eins" (German for "one") or press the Ctrl and Alt keys in response to the spoken letters "X" and "M" or square and circle shapes on screen. However, Schacherer and Hazeltine (2019) pointed out that this task still featured conceptual overlap, in terms of all stimuli and responses in the auditory-vocal task being alphanumeric characters. When Schacherer and Hazeltine (2019) also reduced conceptual overlap in all tasks, the effect of modality compatibility on switch costs vanished. Nevertheless, modality compatibility still influenced mixing costs, which were higher in the modality-incompatible condition.

In Study I, we showed that the influence of modality compatibility on mixing costs could be further modulated by using verbal processing codes, compared to the spatial-location processing codes in the task devised by (Stephan & Koch, 2010). We found a similar pattern in Experiment 2 of Study I, when we compared performance on the baseline of the spatial-discrimination task against a temporal-discrimination task, with the latter leading to a larger modality-compatibility effect on mixing costs, as well[2]. Much like with verbal processing codes, we attributed this modulation to a strengthening of the auditory-vocal coupling with temporal-discrimination task demands: According to the modality-appropriateness hypothesis (Freides, 1974; Talsma et al., 2010; Welch & Warren, 1980), in multitasking settings, audition is the superior modality to vision for temporal discrimination, whereas vision is superior for spatial discrimination. This idea is backed up by findings on crossmodal task switching, with auditory dominance in temporal discrimination (Lukas et al., 2014), and visual dominance in spatial discrimination (Lukas et al., 2010).

[2] Note that Study I found an unclear speed-accuracy trade-off for the modality-compatibility effect on switch costs with the spatial-discrimination task in both experiments.

3.2.1 Integration of the crosstalk account and working-memory account

In Study I, we found a larger effect of modality compatibility on mixing costs (that is, higher mixing costs in the modality-incompatible condition) in blocks involving spatial-verbal processing codes (the written or spoken words "left" and "right" in German, Experiment 1) or temporal-discrimination task demands (white diamond shapes on screen and beep tones via headphones that could either have a short or long duration, Experiment 2). In both experiments, the respective manipulation was compared to blocks involving spatial-location processing codes, that is, spatial-discrimination task demands (as in Stephan & Koch, 2010). Schacherer and Hazeltine (2019) demonstrated that the effect of modality compatibility on mixing costs seems to be more robust than the effect of modality compatibility on switch costs, which can be modulated by other factors, such as conceptual overlap. Mixing costs are assumed to reflect either the uncertainty about the upcoming task (Poljac et al., 2009; Rubin & Meiran, 2005), or the requirement to maintain two task sets in an activated state in working memory instead of just one (Los, 1996). Therefore, in the discussion of Study I, we integrated two of the accounts that could explain the modality-compatibility effect on mixing costs: the working-memory account by Maquestiaux et al. (2018) and the crosstalk account by Stephan and Koch (2010, 2011). The reasoning is as follows:

In a modality-compatible multitasking setting, a visual-manual task would only rely on the visuo-spatial sketchpad, since both the stimulus modality and the modality of the anticipated response effect refer to it; likewise, an auditory-vocal task would only rely on the phonological loop. In a modality-incompatible multitasking setting, though, both tasks would refer to both subsystems of working memory: The visual-vocal task would involve the visuo-spatial sketchpad for visual stimulus processing, and the phonological loop for the processing of the anticipated auditory response effect; in turn, the auditory-manual task would refer to the phonological loop for auditory stimulus processing, and the visuo-spatial sketchpad for processing of the anticipated visual response effect.

Note that, by itself, the working-memory account for modality-compatibility effects in multitasking (Maquestiaux et al., 2018) is entirely *structural;* it does not pose the question of where these structural limitations *come from.* This differs from the crosstalk account (Stephan & Koch, 2010, 2011), which is more specific with regards to the origin of the structural limitations: Namely, the crosstalk account assumes that the modality-compatible associations result from lifelong ideomotor learning – the everyday experience that manual actions tend to have visible effects, and that vocal actions tend to have auditory effects. Through this mechanism

based on lifelong ideomotor learning, the *plasticity* dimension of multitasking creates a *structural* constraint, which then in turn biases the *flexible* processes of task switching.

Due to its ideomotor tradition (Greenwald, 1970, 1972; James, 1890), the crosstalk account also represents a departure from the notion of distinct, strictly separate processing stages, as assumed by both the bottleneck accounts (Pashler, 1994) and the Multiple Resource theory (Wickens, 2008; Wickens et al., 1983). Rather, perception, response selection, and action are regarded as one continuous process (Hommel, 1997; Kunde et al., 2004), relying on the same codes for perception and action, as in the Theory of Event Coding (Hommel et al., 2001). This will become crucial later, as I discuss the localisation of where modality-specific between-task crosstalk might be occurring.

3.3 Forced-Choice vs. Voluntary Task Switching

In all studies included in the present dissertation, there were occasional local speed-accuracy trade-offs for the modality-compatibility effect on switch costs: In RT, switch costs were larger in the modality-compatible condition, whereas in errors, switch costs were larger in the modality-incompatible condition, as expected based on previous studies. In Study I, these trade-offs were featured in the spatial-discrimination task, to which the novel manipulations of spatial-verbal processing codes (Experiment 1) and temporal-discrimination task demands (Experiment 2) were being compared. In Study II, Experiment 1 was a Simon task, yielding the modality-compatibility effect in the expected direction (larger switch costs in the modality-incompatible condition) in both RT and error rates (no trade-off); however, Experiment 2, again featuring the spatial discrimination task, yielded such a trade-off. In Study III, in the analysis of inverse efficiency scores (IES), a joint measure of speed and accuracy (Liesefeld & Janczyk, 2019; Vandierendonck, 2017, 2018), the effect of modality compatibility on switch costs disappeared entirely. Before getting to my proposed explanation for the repeated finding of speed-accuracy trade-offs in the forced-choice experiments, I shall first address Study III, since it differs from the remaining studies in a crucial way.

3.3.1 Modality compatibility in Voluntary Task Switching

Study III was a VTS study, only the second one on modality compatibility to date; in the very first study on modality compatibility in VTS (Fintor et al., 2020), the authors were not even sure in advance whether the modality-compatibility effect on switch costs would arise in VTS in the first place. There are reasons to doubt that modality-compatibility effects on switch costs are a common occurrence in VTS, since the freedom for the participant to select the

individual modality mappings themselves means that all four S-R modality mappings (visual-manual, auditory-vocal, visual-vocal, auditory-manual) will be featured within the same block – rather than just two modality-compatible mappings in one block vs. two modality-incompatible mappings in another block. As a consequence, there will be fewer trials per block for each individual mapping.

Fintor et al. (2018) discovered that variability of both stimulus modality and response modality within the same block seems to be required to elicit modality-compatibility effects on switch costs – and such variability was indeed given in the VTS studies. However, only switches *within* the same modality-compatibility condition (visual-manual to auditory-vocal or vice versa for modality-compatible; visual-vocal to auditory-manual or vice versa for modality-incompatible) can be used for the analysis of the modality-compatibility effect on switch costs, in order to keep the conditions comparable to forced-choice studies. With fewer trials per block per individual mapping to begin with, there are also fewer trials eligible for analysing the within-compatibility switch costs this way. Trials featuring switches between modality compatibility (visual-vocal to visual-manual, auditory-manual to auditory-vocal, visual-vocal to auditory-vocal, or auditory-manual to visual-manual, or vice versa for any of these transitions) do not enter the analysis.

As a result, it may be harder to detect the modality-compatibility effect on switch costs in VTS, even if it is present – at least with the same number of trials per block as in forced-choice studies. Alternatively, if the modality-compatibility effect on switch costs might not always be present in VTS to begin with, this may be because task-choice errors, and therefore potentially also delays of correct responses due to confusion about which task has to be performed on a given trial, are ruled out by design: If subjects are free to choose the task, they cannot perform the wrong task; they can only select a wrong response within the task they have chosen, or fail to respond in time altogether.

There were further minor dissociations between Fintor et al. (2020) and our Study III: Fintor et al. (2020) found vocal dominance and a mapping-switch bias, whereas we found manual dominance and a mapping-repetition bias. The much more robust finding in VTS, reported by Fintor et al. (2020) and in both experiments of Study III, was that modality-compatibility biased task-choice rates, with participants forming a greater share of modality-compatible mappings than modality-incompatible mappings. In Experiment 1 of Study III, we replicated this bias with a larger number of stimulus- and response alternatives (the number words one, two, three, and four as visual and auditory stimuli, requiring one of four keypresses as manual

responses or the spoken letters A, B, C, and D as vocal responses). In Experiment 2 of Study III, we discovered that, in contrast to other task-selection biases in VTS, like the task-repetition bias, the modality-compatibility bias on choice rates was not sensitive to RSI manipulations.

The task-repetition bias (understood here as a bias to repeat the response modality, or even the entire S-R modality mapping) has been attributed to bottom-up processes selecting the most (recently) activated task representation from working memory (Botvinick et al., 2001; Fintor et al., 2020; Orr et al., 2012). Hence, the observation that short RSIs did *not* increase the share of compatible modality mappings on the subsequent trials led us to conclude that modality-compatible mappings probably do not have stronger working-memory representations per se – contrary to what Fintor et al. (2020) suggested. Instead, the issue may again be that modality-incompatible mappings are *both* partly represented in *both* modality-specific subsystems of working memory – the visuo-spatial sketchpad and the phonological loop – as outlined in the previous section, and in Study I (see also Maquestiaux et al., 2018).

Given that we have argued in Study I that the working-memory account for modality-compatibility effects is essentially just a less-specific version of the crosstalk account (Stephan & Koch, 2010, 2011), we would expect the modality-compatibility bias on choice rates to be caused by crosstalk, too: Selecting a modality-incompatible mapping from working memory should be harder than selecting a modality-compatible mapping, since the stimulus modality and anticipated response-effect modality refer to different subsystems – and yet, simultaneously, to the same two subsystems that the other modality-incompatible mapping featured in the same block refers to – whereas a modality-compatible mapping could selected from either just the visuo-spatial sketchpad (the visual-manual task), or from just the phonological loop (the auditory-vocal task).

However, we cannot conclude that all kinds of modality-specific between-task crosstalk affect the same processes – in fact, the observation that the modality-compatibility bias on choice rates occurred in Study III in both experiments, but both times in the absence of the modality-compatibility effect on switch costs (when using IES as a measure), suggests the polar opposite: That the effect on choice rates and the effect on switch costs may be attributable to *different* processes. I will elaborate further on this idea in section 4. Before we get to that, though, now that we have an explanation for the disappearance of the modality-compatibility effect on switch costs in VTS (as a result of a speed-accuracy trade-off), that still leaves us to explain the speed-accuracy trade-off in the forced-choice experiments.

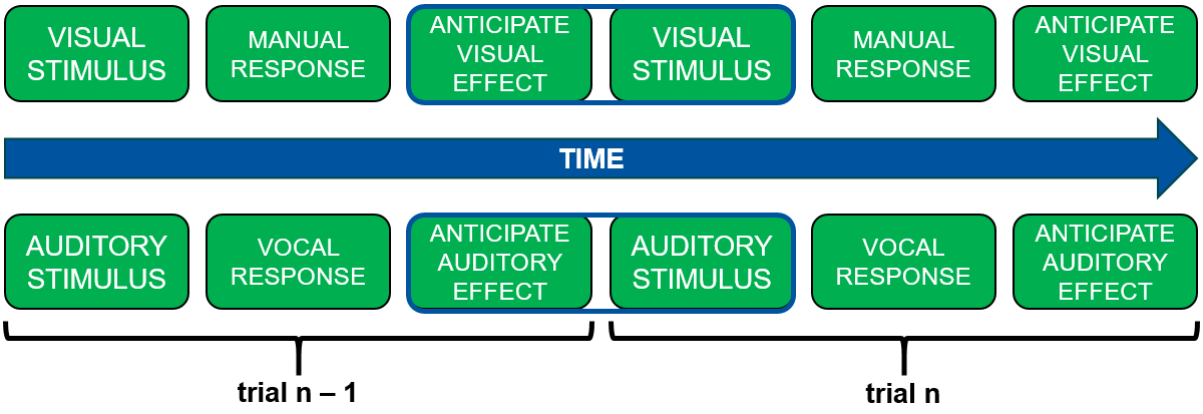
3.3.2 Forced-choice experiments

Switch costs can be increased in one condition compared to another condition due to a performance decrement on the switch trials themselves. However, since switch costs merely describe the overall difference between switch trials and repetition trials on mixed-task blocks within the same condition, this overall difference can of course also be increased by a performance benefit on the repetition trials. In particular, if there is a benefit for modality-compatible repetition trials, and this benefit is larger than the disadvantage for modality-incompatible switch trials, overall switch costs can be larger for the modality-compatible condition than for the modality-incompatible condition – even though those larger switch costs do not actually represent an overall performance decrement for the modality-compatible condition.

Such a benefit specifically for modality-compatible repetitions may indeed occur due to modality priming effects: As shown in Figure 2, with modality-compatible repetitions, the modality of the anticipated response effect on one trial always matches the stimulus modality on the subsequent trial (manual-visual; vocal-auditory). This primes the system for visual or auditory input, respectively, which it promptly receives on the next trial. These anticipatory priming effects could allow for the advance preparation of the next response (manual-visual-manual; vocal-auditory-vocal), which would then entail a speed benefit if the imperative stimulus modality (and thereby the task) does indeed repeat.

Figure 2

Modality-priming effects leading to performance benefits on modality-compatible repetition trials



Meanwhile, modality-incompatible conditions should not benefit from such priming effects – because the modality of the anticipated response effect still refers to the stimulus modality of the competing task. Consequently, modality priming effects with modality-incompatible

mappings, if they occur, should only benefit switch trials. In combination, if such priming effects in the modality-compatible condition accelerate responses on repetition trials, thereby increasing the difference to modality-compatible switches, and simultaneously, priming effects in the modality-incompatible condition accelerate responses on switch trials, thereby counteracting the influence of increased between-task crosstalk, the overall switch-cost difference in RT may indeed become larger in the modality-compatible condition than in the modality-incompatible condition. However, it would not be plausible to then interpret this pattern as evidence of greater between-task crosstalk with modality-compatible mappings – since based on the respective anticipated response effects, crosstalk should still be higher with modality-incompatible mappings. Now, with the reported inversions of the modality-compatibility effect between RT and error rates addressed, I will move on to discussing where such between-task crosstalk might actually be occurring.

4. Localising crosstalk

While researchers have been gathering more and more converging evidence for the crosstalk account, this alone does not tell us much about the nature of "central" processes. If modality-compatibility effects in task-switching and dual-tasking seem to be based on effect anticipation, but effect anticipation is associated with both the central process of response selection *and* the post-central process of response initiation (Kunde et al., 2004), we cannot really infer yet to which extent the central processes themselves might be (at least in part) modality-specific or not. In order to localise modality-compatibility effects, we therefore need to investigate them together with other effects, which have already been localised at the central process of response selection through previous research. If modality-compatibility effects then interact with these other effects localised at response selection, the conclusion that modality compatibility affects those same "central" response-selection processes becomes more likely.

The mere concept of "central" processes, occurring between stimulus perception and response execution, carries with itself strong implications about a traditional stage logic: If central processes are amodal by definition, they need to be distinct from perception and action – and therefore, the response-selection stage where these central processes are presumed to be located would also have to be clearly separated from perception and action. Even though such a separation of perception and action is antithetical to the ideomotor tradition on which most modality-compatibility research rests, I will nevertheless try in the following section to account for the findings of the present dissertation (and other studies published during this time frame) within a classical stage logic. After that, I shall offer an alternative explanation that, while

similar to the first one I am about to propose, will not rely (or at least not as heavily) on the notion of processing stages.

4.1 Pre-central vs. post-central crosstalk

Converging evidence for modality-compatibility effects occurring (at least in part) outside central processing was provided by the aforementioned study by (Wirth et al., 2020) (in dual tasking) and by Study II (in task switching). Experiment 1 was a Simon task (Hommel, 1993a, 1993b, 1995, 2011; Simon & Rudell, 1967): We had participants respond with left and right keypresses or by saying the words "left" and "right" in response to the colour words blue or red (written on screen or presented via headphones). These colour words were presented laterally either on the left or the right side, but whether a left or right response would be required was determined by the colour-word meaning, not by the spatial stimulus location (that is, stimulus-location was task-irrelevant). In Experiment 2, stimulus location was task-relevant, since we used the same spatial-discrimination paradigm as in several previous studies (Fintor et al., 2020; Fintor et al., 2018, 2019; Stephan & Koch, 2010, 2015, 2016; Stephan et al., 2013). However, where all of these studies had exclusively used spatially S-R compatible conditions (left stimuli requiring left responses, right stimuli requiring right responses), we additionally also included a spatially S-R incompatible condition (left stimuli requiring right responses, right stimuli requiring left responses).

As expected, S-R incompatibility negatively affected performance, even when stimulus location was task-irrelevant (the Simon effect), as in Experiment 1. Also as expected, modality incompatibility led to larger switch costs (with the previously discussed trade-off in Experiment 2). However, S-R compatibility and modality compatibility did not interact, neither directly with each other, nor in form of any three-way interactions with switch costs – which, using additive-factors logic (Sternberg, 1969), suggests that these two types of compatibility affect different processes. With S-R compatibility effects traditionally localised at response selection, this led us to conclude that modality-compatibility effects in Study II, and the between-task crosstalk we assume they represent, occurred either before or after response selection, that is, were either pre-central or post-central.

Conversely, Study I did show three-way interactions between modality compatibility, mixing or switching, respectively, and the manipulation of processing codes (Experiment 1) or task demands (Experiment 2). This may include modulations of crosstalk at the central stage, because Wickens (1984, 2008) linked spatial vs. verbal processing codes to all three stages of perception, cognition, and action. However, the interaction does not necessarily imply that the

modulation occurs centrally – in fact, the model would suggest the opposite, as the modalities dimension (visual and manual) in the model is restricted to perception, and the response modalities (manual and vocal) restricted to action. Thus, if the modulation of the modality-compatibility effect on mixing costs (that is, working memory or task uncertainty) and switch costs (reconfiguration or interference) occurred prior to or after central processing, this would still also account for the results of Study I, since processing codes are assumed to be involved in both pre-central and post-central stages, too.

Ultimately, the same logic could be applied to explain non-interactions in previous modality-compatibility research, too – notably, the lack of a modulation of preparation effects by modality compatibility in Fintor et al. (2019): As the authors outlined, the cue allowed for a preparation of the task, but not of the specific response. In forced-choice experiments with univalent stimuli and without cues, it is stimulus modality that commands the required response modality, depending on the written instructions given at the beginning of the block (modality-compatible mappings vs. modality-incompatible mappings). The share of between-task confusion that would result in task-choice errors, and would normally occur between stimulus onset and response selection, could now already take place between cue onset and stimulus onset. If at long CSIs, this modality-based conflict could be resolved completely before stimulus presentation, then response selection should have occurred at a time when task selection had already been completed. Thus, response selection would only have required selecting the correct response identity, but not selecting the correct task anymore. Hence, switch costs vanished completely at the long CSI, with no further modulation by modality compatibility. The short CSI, meanwhile, may have been too short to resolve the entire task-selection conflict before stimulus onset (that is, before response selection in terms of selecting response identity became possible). Hence, task confusion due to crosstalk still had some time to influence task selection, and therefore, the modality-compatibility effect on switch costs did occur at short CSIs. And if there are no cues, but the target stimulus instructs both the task and response identity, the CSI is effectively 0 ms.

At this point, the question whether stages are strictly serial or can proceed in parallel becomes important – and, as outlined before, in our studies we did not assume such a strict serial separation: Just because we assumed task selection and response selection to be independent processes, this does not mean they cannot still overlap on a purely temporal level. Task selection may be likely to start at some point before response selection, but it might not be fully completed yet when response selection (that is, choosing response identity, like left or right)

occurs, or even after that. And thus, even if between-task crosstalk already begins before the central stage, some between-task confusion might still be present after response selection, due to yet unresolved crosstalk between the task sets. Based on the reasoning proposed in the previous paragraph, this might be especially likely to happen when there are no cues, so that task selection and response selection must both be accomplished within the same time frame. This would explain why in the cued task-switching study by (Fintor et al., 2019), modality-compatibility effects on switch costs were smaller overall than in other forced-choice studies without any task cues.

Wirth et al. (2020) suggested two possible pre-central mechanisms that might contribute to modality-compatibility effects *before* response selection: Effector-set priming (stimulus modality priming response modality) and stimulus-uptake facilitation (response modality priming stimulus modality). Effector-set priming means that the stimulus modality on a given trial primes the response modality which can be anticipated to produce an effect in the same (or most similar) modality as the stimulus (visual stimuli priming manual responses; auditory stimuli priming vocal responses). Stimulus-uptake facilitation means that the response modality required on a given trial (as evident from the imperative stimulus) facilitates the processing of stimuli that are in the same modality as the anticipated effect of the required response (manual responses priming visual stimuli; vocal responses priming auditory stimuli). Consequently, with incompatible modality mappings, effector-set priming would prime the selection of the wrong responsible modality; and stimulus-uptake facilitation would hinder the processing of the actual current stimulus, since the required response would instead prime the system for processing input in the modality of the competing task. If the modality-compatibility bias on choice rates in VTS occurs as part of task selection before response selection, too, just like (Wirth et al., 2020) assumed for the modality-compatibility effect on dual-task costs, both may indeed be at least partially caused by effector-set priming and stimulus-uptake facilitation. Furthermore, considering that also in forced-choice task switching, choosing the wrong response modality is essentially a task-choice error, it would logically follow that the modality-compatibility effect on switch costs, at least to the extent that it occurs in error rates, should also have such a pre-central component.

For the modality-compatibility effect on switch costs in RT, however, we suggested in Study II that this effect might predominantly occur *after* response selection – namely, at *response initiation,* once the response is already known, and its effect (including the modality of the effect) can therefore be clearly anticipated. This idea is supported by related findings from

dual-task research, showing additive effects of manipulations of SOA and action-effect compatibility, which suggested either the central stage or a post-central stage as a locus of effect anticipation (Paelecke & Kunde, 2007; Wirth et al., 2015), and then employed effect-propagation logic to identify the post-central stage as the locus over the central stage (see Janczyk & Kunde, 2020, for a review). If the anticipated effect now refers to the stimulus modality of the competing, currently irrelevant task, this might still cause between-task confusion about whether it is actually appropriate to execute the response which has already been selected. As a consequence, there would be a larger delay before the execution of the response if the modality mappings are incompatible than if they are compatible.

This proposal is not in line with a strict version of ideomotor theory, in which effect anticipation would already be required to select the response in the first place (Shin et al., 2010). Rather, it is in accordance with those ideomotor accounts which state that actions are *initiated* based on their anticipated effects, whereas especially response selection may still involve additional cognitive processes that do not necessarily have to be modality-specific.

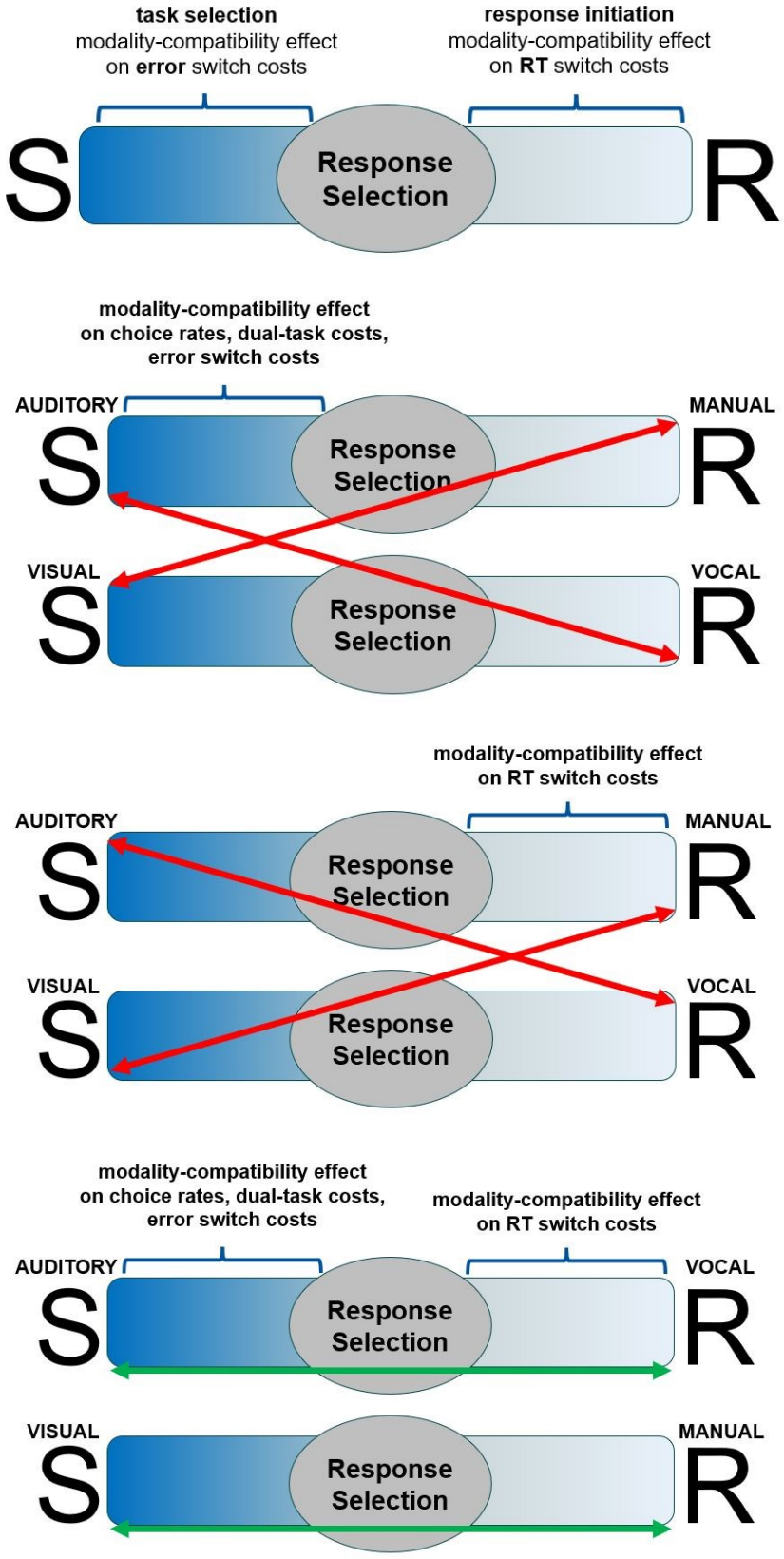
4.2 Reasons for separate loci for the modality-compatibility effect on RT and error rates

The idea that task selection and response selection might be separate processes, and that task selection (as in VTS) would occur before response selection, might still be fairly intuitive. Even if, say, in a spatial-discrimination task, the response side (left or right) might be identified before the response modality (manual or vocal) is chosen, selecting the actual complete response identity (left keypress vs. saying "left") should only be possible once a response modality – which in this case equals the chosen task – has been selected.

Based on these assumptions, it no longer seems that striking that the modality-compatibility effect on task-choice rates (participants forming a greater share of modality-compatible mappings than modality-incompatible mappings) and the modality-compatibility effect on switch costs (larger switch costs in the modality-incompatible condition) can occur independently of each other, as Study III has shown. But why should modality-compatibility effects on dual-task costs arise from different processes than modality-compatibility effects on task-switching costs (that is, both mixing costs and switch costs)? In terms of stage logic, why should the modality-compatibility effect on dual-task costs occur *before* response selection, and also the modality-compatibility effect on error switch costs occur *before* response selection, but the modality-compatibility effect on RT switch costs *after* response selection?

Figure 3

Proposed loci of modality-specific between-task crosstalk in a continuous response-production process (no strict serial stage logic)



Note: S = stimulus, R = response. With modality-compatible mappings (green arrows), between-task crosstalk should be lower. With modality-incompatible mappings (red arrows), between-task crosstalk can occur before response selection, biasing task choice (in voluntary task switching) and/or leading to response-modality errors (visible in error mixing costs and switch costs in forced-choice experiments); between-task crosstalk can also occur after response selection, delaying the initiation of a response after it has already been selected (visible in RT effects).

At this point, it seems worth considering the similarities between a dual-tasking paradigm with two stimulus- and response modalities and a VTS paradigm with two stimulus- and response modalities. In VTS, participants are instructed to try and perform both tasks equally often, without resorting to any kind of regularity. In other words: Participants are instructed to give equal priority to the tasks. In some dual-task studies, participants are also instructed to give equal priority to both tasks, and the SOA can be set to 0 ms to facilitate this (Hazeltine et al., 2006; Hazeltine et al., 2002; Schumacher et al., 2001). If perfect time sharing is not possible, participants now have to choose (voluntarily) which of the two tasks to perform first (assuming a strategic bottleneck). If there are two stimulus modalities (visual and auditory) and two response modalities (manual and vocal), in both dual-tasking and VTS, participants have four possible combinations of stimulus- and response modalities to choose from: visual-manual, auditory-vocal, visual-vocal, and auditory-manual.

The difference is of course that in the dual-tasking paradigm, two of these choices will be false (task-selection errors, not response-selection errors): In a modality-compatible dual-task block, responding vocally to the visual stimulus or manually to the auditory stimulus will be incorrect; and in a modality-incompatible block, responding manually to the visual stimulus or vocally to the auditory stimulus will be incorrect. In the VTS paradigm, all four S-R modality mappings are permissible; no task-selection errors are possible, only response-selection errors. If, however, there is a bias to form more modality-compatible mappings than modality-incompatible mappings, then this same bias would consequently lead to a greater number of incorrect responses (due to task-selection errors) on modality-incompatible dual-task blocks.

Likewise, the same task-selection error can occur in task switching; this should result in higher error switch costs with modality-incompatible mappings (which we have found in all Studies I – III). A bias to respond manually to visual stimuli, and to respond vocally to auditory stimuli (as evident from VTS), even when those stimuli are presented on consecutive trials, would still result in the selection of the wrong response modality in forced-choice task-switching experiments if the current block requires modality-incompatible mappings (that is, vocal

responses to visual stimuli, manual responses to auditory stimuli). This way we can link the modality-compatibility effect on choice rates in VTS, on dual-task costs in dual tasking, and on error switch costs in task switching to the common source of pre-central crosstalk. Why now should the modality-compatibility effect specifically on RT switch costs occur *after* response selection, due to post-central crosstalk?

Here we have to bear in mind that RT analysis usually only includes trials that featured a correct response. Therefore, an effect of any kind on RT can by design only reflect a delay in response production, but not a lack of accuracy. If pre-central between-task crosstalk is strong enough on a given trial to result in the selection of the wrong response, or at least the selection of the wrong response modality (that is, the selection of the wrong task), then this trial is not going to enter RT analysis to begin with. The mere existence of trials eligible for RT analysis in the data hence means that either, the pre-central crosstalk was too low to result in a task-selection error (less bottom-up interference), or that this pre-central crosstalk has already been overcome successfully (by top-down processes selecting the correct S-R modality mapping). If task selection precedes response selection (as Study II suggests they may be independent processes), then, once the correct task has been selected (that is, the correct modality mapping has been chosen), and the response itself (that is, response identity, e.g., left or right) has also been selected, any remaining crosstalk can only delay the onset of the response: If task selection has resulted in the selection of a manual response, visible feedback should now be anticipated; if task selection has resulted in the selection of a vocal response, auditory feedback should now be anticipated. At this point in time, though, the stimulus is still being presented – it only stops being presented once the response is actually executed. Thus, confusion between the modality of the anticipated effect of the selected response and the modality of the currently perceived stimulus should still have the potential to lead to a delay during response initiation – that is, the time frame between response selection and response execution.

Response selection itself, meanwhile, would mainly be responsible for the selection of response identity in this framework (like choosing between left and right in a spatial-discrimination task). Selecting the proper spatial response can then of course be hindered by spatial S-R incompatibility, that is, if a left stimulus requires a right response, and a right stimulus requires a left response, rather than vice versa. Such effects of element-level compatibility should of course influence response (identity) selection, irrespective of whether the spatial feature of the stimulus is task-irrelevant (Study II, Experiment 1) – a Simon task – or whether the spatial feature of the stimulus is task-relevant (Study II, Experiment 2) – a spatial S-R compatibility

task. As mentioned before, both experiments in Study II did indeed yield such spatial S-R compatibility effects, as well as yielding modality-compatibility effects. However, there was no interaction between these two different types of compatibility, which led us to assume in Study II that S-R compatibility and modality compatibility might affect different process. Using the framework suggested above, it would now be possible to name these processes more specifically: S-R compatibility being associated with response (identity) selection, whereas modality compatibility can be associated with task selection (pre-central) and response initiation (post central).

This explanation however rests quite strongly on remaining close to a traditional stage logic – even if it does not assume a strictly independent and sequential order, but merely different points or periods in time over the course of one continuous response-production process (Hommel, 1997; Kunde et al., 2004). Hence, in the following section, I will propose an alternative explanation for the different processes that might be represented by S-R compatibility effects vs. modality compatibility effects, without relying on the notion of stages.

4.3 Set-level vs. element-level

In the last section, I already briefly equated S-R compatibility effects (those which are commonly associated with response-selection processes) with effects of *element-level compatibility* (Fitts & Deininger, 1954; Kornblum et al., 1990; Wang & Proctor, 1996). Using the common example of a spatial-discrimination task, an S-R incompatible condition in which each left or right stimulus requires a spatial response on the respective other side should entail (more) crosstalk between the spatial features of the stimuli and the spatial features of the response, whereas the corresponding S-R compatible condition, in which each left or right stimulus requires a spatial response on the same side, should not. Such a kind of crosstalk would therefore occur between the stimuli and responses of the same task – in other words, S-R compatibility effects can be understood as representing *within-task crosstalk*.

Conversely, as mentioned repeatedly throughout the previous paragraphs, modality-compatibility effects have been attributed, among others, to *between-task crosstalk*. Thus, they refer to the entire task set, or *set-level compatibility* (Fitts & Seeger, 1953). Prior to our Study II, most modality-compatibility research employing spatial-discrimination tasks exclusively used spatially S-R compatible mappings – meaning, left stimuli always required left responses, right stimuli always required right responses, and only the S-R modality mappings changed (visual-manual and auditory-vocal vs. visual-vocal and auditory-manual). *Within-task crosstalk*

in such experiments should therefore have been low, even when *between-task crosstalk* was high (in the modality-incompatible conditions).

If response-selection processes reflect S-R compatibility effects, which, as Study II suggests, do not (at least not necessarily) interact with modality-compatibility effects, and S-R compatibility effects represent within-task crosstalk, this suggests that *within-task crosstalk* might indeed be an *amodal* kind of crosstalk – one that occurs, for example, between the spatial features of stimuli and responses, but is independent of the modality in which these stimuli are being presented or in which these responses must be executed. Conversely, *between-task crosstalk* would be *modality-specific,* and in turn without depending on S-R compatibility to occur: While there have indeed been a lot of modality-compatibility studies using spatially compatible S-R mappings of left and right (e.g., Fintor et al., 2020; Fintor et al., 2018, 2019; Stephan & Koch, 2010, 2015; Stephan et al., 2013), other studies have shown that such strong dimensional overlap (Kornblum et al., 1990) is not necessary to find modality-compatibility effects (Schacherer & Hazeltine, 2019; Stephan & Koch, 2011). What does seem to be necessary in order to elicit modality-compatibility effects is the combination of two modality-incompatible mappings within the same block (be it a dual-task or a task-switching block), contrasted against a block featuring two modality-compatible mappings (Fintor et al., 2018). In other words, modality compatibility can be understood as a phenomenon occurring at the *set level,* not at element level. In fact, in modality-compatibility studies, the data is commonly collapsed across the two modality-compatible tasks vs. the two modality-incompatible tasks, in order to eliminate the influences of the individual stimulus modalities (visual and auditory) and response modalities (manual and vocal).

This idea indeed matches the pattern of interactions (and absence of interactions) in all three Studies I – III: Study I demonstrated interactions of modality compatibility and spatial-verbal processing codes and temporal-discrimination task demands, and the latter manipulations are at the *set level;* Study II showed no interactions of modality compatibility and S-R compatibility, because spatial S-R compatibility is *element-level* compatibility; and Study III replicated the modality-compatibility bias on choice rates in VTS, because it is entire *task sets* being chosen by the participants, rather than just the individual responses to individual stimuli. Thus, we again arrive at the idea that task selection *(set level)* and response selection *(element level)* may be separate processes.

While we replicated the typical effects of RSI on task choice in Study III (the task-repetition bias, both in form of repeating the response modality and repeating the entire S-R

modality mapping), critically, the bias to form more modality-compatible mappings than modality-incompatible mappings was not further modulated by RSI. Analogously to the absence of an interaction in the task-cuing study by (Fintor et al., 2019), this suggests that the modality-compatibility bias on choice rates might refer to a different mechanism than the task-repetition bias in voluntary task switching. In particular, where the task-repetition bias is assumed to arise from bottom-up processes selecting the most (recently) activated task representation from working memory (Botvinick et al., 2001; Fintor et al., 2020; Orr et al., 2012), the modality-compatibility bias on choice rates may instead again occur due to between-task crosstalk, based on the modalities of the anticipated response effects (Schacherer & Hazeltine, 2020, 2021; Stephan & Koch, 2010, 2011).

Thus, irrespective of whether task selection, response selection, and response initiation occur in sequential order or not, we can still distinguish the different processes presumed to be underlying S-R compatibility effects vs. modality compatibility effects, and characterise their differences in several ways: There may indeed be generic *response-selection* processes, responsible for task reconfiguration and for content-independent S-R translations, which would therefore also have to deal with *within-task crosstalk* / effects of *element-level compatibility*. And simultaneously, there would be modality-specific task-selection and response-initiation processes, affected by *between-task crosstalk*, which would therefore have to deal with the problem of between-task binding (e.g., Frings et al., 2020; Logan & Gordon, 2001) / effects of *set-level compatibility.*

5 Open issues

Separating generic / amodal components from modality-specific components to switch costs can be empirically difficult (and the speed-accuracy trade-offs we found with some tasks further complicate the interpretation of the data). In a practice study to examine the plasticity aspect of multitasking (in preparation, not part of the present dissertation), we aimed at such a separation of generic and modality-specific components: We independently manipulated whether participants would practise with modality-compatible mappings vs. with modality-incompatible mappings, and whether they would practise switching between those mappings (mixed-task practice) or practise the individual component tasks separately in succession (single-task practice). Results revealed stronger reductions in switch costs if pre-test, practice, and post-test were modality-compatible than if they were modality-incompatible – analogously to previous studies reporting reduced dual-task costs with modality-compatible mappings after practice (e.g., Hazeltine et al., 2002; Ruthruff et al., 2006; Schumacher et al., 2001). However,

mixed-task practice vs. single-task practice yielded no main effects, or interactions with switch costs alone – only more complex interactions, which included at least one of the modality-compatibility manipulations. Thus, there was little evidence of a generic, amodal intertask coordination skill, as proposed by Liepelt, Strobach, et al. (2011), in this particular study.

One empirical approach that we did not get to test during the time frame of the present dissertation was to look for potential interactions between modality compatibility and cued judgement switching. A common paradigm for this consists of presenting digits from 1 through 9, excluding 5, and having participants judge whether they are larger or smaller than 5 (magnitude task), vs. having them judge whether they are odd or even (parity task) (Koch & Allport, 2006; Stephan et al., 2018). Based on the findings of Study II, we would not expect such an interaction, but would rather expect such a manipulation to provide more evidence for task selection and response selection being separate processes: In contrast to modality-compatibility effects on switch costs (attributed to crosstalk based on the anticipated response effects), judgement switch costs can be attributed to interference control between different rules for stimulus classification, such as task-set shielding. Shielding is commonly measured in form of congruency effects, that is, the performance benefit on congruent trials, on which both tasks require the same response, over incongruent trials, on which each task requires a different response. This task-shielding ability has been shown to interact with postural control (Rosenbaum et al., 2017; Stephan et al., 2018), which in turn has been shown to interact with modality compatibility (Stelzel et al., 2017). Thus, it is not entirely out of the question that task shielding might interact with modality compatibility, too, by also helping to decrease between-task crosstalk between the modality mappings (not just between the magnitude/parity judgement tasks). An absence of such an interaction of modality-compatibility effects on switch costs and cued judgement switching, however, would provide more support to the suggestion from Study II that modality-compatibility effects occur based on the anticipated effect of an already selected response.

Aside from the challenge of how to distinguish task selection from response selection empirically, there is also the challenge of how to distinguish response selection from response initiation (Kunde et al., 2004). This could be accomplished, among others, by examining modality compatibility in go/no-go tasks, where responses to certain stimuli might be selected, but not executed, and therefore perhaps also not initiated in the first place. In a first pilot study on this (in preparation), we found that the modality-compatibility effect on switch costs was no longer significant in mixed-task blocks if single-task blocks were replaced by go/no-go blocks,

during which both visual and auditory stimuli were presented, but participants were supposed to only respond to either of them, while ignoring the other stimulus modality. However, the modality-compatibility effect on mixing costs was still pronounced, with larger mixing costs in the modality-incompatible condition (two consecutive go-trials in the go/no-go blocks were treated as an approximation of repetition trials in single-task blocks, so that they were compared against repetition trials in the mixed-task blocks to calculate the mixing costs). Thus, one could speculate that perhaps, the go/no-go blocks allowed participants to gain some practice at *selecting,* but not *initiating,* a response in the wrong modality (manual vs. vocal), which then also benefitted them when switching between both modality mappings in the mixed-task blocks.

6 Conclusion

The present dissertation started out by seeking to modulate the modality-compatibility effect on mixing costs and switch costs in various ways: Through the variation of processing codes, task demands, S-R / element-level compatibility, and in Voluntary Task Switching. The overarching goal to localise crosstalk, in order to further explore the nature of central processes, arose from the pattern of interactions and non-interactions with modality compatibility that were discovered over the course of conducting these three studies. While modality-compatibility research began by questioning the notion of generic central processes, and still provides ample evidence against that claim, newer studies from both dual tasking and task switching in turn provide evidence for some modality-specific influences indeed occurring outside a central stage. When using this terminology, it is not necessary to presume strictly serial and independent stages, since perception, response selection, response initiation, and motor execution can simply be regarded as different time periods within one continuous response-production process. This allows for the reconciliation of traditional and ideomotor accounts of multitasking, and thereby also for the reconciliation of generic and modality-specific accounts. Future research on cognitive control should therefore put more emphasis on disentangling the respective generic and modality-specific components, rather than trying to prove the veracity of one account over the other. Ideally, this should lead to a wider picture of multitasking overall, especially by regarding dual tasking and task switching through a shared lens. Such a more generalised understanding of multitasking may ultimately allow us to minimize the associated costs across different domains, and thus deal more adeptly with the increasingly more common requirements to engage in multitasking in our day-to-day lives.

References

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance series. Attention and performance 15: Conscious and nonconscious information processing* (pp. 421–452). The MIT Press.

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, *15*(9), 610-615. https://doi.org/10.1111/j.0956-7976.2004.00728.x

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(4), 683-702. https://doi.org/10.1037/0278-7393.31.4.683

Baddeley, A. (1992). Working memory. *Science*, *255*, 556-559. https://doi.org/10.1126/science.1736359

Baddeley, A. (2010). Working memory. *Current Biology*, *20*, R136-R140. https://doi.org/10.1016/j.cub.2009.12.014

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624-652. https://doi.org/10.1037/0033-295x.108.3.624

Broadbent, D. E. (1958). *Perception and communication*. Pergamon Press.

De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(5), 965-980. https://doi.org/10.1037//0096-1523.19.5.965

Demanet, J., Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2010). Voluntary task switching under load: Contribution of top-down and bottom-up factors in goal-directed behavior. *Psychonomic Bulletin & Review*, *17*(3), 387-393. https://doi.org/10.3758/PBR.17.3.387

Donders, F. C. (1868/1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412-&. https://doi.org/10.1016/0001-6918(69)90065-1

Fintor, E., Poljac, E., Stephan, D. N., & Koch, I. (2020). Modality compatibility biases voluntary choice of response modality in task switching. *Psychological Research*, *84*(2), 380-388. https://doi.org/10.1007/s00426-018-1040-5

Fintor, E., Stephan, D. N., & Koch, I. (2018). Emerging features of modality mappings in task switching: Modality compatibility requires variability at the level of both stimulus and response modality. *Psychological Research*, *82*(1), 121-133. https://doi.org/10.1007/s00426-017-0875-5

Fintor, E., Stephan, D. N., & Koch, I. (2019). The interplay of crossmodal attentional preparation and modality compatibility in cued task switching. *Quarterly Journal of Experimental Psychology*, *72*(4), 955-965. https://doi.org/10.1177/1747021818771836

Fitts, P. M., & Deininger, R. L. (1954). S-R Compatibility - Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*(6), 483-492. https://doi.org/10.1037/h0054967

Fitts, P. M., & Seeger, C. M. (1953). S-R Compatibility - Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*(3), 199-210. https://doi.org/10.1037/h0062827

Foerster, A., Wirth, R., Berghoefer, F. L., Kunde, W., & Pfister, R. (2019). Capacity limitations of dishonesty. *Journal of Experimental Psychology: General*, *148*(6), 943-961. https://doi.org/10.1037/xge0000510

Földes, N., Philipp, A. M., Badets, A., & Koch, I. (2017). Exploring modality compatibility in the response-effect compatibility paradigm. *Advances in Cognitive Psychology*, *13*, 97-104. https://doi.org/10.5709/acp-0210-1

Freides, D. (1974). Human information processing and sensory modality: Cross-modal functions, information complexity, memory, and deficit. *Psychological Bulletin*, *81*, 284-310. https://www.ncbi.nlm.nih.gov/pubmed/4608609

Friedgen, E., Koch, I., Poljac, E., Liefooghe, B., & Stephan, D. N. (2022). Voluntary task switching is affected by modality compatibility, set size, and response-stimulus interval. Manuscript submitted for publication.

Friedgen, E., Koch, I., & Stephan, D. N. (2021). Modality compatibility in task switching depends on processing codes and task demands. *Psychological Research*, *85*(6), 2346-2363. https://doi.org/10.1007/s00426-020-01412-2

Friedgen, E., Koch, I., & Stephan, D. N. (2022). Dissociating stimulus-response compatibility and modality compatibility in task switching. *Memory & Cognition*, (Online First). https://doi.org/10.3758/s13421-022-01276-4

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Moller, M., Pfister, R., & Philipp, A. (2020). Binding and retrieval in action control (BRAC). *Trends in Cognitive Sciences*, *24*(5), 375-387. https://doi.org/10.1016/j.tics.2020.02.004

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition*, *150*, 92-108. https://doi.org/10.1016/j.cognition.2016.02.003

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*(2), 73-99. https://doi.org/10.1037/h0028689

Greenwald, A. G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*(1), 52-57. https://doi.org/10.1037/h0032762

Greenwald, A. G. (2003). On doing two things at once: III. Confirmation of perfect timesharing when simultaneous tasks are ideomotor compatible. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(5), 859-868. https://doi.org/10.1037/0096-1523.29.5.859

Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once: II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology*, *101*(1), 70-76. https://doi.org/10.1037/h0035451

Halvorson, K. M., Ebner, H., & Hazeltine, E. (2013). Investigating perfect timesharing: The relationship between IM-compatible tasks and dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 413-432. https://doi.org/10.1037/a0029475

Halvorson, K. M., & Hazeltine, E. (2015). Do small dual-task costs reflect ideomotor compatibility or the absence of crosstalk? *Psychonomic Bulletin & Review*, *22*(5), 1403-1409. https://doi.org/10.3758/s13423-015-0813-8

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291-345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 527-545. https://doi.org/10.1037/0096-1523.28.3.527

Hommel, B. (1993a). Inverting the Simon Effect by intention - Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research*, *55*(4), 270-279. https://doi.org/10.1007/Bf00419687

Hommel, B. (1993b). The relationship between stimulus processing and response selection in the Simon task: Evidence for a temporal overlap. *Psychological Research*, *55*(4), 280-290. https://doi.org/10.1007/BF00419688

Hommel, B. (1995). Stimulus-response compatibility and the Simon effect: Toward an empirical clarification. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(4), 764-775. https://doi.org/10.1037/0096-1523.21.4.764
Hommel, B. (1997). Toward and action-concept model of stimulus response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus–response compatibility* (pp. 281-320). Elsevier.
Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*(2), 189-202. https://doi.org/10.1016/j.actpsy.2010.04.011
Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*(5), 849-937. https://doi.org/10.1017/s0140525x01000103
James, W. (1890). *The principles of psychology* (Vol. 2). Dover.
Janczyk, M., & Kunde, W. (2020). Dual tasking from a goal perspective. *Psychological Review*, *127*(6), 1079-1096. https://doi.org/10.1037/rev0000222
Kahneman, D. (1973). *Attention and effort*. Prentice-Hall.
Keele, S. W. (1973). *Attention and human performance*. Goodyear.
Keller, P. E., & Koch, I. (2008). Action planning in sequential skills: Relations to music performance. *Quarterly Journal of Experimental Psychology*, *61*(2), 275-291. https://doi.org/10.1080/17470210601160864
Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - A review. *Psychological Bulletin*, *136*(5), 849-874. https://doi.org/10.1037/a0019842
Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition*, *34*(2), 433-444. https://doi.org/10.3758/Bf03193420
Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking - An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557-583. https://doi.org/10.1037/bul0000144
Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility - A model and taxonomy. *Psychological Review*, *97*(2), 253-270. https://doi.org/10.1037/0033-295X.97.2.253
Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(2), 387-394. https://doi.org/10.1037//0096-1523.27.2.387
Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *Quarterly Journal of Experimental Psychology*, *57A*(1), 87-106. https://doi.org/10.1080/02724980343000143
Liberman, A. M., & Mattingly, I. G. (1989). A specialization for speech perception. *Science*, *243*(4890), 489-494. https://doi.org/10.1126/science.2643163
Liepelt, R., Fischer, R., Frensch, P. A., & Schubert, T. (2011). Practice-related reduction of dual-task costs under conditions of a manual-pedal response combination. *Journal of Cognitive Psychology*, *23*(1), 29-44. https://doi.org/10.1080/20445911.2011.448025
Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Quarterly Journal of Experimental Psychology*, *64*(7), 1251-1272. https://doi.org/10.1080/17470218.2010.543284
Liesefeld, H. R., & Janczyk, M. (2019). Combining speed and accuracy to control for speed-accuracy trade-offs(?). *Behavior Research Methods*, *51*(1), 40-60. https://doi.org/10.3758/s13428-018-1076-x
Logan, G. D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science*, *12*(2), 45-48. https://doi.org/10.1111/1467-8721.01223
Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*(2), 393-434. https://doi.org/10.1037//0033-295X.108.2.393

Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*(2), 145-188. https://doi.org/10.1016/0001-6918(95)00050-X
Lukas, S., Philipp, A. M., & Koch, I. (2010). Switching attention between modalities: Further evidence for visual dominance. *Psychological Research*, *74*, 255-267. https://doi.org/10.1007/s00426-009-0246-y
Lukas, S., Philipp, A. M., & Koch, I. (2014). Crossmodal attention switching: Auditory dominance in temporal discrimination tasks. *Acta Psychologica*, *153*, 139-146. https://doi.org/10.1016/j.actpsy.2014.10.003
Macleod, C. M. (1991). Half a century of research on the Stroop effect - An Integrative Review. *Psychological Bulletin*, *109*(2), 163-203. https://doi.org/10.1037/0033-2909.109.2.163
Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception, & Psychophysics*, *80*, 752-772. https://doi.org/10.3758/s13414-017-1469-4 29285603
Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1124-1140. https://doi.org/10.1037/0278-7393.26.5.1124
Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, *104*(1), 3-65. https://doi.org/10.1037/0033-295x.104.1.3
Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of Psychological Refractory-Period phenomena. *Psychological Review*, *104*(4), 749-791. https://doi.org/10.1037/0033-295X.104.4.749
Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167-202. https://doi.org/10.1146/annurev.neuro.24.1.167
Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford University Press.
Mittelstädt, V., Dignath, D., Schmidt-Ott, M., & Kiesel, A. (2018). Exploring the repetition bias in voluntary task switching. *Psychological Research*, *82*(1), 78-91. https://doi.org/10.1007/s00426-017-0911-5
Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. https://doi.org/10.1006/cogp.1999.0734
Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134-140. https://www.ncbi.nlm.nih.gov/pubmed/12639695
Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition*, *31*(3), 327-342. https://www.ncbi.nlm.nih.gov/pubmed/12795475
Navon, D., & Gopher, D. (1979). Economy of the human processing system. *Psychological Review*, *86*(3), 214-255. https://doi.org/10.1037/0033-295x.86.3.214
Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(3), 435-448. https://doi.org/10.1037//0096-1523.13.3.435
Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology*, *44*(3), 193-251. https://doi.org/10.1006/cogp.2001.0767
Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In *Consciousness and self-regulation* (pp. 1-18). Springer.
Orr, J. M., Carp, J., & Weissman, D. H. (2012). The influence of response conflict on voluntary task switching: A novel test of the conflict monitoring model. *Psychological Research*, *76*(1), 60-73. https://doi.org/10.1007/s00426-011-0324-9
Paelecke, M., & Kunde, W. (2007). Action-effect codes in and before the central bottleneck: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology:*

Human Perception and Performance, *33*(3), 627-644. https://doi.org/10.1037/0096-1523.33.3.627

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*(2), 220-244. https://www.ncbi.nlm.nih.gov/pubmed/7972591

Poljac, E., Koch, I., & Bekkering, H. (2009). Dissociating restart cost and mixing cost in task switching [Peer Reviewed]. *Psychological Research*, *73*(3), 407-416. https://doi.org/10.1007/s00426-008-0151-9

Proctor, R. W., & Vu, K.-P. L. (2006). *Stimulus-response compatibility principles: Data, theory, and application*. CRC/Taylor & Francis.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks [Peer Reviewed]. *Journal of Experimental Psychology: General*, *124*(2), 207-231. https://doi.org/10.1037/0096-3445.124.2.207

Rosenbaum, D., Mama, Y., & Algom, D. (2017). Stand by your Stroop: Standing up enhances selective attention and cognitive control. *Psychological Science*, *28*(12), 1864-1867. https://doi.org/10.1177/0956797617721270

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(6), 1477-1491. https://doi.org/10.1037/0278-7393.31.6.1477

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(4), 763-797. https://doi.org/10.1037//0096-1523.27.4.763

Ruthruff, E., Hazeltine, E., & Remington, R. W. (2006). What causes residual dual-task interference after practice? *Psychological Research*, *70*(6), 494-503. https://doi.org/10.1007/s00426-005-0012-8

Sanders, P. (1998). Random permutations on distributed, external and hierarchical memory. *Information Processing Letters*, *67*(6), 305-309. https://doi.org/10.1016/S0020-0190(98)00127-6

Schacherer, J., & Hazeltine, E. (2019). How conceptual overlap and modality pairings affect task-switching and mixing costs. *Psychological Research*, *83*(5), 1020-1032. https://doi.org/10.1007/s00426-017-0932-0

Schacherer, J., & Hazeltine, E. (2020). Cue the effects: Stimulus-action effect modality compatibility and dual-task costs. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(4), 350-368. https://doi.org/10.1037/xhp0000719

Schacherer, J., & Hazeltine, E. (2021). Crosstalk, not resource competition, as a source of dual-task costs: Evidence from manipulating stimulus-action effect conceptual compatibility. *Psychonomic Bulletin & Review*, *28*(4), 1224-1232. https://doi.org/10.3758/s13423-021-01903-2

Schäffner, S., Koch, I., & Philipp, A. M. (2018). Sensory-motor modality compatibility in multitasking: The influence of processing codes. *Acta Psychologica*, *191*, 210-218. https://doi.org/10.1016/j.actpsy.2018.09.012

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, *12*(2), 101-108. https://doi.org/10.1111/1467-9280.00318

Schweickert, R. (1978). Critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology*, *18*(2), 105-139. https://doi.org/10.1016/0022-2496(78)90059-7

Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal*, *27*(3), 379-423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943–974. https://doi.org/10.1037/a0020541

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*(3), 300-304. https://doi.org/10.1037/h0020586

Stelzel, C., Schauenburg, G., Rapp, M. A., Heinzel, S., & Granacher, U. (2017). Age-related interference between the selection of input-output modality mappings and postural control - A Pilot Study. *Frontiers in Psychology*, *8*, 613. https://doi.org/10.3389/fpsyg.2017.00613

Stelzel, C., & Schubert, T. (2011). Interference effects of stimulus-response modality pairings in dual tasks and their robustness. *Psychological Research*, *75*(6), 476-490. https://doi.org/10.1007/s00426-011-0368-x 21811837

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychological Research*, *70*(6), 514-525. https://doi.org/10.1007/s00426-005-0013-7

Stephan, D. N., Fintor, E., & Koch, I. (2022). Short-term pre-exposure to modality mappings: Modality-incompatible single-task exposure reduces modality-specific between-task crosstalk in task-switching. *Acta Psychologica*, *224*. https://doi.org/10.1016/j.actpsy.2022.103502

Stephan, D. N., Hensen, S., Fintor, E., Krampe, R., & Koch, I. (2018). Influences of postural control on cognitive control in task switching. *Frontiers in Psychology*, *9*, 1153. https://doi.org/10.3389/fpsyg.2018.01153

Stephan, D. N., Josten, J., Friedgen, E., & Koch, I. (2021). Crossmodal effects in task switching: Modality compatibility with vocal and pedal responses. *Journal of Cognition*, *4*(1), 1-14. https://doi.org/10.5334/joc.129

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(4), 1075-1081. https://doi.org/10.1037/a0019695

Stephan, D. N., & Koch, I. (2011). The role of input-output modality compatibility in task switching. *Psychological Research*, *75*(6), 491-498. https://doi.org/10.1007/s00426-011-0353-4

Stephan, D. N., & Koch, I. (2015). Tactile stimuli increase effects of modality compatibility in task switching. *Experimental Psychology*, *62*(4), 276-284. https://doi.org/10.1027/1618-3169/a000291

Stephan, D. N., & Koch, I. (2016). Modality-specific effects on crosstalk in task switching: Evidence from modality compatibility using bimodal stimulation. *Psychological Research*, *80*(6), 935-943. https://doi.org/10.1007/s00426-015-0700-y

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task switching, modality compatibility, and the supra-modal function of eye movements. *Experimental Psychology*, *60*, 90-99. https://doi.org/10.1027/1618-3169/a000175

Sternberg, S. (1969). Discovery of processing stages - Extensions of Donders' method. *Acta Psychologica*, *30*, 276-315. https://doi.org/10.1016/0001-6918(69)90055-9

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences*, *14*, 400-410. https://doi.org/10.1016/j.tics.2010.06.008

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, *14*(1), 1-36. https://doi.org/10.1037/h0073262

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 3-18. https://www.ncbi.nlm.nih.gov/pubmed/12669744

Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods*, *49*(2), 653-673. https://doi.org/10.3758/s13428-016-0721-5

Vandierendonck, A. (2018). Further tests of the utility of integrated speed-accuracy measures in task switching. *Journal of Cognition*, *1*(1), 1-16. https://doi.org/10.5334/joc.6

Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin*, *136*(4), 601-626. https://doi.org/10.1037/a0019791

Wang, H. F., & Proctor, R. W. (1996). Stimulus-response compatibility as a function of stimulus code and response modality. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1201-1217. https://doi.org/10.1037/0096-1523.22.5.1201

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, *88*, 638-667. https://www.ncbi.nlm.nih.gov/pubmed/7003641

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance - A review and a theory. *British Journal of Psychology*, *43*(1), 2-19. https://doi.org/10.1111/j.2044-8295.1952.tb00322.x

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63-101). Academic Press.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449-455. https://doi.org/10.1518/001872008X288394

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. *Human Factors*, *25*(2), 227-248.

Wickens, C. D., Vidulich, M., & Sandrygarza, D. (1984). Principles of S-C-R compatibility with spatial and verbal tasks - the role of display-control location and voice-interactive display-control interfacing. *Human Factors*, *26*(5), 533-543. https://doi.org/10.1177/001872088402600505

Wirth, R., Koch, I., & Kunde, W. (2020). Localizing modality compatibility effects: Evidence from dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(12), 1527-1537. https://doi.org/10.1037/xhp0000873

Wirth, R., Pfister, R., Janczyk, M., & Kunde, W. (2015). Through the portal: Effect anticipation in the central bottleneck. *Acta Psychologica*, *160*, 141-151. https://doi.org/10.1016/j.actpsy.2015.07.007

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait and Posture*, *16*(1), 1-14. https://doi.org/10.1016/s0966-6362(01)00156-4

Study I

Friedgen, E., Koch, I., & Stephan, D. N. (2021). Modality compatibility in task switching depends on processing codes and task demands. *Psychological Research*, *85*(6), 2346-2363. https://doi.org/10.1007/s00426-020-01412-2

Modality compatibility in task switching depends on processing codes and task demands

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Abstract

Modality compatibility denotes the match between sensory stimulus modality and the sensory modality of the anticipated response effect (for example, vocal responses usually lead to auditory effects, so that auditory-vocal stimulus-response mappings are modality-compatible, whereas visual-vocal mappings are modality-incompatible). In task switching studies, it has been found that switching between two modality-incompatible mappings (auditory-manual and visual-vocal) resulted in higher switch costs than switching between two modality-compatible mappings (auditory-vocal and visual-manual). This finding suggests that with modality-incompatible mappings, the anticipation of the effect of each response primes the stimulus modality linked to the competing task, creating task confusion. In Experiment 1, we examined whether modality-compatibility effects in task switching are increased by strengthening the auditory-vocal coupling by using spatial-verbal stimuli relative to spatial-location stimuli. In Experiment 2, we aimed at achieving the same goal by requiring temporal stimulus discrimination relative to spatial stimulus localisation. Results suggest that both spatial-verbal stimuli and temporal discrimination can increase modality-specific task interference through a variation of the strength of anticipation in the response-effect coupling. This provides further support for modality-specificity of cognitive control processes in task switching.

(182 words)

When two tasks have to be performed in alternation, higher response time (RT) and error rates can be observed (see Kiesel et al., 2010; Koch et al., 2018, for reviews). Such costs do not only arise when switching from one task to the other (switch costs), but occur even when a task is repeated: The mere presence of another task in the same block of trials leads to worse performance compared to a block containing only one of the two tasks (mixing costs).

In research on task switching, switch costs are often understood as reflecting the competition of task representations (task sets) and the need to "reconfigure" the current task set (Monsell, 2003). Meanwhile, mixing costs have been interpreted as either reflecting the higher load on working memory that arises from having to maintain two task sets in an activated state rather than just one (e.g. Los, 1996), or, alternatively, to the uncertainty of which task will have to be performed next (e.g. Poljac et al., 2009; Rubin & Meiran, 2005).

In dual-task research, such performance costs of multitasking have often been attributed to a structural bottleneck (Pashler, 1994) or to a shared, but content-free resource (Kahneman, 1973). In contrast, Wickens (1984, 2008) proposed a modality-specific model in which visual and auditory perception rely on different resources. Recent evidence has been hinting towards modality-specific influences on control processes in addition to central interference (e.g. Hazeltine et al., 2006; Schacherer & Hazeltine, 2020; see Koch et al., 2018, for a review). In the present study, we focus on modality-specific effects in task switching.

Stephan and Koch (2010) developed a spatial-discrimination paradigm to investigate modality-compatibility effects in task switching. Modality compatibility refers to the degree of similarity between the modality of the stimulus and the modality of the sensory consequences related to the response (Stephan & Koch, 2010). The concept of modality compatibility is based on the idea of ideomotor compatibility (Greenwald, 1972), which considers a stimulus and a sensory response effect compatible to the extent that they are similar to each other. This similarity, however, includes stimulus identity (for example, having to say "left"

in response to hearing the word “left”), and is therefore more narrow than the idea of modality compatibility. In contrast, the setup of a consecutive study by Stephan and Koch (2011) where participants had to respond by saying “A” or “one” in response to the auditory stimuli “X” and “M” would be considered modality-compatible because the sensory modality of the response effect is in accordance with the modality of the stimulus (see also Schacherer & Hazeltine, 2019); however, it would not be ideomotor-compatible because stimulus identity and response identity were not the same.

It should be noted that the concept of ideomotor compatibility is based on the ideomotor principle (James, 1890), which states that actions are initiated on the basis of their anticipated effects (see also Hommel et al., 2001), and recent evidence suggests people also monitor whether these action effects actually occur (Wirth, Janczyk, & Kunde, 2018; Wirth, Steinhauser et al., 2018). Thus, throughout our lives, we experience that vocal responses usually lead to auditory effects, whereas manual actions tend to result in visible changes in the environment, such as when viewing the hand moving in the case of eye-hand coordination in grasping actions. Therefore, an auditory-vocal and a visual-manual stimulus-response mapping can be considered modality-compatible, relatively speaking, while the opposite mappings, that is, auditory-manual or visual-vocal, would be classified as less modality-compatible or, relatively, modality-incompatible (Stephan & Koch, 2011, 2015).

In their study, Stephan and Koch (2010) found that switch costs were larger with modality-incompatible mappings (visual-vocal and auditory-manual) than with modality-compatible mappings (visual-manual and auditory-vocal). In order to understand the origins of the influence of modality compatibility in task switching, first one needs to note that this increase in switch costs has only been found when switching between *two* modality-incompatible mappings compared to *two* modality-compatible mappings, suggesting that interference only arises with specific combinations of modality mappings, rather than with individual

incompatible modality mappings per se (Fintor, Stephan, & Koch, 2018a). For example, in a modality-incompatible condition, performing a vocal response following a visual stimulus primes, by means of the anticipated action effect, the processing of auditory input, that is, the competing auditory-manual task, resulting in task confusion; the two task-sets interfere and create crosstalk (Stephan & Koch, 2011, 2015, 2016). If the stimulus is now manipulated to be even more similar to the anticipated response effect – for example, an auditory stimulus which is also a word (Schäffner et al., 2018), like the usually verbal output of a vocal response – this between-task confusion should become even stronger: A vocal response to a verbal stimulus would prime the processing of verbal auditory input, even if the stimulus instructing this vocal response is in fact a visual stimulus. Likewise, an auditory verbal stimulus would prime a vocal response even more strongly; the added similarity to the anticipated effect of said response would further simplify the response-selection process (Schacherer & Hazeltine, 2020). Consequently, this priming should then also occur if the instruction actually requires a manual response to auditory stimuli. If both of these primes occur in the same block (i.e. a block using two incompatible modality mappings), crosstalk between these two tasks should be increased.

In the present study, we aimed at examining whether modality compatibility is affected by variations in the type of task (spatial stimulus localisation vs. temporal stimulus-duration discrimination) and the type of the processing code (spatial-location vs. spatial-verbal codes) in two experiments. In both experiments we asked for manual vs. vocal responses. Note that we also included single-task blocks in order to assess mixing costs in addition to switch costs in mixed-task blocks.

Our basic predictions could be related to the modality-specific resource model suggested by Wickens (1984, 2008), which distinguishes between spatial and verbal processing codes. Specifically, the model links manual responses to the spatial processing code and vocal

responses to the verbal processing code. By extension, since manual responses are modality-compatible with visual stimuli and vocal responses are modality-compatible with auditory stimuli, Wickens et al. (1984) also proposed a connection between the spatial processing code and visual perception, as well as between the verbal processing code and auditory perception, because verbal stimuli are usually encountered in the context of speech.

In the present Experiment 1, we tested whether the use of spatial-verbal stimulus material would strengthen the auditory-vocal coupling compared to stimuli referring to spatial location. To this end, we employed the spatial-location discrimination task employed by Stephan and Koch (2010), who used visual stimuli presented on the left or right side of the screen and auditory stimuli (tones) presented on the left or right ear, and compared the influence of modality compatibility on task switching with these spatial-location stimuli to that on a similar paradigm using stimuli with the spatial-verbal meaning "left" and "right." We expected a larger influence of modality compatibility with spatial-verbal stimuli based on previous findings reported by Schäffner et al. (2018), who had already demonstrated larger effects of modality compatibility on switch costs with verbal stimuli compared to nonverbal stimuli (see also Göthe et al., 2016, for related ideas in dual-task research). However, they examined the influence of verbal vs. spatial stimuli in a between-subjects design using semantic classification tasks; in contrast, we aimed at isolating, more specifically, the role of spatial-location stimuli vs. spatial-verbal stimuli in modality compatibility in task switching.

In Experiment 2, we considered another possibility to strengthen the auditory-vocal coupling, namely by using a temporal-discrimination task compared to a spatial-discrimination task. In research on crossmodal attention, it has been found that spatial-discrimination tasks usually elicit visual dominance (e.g., Lukas et al., 2010; see also Spence et al., 2012; for a review), whereas temporal-discrimination tasks often elicit auditory dominance (e.g., Lukas et al., 2014; Repp & Penel, 2002). Therefore, in Experiment 2, we compared modality

compatibility effects with spatial-location stimuli with those in a temporal duration discrimination task, in which stimuli were either presented for a short or long time.

Increasing the strength of the coupling between a response modality and the modality of its anticipated effect should result in larger interference between mappings. Spatial-verbal processing codes and/or temporal-discrimination task demands should increase the auditory-vocal coupling compared to spatial-location stimuli and thus lead to a larger effect of modality compatibility on mixing costs and switch costs. Consequently, we expected an increased modality-compatibility effect on mixing costs and switch costs for spatial-verbal processing codes (Experiment 1) and temporal-duration task demands compared to spatial-location processing codes / task demands (Experiment 2).

Experiment 1

In Experiment 1, we used a spatial-discrimination task with spatial-verbal and spatial-location stimuli in modality-compatible and in modality-incompatible stimulus-response mappings. The spatial relation between stimulus and response was always compatible (for example, "left" stimuli always call for "left" responses).

Schäffner et al. (2018) systematically combined verbal vs. non-verbal stimulus codes (that is, written/spoken words vs. pictures/sounds) and spatial vs. nominal response codes (that is, words which describe a location, like "left" / "right", vs. a category/concept, like "insect" or "instrument") with compatible and incompatible modality mappings. The authors found larger switch costs when switching between two incompatible modality mappings compared to switching between two compatible modality mappings, but these modality-compatibility effects were larger for verbal input codes compared to non-verbal input codes. Schäffner et al. (2018) attributed these findings to more pronounced links between verbal stimuli and verbal response effects. However, their verbal stimuli required semantic categorisation (into the categories "living" and "non-living"), and only the responses consisted of saying the words "left" and "right"

or pressing left and right keys. In contrast, in our study, the dichotomy was spatial-location vs. spatial-verbal input codes, that is, the verbal stimuli still referred to spatial positions (the words "left" and "right").

We predicted a larger influence of modality compatibility on mixing costs and switch costs with spatial-verbal stimuli compared to spatial-location stimuli. Since we attribute such effects of modality compatibility to crosstalk between the tasks, which can only arise in mixed-task blocks, we did not predict any particular impact of modality compatibility on single-task performance. However, we still included single-task blocks in the experiment to be able to calculate mixing costs. Like in previous studies (Stephan & Koch, 2010, 2011, 2015, 2016), we collapsed the data across both modality-compatible tasks and across both modality-incompatible tasks to equate any trivial processing differences between different stimulus modalities (visual vs. auditory) or response modalities (manual vs. vocal) by themselves (such as vocal responses being generally slower than manual responses), since the term modality compatibility refers specifically to the interaction of stimulus modality and response modality (see Stephan & Koch, 2015, 2016).

Schacherer and Hazeltine (2019; see also Maquestiaux et al., 2018) suggested that compatible modality mappings could be maintained separately in a visual-spatial subsystem and an auditory-verbal subsystem (e.g. Baddeley, 1992, 2010); thus, when two tasks have to be maintained in working memory at the same time (Los, 1996), the load would still be lower for two compatible mappings than for two incompatible modality mappings. Hence, we expected that task confusion with incompatible modality mappings would affect both mixing costs and switch costs because between-task crosstalk should generally be larger in mixed-task blocks. However, switch trials should lead to particularly strong crosstalk-based interference because of the recent activation of the competing modality mapping.

Method

Participants. 24 subjects were tested[3] (21 female, 23 right-handed; mean age = 22.08, SD = 2.858, age range = 19-31). All of them reported normal or corrected-to-normal vision and hearing. Participants gave their informed consent and were compensated (received 6 € or partial course credit) for participating in the study. Both experiments were conducted in accordance with the ethical principles of the Declaration of Helsinki.

Stimuli and apparatus. The experiment was programmed using version 1.83.03 of PsychoPy2 (Peirce et al., 2019) and ran on a Linux computer using a 15.4" screen. Auditory spatial-location stimuli were generated in the software Audacity. Spatial-verbal auditory stimuli were recorded in a non-reflecting chamber.

Figure 1 provides an overview over all possible combinations of stimuli and responses. Visual spatial-location stimuli were white diamonds of 1.5 cm in width and height, presented on a black background, either 1.25 cm to the left or right of the centre of the screen. Auditory spatial-location stimuli were beep tones at 400 Hz presented via headphones on either the left or right ear. Visual spatial-verbal stimuli were the German words "LINKS" (left) and "RECHTS" (right) presented centrally in white capital letters and also 1.5 cm in height. Auditory spatial-verbal stimuli were the same German words in spoken form and presented binaurally. All stimuli lasted until a response occurred, or, in case of auditory spatial-verbal stimuli, for the duration of the spoken words, which was comparable since both words were monosyllabic. No visual fixation cross was presented to prevent priming of the visual modality. The decision to present stimuli until a response occurred (which was possible for all conditions except auditory spatial-verbal trials) was made to remain consistent with previous studies using the spatial-location paradigm (Fintor, Poljac, et al., 2018; Fintor, Stephan, & Koch, 2018a,

[3] The influence of modality compatibility on switch costs has been repeatedly replicated with sample sizes of 16 participants (Stephan & Koch, 2010, 2011). Testing 24 participants allowed us to detect a large effect (d_z = .8) at a significance level of α = .05 with a power of > .96 (Faul et al., 2007).

2018b; Stephan & Koch, 2010, 2015, 2016). We did not see any reason to assume that a longer presentation duration for the visual spatial-verbal stimuli compared to the auditory spatial-verbal stimuli should have a specific effect on modality compatibility.

---------- *Fig. 1* ----------

Procedure. Each trial began with the presentation of the target stimulus for a maximum duration of 1500 ms; stimulus presentation stopped when a response was detected. Depending on the instructed modality mapping (compatible vs. incompatible), a visual or auditory stimulus required a vocal or a manual response. Because modality compatibility was blocked, no explicit cues were required to instruct the response modality. The spatial stimulus-response (S-R) mapping was compatible for all subjects (that is, a left stimulus always required a left response, a right stimulus a right response). Manual responses were button presses with the left and right index finger; vocal responses were the German words “links” (= left) and “rechts” (= right) and recorded via a microphone, with both the microphone and the board featuring the buttons being connected to a response box. After a response had occurred, a response-stimulus interval (RSI) of 600 ms followed. Accuracy of vocal responses was coded by the experimenter during this interval; this allowed for error feedback to be presented after incorrect responses in either response modality. In case of an incorrect response (which included the case of a response on the correct spatial side but in the wrong modality), error feedback was presented bimodally – a red exclamation mark in the centre of the screen and a binaurally presented “boing” sound, both for 400 ms, after the standard RSI of 600 ms. Bimodal, nonverbal and centrally / binaurally presented error feedback was selected to ensure the error message would neither prime one modality (visual or auditory) nor one processing code (spatial-verbal or spatial-location) over the other. Error feedback was followed by a blank screen and silence on the headphones for 100 ms, lengthening the total RSI in case of an error to 1100 ms.

---------- *Fig. 2* ----------

The experiment was split in halves, a modality compatible and an incompatible condition (see Fig. 2). Within each condition, spatial-verbal and spatial-location stimuli were blocked, in counterbalanced order. Within each processing code condition, the block sequence was two single-task blocks of 40 trials each, one for each response modality (vocal and manual), followed by two mixed-task blocks of 80 trials each, featuring switches between the two previously introduced tasks. This means that within a given block, participants either switched between two compatible modality mappings (visual-manual and auditory-vocal), or between two incompatible modality mappings (visual-vocal and auditory-manual), responding to either only written and spoken words (spatial-verbal) in some blocks, or only to left and right diamond shapes and beep sounds (spatial-location) in other blocks. There were additional practice trials, 4 for each single-task block, 8 for the first of each two identical mixed-task blocks, as well as 2 warm-up trials after practice, at the beginning of the proper test phase of each block. The order of modality compatibility, processing code, and response modality (regarding which single-task came first) was counterbalanced across all participants. The overall duration of the experiment was about 45 minutes.

Design. The experiment had a within-subjects design with the independent variables processing code (spatial-verbal vs. spatial-location), modality compatibility (compatible vs. incompatible), and transition (repetitions in mixed-task blocks vs. single-task blocks for the mixing-cost contrast; switch vs. repetition in mixed-task blocks for the switch-cost contrast). The dependent variables were RT and error rates. All analyses were conducted at $\alpha = .05$.

Note that task-switching costs in our study refer to switching between modality mappings, so that a switch in stimulus modality always also entailed a switch in response modality. Results were analysed averaged across both compatible modality mappings (visual-manual vs. auditory-vocal) vs. across both incompatible modality mappings (visual-vocal vs. auditory manual), so that the main effect of modality compatibility describes the difference in RT

and error rates between the average of the two compatible modality mappings and the average of the two incompatible modality mappings. As such, our modality-compatibility contrast is independent of shifts in stimulus modality and response modality per se because both are strictly comparable when switching between modality incompatible modality mappings and when switching between modality compatible mappings.

Results

The practice trials and the first two test trials of each block were excluded from the analysis, as well as all trials with RT outside +/- 3 z around the mean per participant and block, and/or RT below 50 ms (0.003% of the data); RT analysis excluded all error trials and trials following an error trial, and error analysis excluded trials succeeding an error trial.

For the single-task blocks, we ran a repeated-measures ANOVA with the variables modality compatibility (incompatible vs. compatible) and processing code (spatial-verbal vs. spatial-location). For the analysis of mixed-task blocks, we calculated two ANOVAs each for RT and error rates, involving the independent variables modality compatibility (incompatible vs. compatible), processing code (spatial-verbal vs. spatial-location), and transition ([mixed repeat vs. single task (which is repetition by definition) for the mixing-cost contrast]; [switch vs. repetition the switch-cost contrast]). To follow up significant interactions, paired-sample *t*-tests were calculated. All analyses were conducted at $\alpha = .05$.

Single-task analysis. The ANOVA for single-task RT yielded a significant main effect of modality compatibility, $F(1, 23) = 9.546$, $p = 0.005$, $\eta^2_p = 0.293$, showing higher RT on modality-compatible trials than incompatible trials (614 ms vs. 589 ms). Thus, any differences between modality-compatible mappings and modality-incompatible mappings in the task-switching analysis cannot be attributed to higher RT, due to greater single-task difficulty, for modality incompatible mappings (see Fig. 3). The effect of processing code was also significant, $F(1, 23) = 524.833$, $p < 0.001$, $\eta^2_p = 0.958$, revealing slower responses for spatial-verbal

stimuli than for spatial-location stimuli (660 ms vs. 543 ms). Finally, there was a significant interaction of modality compatibility and processing code, $F(1, 23) = 26.256$, $p < 0.001$, $\eta^2_p = 0.533$, indicating that the modality-compatibility effect was larger for spatial-verbal than for spatial-location stimuli (-56 ms vs. 5 ms).

The single-task analysis of error rates yielded a significant effect of modality compatibility, $F(1, 23) = 13.776$, $p = 0.001$, $\eta^2_p = 0.375$, showing more errors for modality compatible than incompatible trials (2.6% vs. 1.5%) (see Table 1). There was also an effect of processing code, $F(1, 23) = 19.693$, $p < 0.001$, $\eta^2_p = 0.461$, revealing higher error rates for spatial-verbal than for spatial-location stimuli (3.0% vs. 1.1%). Finally, modality compatibility interacted significantly with processing code, $F(1, 23) = 15.221$, $p = 0.001$, $\eta^2_p = 0.398$, indicating a larger modality-compatibility effect for spatial-verbal stimuli than for spatial-location stimuli (-2.3% vs. 0.1).

Together, there was a performance cost for modality-compatible mappings only when using spatial-verbal stimuli, but this was not the case when using spatial-location stimuli, which is consistent with previous studies using such stimuli (e.g. Stephan & Koch, 2010). Note that single-task conditions did not produce any benefit for modality-compatible mappings (and even a disadvantage with spatial-verbal stimuli), but our predictions refer to conditions that include mapping switches.

---------- *Fig. 3* ----------

Mixing-cost contrast. The mixing-cost analysis of the RTs yielded a significant main effect of mixing, $F(1, 23) = 209.028$, $p < 0.001$, $\eta^2_p = 0.901$, revealing higher RT in the repetition trials in mixed-task blocks compared to single-task blocks (680 ms vs. 601 ms). The main effect of modality compatibility was not significant ($F < 1$). Processing code yielded a significant main effect, $F(1, 23) = 389.147$, $p < 0.001$, $\eta^2_p = 0.944$, indicating slower responses for spatial-verbal than for spatial-location stimuli (699 ms vs. 582 ms).

The expected two-way interaction of modality compatibility and mixing was significant, $F(1, 23) = 39.630$, $p < 0.001$, $\eta^2_p = 0.633$, showing larger mixing costs for the modality-incompatible condition than for the modality-compatible condition (107 ms vs. 50 ms). The interaction of modality compatibility and processing code was significant, too, $F(1, 23) = 12.504$, $p = 0.002$, $\eta^2_p = 0.352$, implying a larger modality-compatibility effect for spatial-location than for spatial-verbal stimuli (20 ms vs. -12 ms). The interaction of processing code and mixing was non-significant ($F < 1$). Notably, the predicted three-way interaction of modality compatibility, mixing, and processing code was significant as well, $F(1, 23) = 15.167$, $p = 0.001$, $\eta^2_p = 0.397$. The post-hoc t-test confirmed that mixing costs were significantly larger in the modality-incompatible condition than in the modality-compatible condition with spatial-verbal processing codes, $t(23) = 8.247$, $p < 0.001$, $d = 1.68$ (121 ms vs. 36 ms), whereas this difference was still significant but just smaller with spatial-location processing codes, $t(23) = 2.241$, $p = 0.035$, $d = 0.46$ (94 ms vs. 65 ms).

The error analysis showed a significant effect of mixing, $F(1, 23) = 6.914$, $p = 0.015$, $\eta^2_p = 0.231$, revealing more errors in repetition trials in mixed-task blocks than in single-task blocks (3.2% vs. 2.1%). There was a non-significant trend towards an effect of modality compatibility, $F(1, 23) = 3.096$, $p = 0.092$, $\eta^2_p = 0.119$, suggesting numerically higher error rates in the modality-compatible than in the incompatible condition (2.9% vs. 2.3%). There was also a significant effect of processing code, $F(1, 23) = 20.983$, $p < 0.001$, $\eta^2_p = 0.477$, with more errors for spatial-verbal than for spatial-location stimuli (3.4% vs. 1.9%).

The two-way interaction between modality compatibility and mixing was not significant, $F(1, 23) = 1.684$, $p = 0.207$, $\eta^2_p = 0.068$; however, mixing costs were still numerically larger in the modality-incompatible condition (1.6%) than in the modality-compatible condition (0.6%). The interaction of processing code and mixing was non-significant, $F(1, 23) = 2.496$, $p = 0.128$, $\eta^2_p = 0.098$. There was a non-significant trend for an interaction between modality

compatibility and processing code, $F(1, 23) = 3.643$, $p = 0.069$, $\eta^2_p = 0.137$, but importantly, like in the RT data, modality compatibility, mixing, and processing code entered a significant three-way interaction, $F(1, 23) = 5.555$, $p = 0.027$, $\eta^2_p = 0.195$. The post-hoc t-test confirmed that spatial-verbal processing codes led to larger mixing costs in the modality-incompatible condition compared to the modality-compatible condition, $t(23) = 2.069$, $p = 0.050$, $d = 0.42$ (1.8% vs. -0.3%), whereas spatial-location processing codes showed no significant difference in mixing cost between modality-incompatible and modality-compatible conditions, $t(23) = 0.293$, $p = 0.772$, $d = 0.06$ (1.3% vs. 1.5%).

---------- *Table 1* ----------

Switch-cost contrast. The RT task-switching analysis in the switch-cost contrast yielded a significant effect of switching, $F(1, 23) = 200.725$, $p < 0.001$, $\eta^2_p = 0.897$, revealing higher RT on switch trials than on repetition trials (771 ms vs. 680 ms). There was also an effect of modality compatibility, $F(1, 23) = 12.218$, $p < 0.002$, $\eta^2_p = 0.347$, with higher RT for the modality-incompatible condition than for the modality-compatible condition (741 ms vs. 709 ms). Finally, there was a main effect of processing code, $F(1, 23) = 246.681$, $p < 0.001$, $\eta^2_p = 0.915$, showing higher RT for spatial-verbal processing codes than for spatial-location processing codes (776 ms vs. 675 ms).

The interaction of modality compatibility and switching was not significant, $F(1, 23) = 0.004$, $p = 0.953$, $\eta^2_p = 0.000$, but switching interacted significantly with processing code, $F(1, 23) = 12.310$, $p = 0.002$, $\eta^2_p = 0.349$, showing larger switch costs with spatial-location codes than with spatial-verbal codes (105 ms vs. 76 ms). The interaction of processing code and modality compatibility was non-significant, $F(1, 23) = 1.995$, $p = 0.171$, $\eta^2_p = 0.080$, but the three-way interaction of modality compatibility, switching, and processing code was significant, $F(1, 23) = 7.074$, $p = 0.014$, $\eta^2_p = 0.235$. The post-hoc t-test showed (non-significantly) larger switch costs in the modality-incompatible condition relative to the modality-compatible condition (85

ms vs. 66 ms) for spatial-verbal processing codes, $t(23) = 0.999$, $p = 0.328$, $d = 0.20$, whereas for spatial-location processing codes there was an unexpected non-significant trend in the opposite direction, $t(23) = 2.001$, $p = 0.057$, $d = 0.41$ (116 ms modality-compatible vs. 95 ms modality-incompatible). Note that the error rates show increased switch costs in the modality-incompatible condition for the spatial-location processing codes, implying a specific speed-accuracy trade-off (see below).

The analysis of error rates in the switch-cost contrast showed that switching led to a significant main effect, $F(1, 23) = 23.260$, $p < 0.001$, $\eta^2_p = 0.503$, revealing more errors on switch trials than on repetition trials (6.8% vs. 3.2%). There was an effect of processing code, $F(1, 23) = 4.455$, $p = 0.046$, $\eta^2_p = 0.162$, revealing higher error rates for spatial-verbal than for spatial-location processing codes (5.3% vs. 4.6%). The interaction between modality compatibility and switching was significant, $F(1, 23) = 5.795$, $p = 0.024$, $\eta^2_p = 0.201$, revealing larger switch costs in the modality-incompatible condition compared to the modality-compatible condition (4.7% vs. 2.6%). However, the three-way interaction together with processing code was not significant, $F(1, 23) = 0.270$, $p = 0.608$, $\eta^2_p = 0.012$, suggesting no difference in the effect of modality compatibility on switch costs between spatial-verbal and spatial-location stimuli. All other effects were non-significant (Fs < 2).

Please note that the error data show generally larger switch costs for modality-incompatible conditions, regardless of whether processing codes were spatial-verbal or spatial-location. Notably, the opposing RT trend with spatial-location stimuli was thus clearly not supported by the error rates, Hence, the data of the switch cost contrast are ambiguous with spatial-location stimuli, suggesting a speed-accuracy trade-off that is not easily explainable, whereas the data show consistently increased switch costs with modality-incompatible mappings when using spatial-verbal stimuli. For the full overview of the data in each component task, please see Table 2.

---------- *Table 2* ----------

Discussion

In Experiment 1, we tested the prediction that modality-compatibility effects in task switching should be larger with spatial-verbal stimuli because these should strengthen particularly the vocal-auditory modality mapping. We found a consistent influence of spatial-verbal stimuli in terms of a larger modality-compatibility effect on mixing costs compared to spatial-location stimuli. We also found increased switch costs with modality incompatibility with spatial-verbal stimuli (even though the trend was non-significant in RT), but for spatial-location stimuli we found it only for error rates, whereas this effect was even non-significantly reversed in RT, hinting at a specific speed-accuracy trade-off. Note that the effect of increased RT switch costs in modality-incompatible conditions has been replicated several times with spatial-location stimuli (Fintor, Stephan, & Koch, 2018a; Stephan & Koch, 2010, 2011, 2015, 2016), so that its absence in the present experiment should not be overemphasized.

Note also that the single-task blocks showed even worse performance in modality-compatible conditions, but this was confined to spatial-verbal conditions. While we have no explanation for this effect, methodologically it rules out that more "difficult" tasks also lead to larger costs in multitasking (Stephan & Koch, 2011) because the data pattern is the opposite.

Using a dual-task setting, Göthe et al. (2016) had performed a modality-compatibility study with spatial-verbal and spatial-location stimuli in a between-subjects design with bimodal stimulation. They found higher dual-task costs not only for modality-incompatible mappings, but also for location-vocal and verbal-manual mappings of processing code and response, compared to the mappings spatial-manual and verbal-vocal. Notably, the highest costs were observed in the group that faced both an incompatible modality mapping and a location-vocal + verbal-manual feature mapping. In our task-switching setup, all factors were varied within subjects. Note also that none of the mappings in the study by Göthe et al. (2016) met the narrow

definition of ideomotor compatibility (Greenwald, 1972), whereas our setup included one ideomotor-compatible condition: the auditory-verbal condition, that is, hearing the word "left" or "right" and responding vocally by saying the same word.

Taken together, the data suggest that spatial-verbal stimuli create greater between-task crosstalk than spatial-location stimuli when two tasks with modality-incompatible stimulus-response mappings have to be maintained in working memory at the same time. Note though that the spatial-verbal and the spatial-location task we used in Experiment 1 were similar to each other because both types of stimuli contained a spatial meaning (left vs. right).

Experiment 2

In Experiment 2 we compared performance with the spatial-discrimination task with that in a genuinely different type of discrimination, namely a temporal-discrimination task. By employing a task that should be more appropriate for the auditory modality in a multitasking setting (Freides, 1974; Lukas et al., 2014; Talsma et al., 2010; Welch & Warren, 1980), once more, like in Experiment 1, we expected the auditory-vocal coupling to be strengthened: The results pattern found for spatial-verbal processing codes and temporal-duration task demands should be comparable, since segmenting speech also requires high temporal resolution (e.g. Bell-Berti & Harris, 1981; Smith, 1978). The likelihood of the anticipation of the effect of a vocal response priming the processing of auditory input should therefore increase, since the auditory modality is the relatively more appropriate one for temporal processing in a multitasking setting to begin with. If such a prime for auditory input occurs when the actual stimulus is visual, the primed task would be the wrong one. Thus we again predicted that mixing costs and switch costs should be larger with modality-incompatible mappings, and this should be even more pronounced with a temporal-duration task than with a spatial-location task.

Method

Participants. 24 new participants who had not taken part in Experiment 1 were tested (18 female, 23 right-handed; mean age = 22.26, SD = 2.490, age span = 19-29). All of them reported normal or corrected-to-normal eyesight and hearing. Each of them gave their informed consent and received 6 € or partial course credit for their participation.

Stimuli and apparatus. Stimuli for the spatial-discrimination task were the same spatial-location stimuli as in Experiment 1. For the temporal-discrimination task, as visual stimuli we used the same diamonds as for the spatial-discrimination task, but presented centrally for either 100 ms (short) or 500 ms (long). The auditory equivalent was the same beep tone as in the spatial-discrimination task (400 Hz), presented binaurally for the respective durations (with parameters borrowed from Lukas et al., 2014). Like in Experiment 1, we used a constant spatially-compatible S-R mapping for all participants, that is, in the spatial-location task, a left stimulus required a left response, a right stimulus a right response. For the temporal-duration task, we argue that left is spatially more compatible with short and right is spatially more compatible with long stimuli (e.g., Walsh, 2003).

Procedure. Trials and the overall experiment followed the same structure as Experiment 1, with the spatial-location condition remaining exactly as in Experiment 1, but with a temporal-duration task replacing the condition with spatial-verbal processing codes. As in Experiment 1, in both tasks, vocal responses were the words “links” (German for “left”) and “rechts” (German for “right”), and manual responses were left and right button presses.

Note that spatial-location stimuli were presented until a response occurred, but the temporal-duration stimuli were presented for constant durations (100 ms vs. 500 ms). Responses for both task demands were possible starting from stimulus onset, so in case a participant was able to identify a long-duration stimulus before 500 ms had elapsed, the stimulus would continue to be presented into the RSI. Once the stimulus had been presented for its designated duration, the remainder of the RSI consisted of silence and a blank screen.

As such, it needs to be considered that the earliest point at which a judgement of the temporal duration of the stimulus could be made was after 100 ms had elapsed. Even though subjects were told to respond as quickly and accurately as possible, we cannot rule out that, in case of a long-duration stimulus, some participants may have waited for the entire 500 ms before judging it as "long". This means that overall RT for long stimuli was by design higher than for short stimuli, so that overall RT for temporal-duration tasks was also higher than overall RT for spatial-location tasks. Consequently, interpretations of main effects of task demand (temporal-discrimination vs. spatial-location-discrimination) are not meaningful, but interactions of task demand with modality compatibility and transition can be interpreted.

Design. The independent within-subjects variables were task demand (temporal-discrimination task vs. spatial-location-discrimination task), modality compatibility (compatible vs. incompatible), and transition (repetitions in mixed-task blocks vs. single-task blocks for the mixing-cost contrast; switch vs. repetition trials in the mixed-task block for the switch-cost contrast). The dependent variables were RT and error rates.

Results

Data analysis proceeded as in Experiment 1. Trials excluded as RT outliers amounted to 0.002%.

Single-task analysis. The ANOVA on RT (see Fig. 4) yielded a significant effect of modality compatibility, $F(1, 23) = 12.683$, $p = 0.002$, $\eta^2_p = 0.355$, revealing slower responses in the modality-compatible condition than in the modality-incompatible condition (673 ms vs. 650 ms). There was also an effect of task demand, $F(1, 23) = 728.613$, $p < 0.001$, $\eta^2_p = 0.969$, indicating higher RT for temporal-duration task demands than for spatial-location task demands (773 ms vs. 550 ms). Finally, there was a significant interaction of modality compatibility and task demand, $F(1, 23) = 18.975$, $p < 0.001$, $\eta^2_p = 0.452$, indicating a larger and reversed

modality-compatibility effect with temporal-duration task demands compared to spatial-location task demands (-56 ms vs. 11 ms).

The error-rate analysis (see Table 3) showed a significant effect of modality compatibility, $F(1, 23) = 7.474$, $p = 0.012$, $\eta^2_p = 0.245$, revealing more errors on modality compatible than incompatible conditions (3.1% vs. 1.9%). There was also an effect of task demand, $F(1, 23) = 75.366$, $p < 0.001$, $\eta^2_p = 0.766$, pointing at higher error rates with temporal than with spatial-location discrimination (4.1% vs. 0.9%). Finally, there was a non-significant trend towards an interaction of modality compatibility and task demand, $F(1, 23) = 3.755$, $p = 0.065$, $\eta^2_p = 0.140$, suggesting a numerically larger modality-compatibility effect for temporal-duration task demands than for spatial-location task demands (-1.9% vs. -0.4%).

---------- *Fig. 4* ----------

Mixing-cost contrast. The RT analysis yielded a main effect of mixing, $F(1, 23) = 106.257$, $p < 0.001$, $\eta^2_p = 0.822$, showing larger RT for repetitions in mixed-task blocks compared to single-task blocks (726 ms vs. 661 ms). There was also a main effect of task demand, $F(1, 23) = 1103.394$, $p < 0.001$, $\eta^2_p = 0.980$, revealing higher RT for temporal-duration task demands than for spatial-location task demands (802 ms vs. 585 ms).

There was an interaction of modality compatibility and mixing, $F(1, 23) = 23.109$, $p < 0.001$, $\eta^2_p = 0.501$, confirming larger mixing costs in the modality-incompatible condition compared to the modality-compatible condition (86 ms vs. 43 ms). Modality compatibility and task demand also interacted significantly, $F(1, 23) = 19.964$, $p < 0.001$, $\eta^2_p = 0.465$, implying a reversed overall influence of modality compatibility in the temporal-duration task compared to an influence of modality compatibility in the expected direction with the spatial-location task (-28 ms temporal-duration vs. 25 ms spatial-location).

Notably, for the predicted three-way interaction of modality compatibility, task demand, and mixing we found a non-significant trend, $F(1, 23) = 3.709$, $p = 0.067$, $\eta^2_p = 0.139$. Despite this non-significant result, we calculated a follow-up test to determine whether at least the direction of this numerical trend was consistent with our hypothesis, since we had indeed found this significant three-way interaction in the mixing-cost contrast of both RT and error rates in Experiment 1, These post-hoc t-tests suggested that the modality-compatibility effect on mixing costs tended to be larger for the temporal-duration task demand, $t(23) = 5.313$, $p < 0.001$, $d = 1.08$ (86 ms mixing costs for the modality-incompatible condition vs. 30 ms mixing costs for the modality-compatible condition) than for the spatial-location task demand, $t(23) = 2.221$, $p = 0.037$, $d = 0.45$ (85 ms modality-incompatible vs. 58 ms modality-compatible). All other effects were non-significant (Fs < 2.2, ps > 0.1).

The error analysis yielded an effect of mixing, $F(1, 23) = 21.298$, $p < 0.001$, $\eta^2_p = 0.481$, indicating more errors for repetitions in mixed-task blocks compared to single-task blocks (4.0% vs. 2.5%). Modality compatibility yielded a significant effect as well, $F(1, 23) = 8.135$, $p = 0.009$, $\eta^2_p = 0.261$, revealing more errors in the modality-compatible compared to the modality-incompatible condition (3.9% vs. 2.6%). There was also an effect of task demand, $F(1, 23) = 95.006$, $p < 0.001$, $\eta^2_p = 0.805$, showcasing higher error rates with temporal-duration task demands than with spatial-location task demands (4.8% vs. 1.7%). Furthermore, there was a significant interaction between modality compatibility and task demand, $F(1, 23) = 9.078$, $p = 0.006$, $\eta^2_p = 0.283$, suggesting that the (reversed) modality-compatibility effect was present with temporal-duration but not with spatial-location task demands (-2.6% vs. 0.0%).

The three-way interaction of modality compatibility, task demand, and mixing again showed a non-significant trend, $F(1, 23) = 3.713$, $p = 0.066$, $\eta^2_p = 0.139$. Again, a post-hoc t-test was calculated to determine the direction of this numerical trend; this test however showed that the effect of modality compatibility on mixing costs was neither significant for temporal-

duration task demands, $t(23) = 1.347$, $p = 0.191$, $d = 0.27$ (0.7% modality-incompatible vs. 2.0% modality-compatible), nor for spatial-location task demands, $t(23) = 1.064$, $p = 0.299$, $d = 0.22$ (1.9% vs. 1.3%). All other effects were non-significant, including the interaction of modality compatibility and mixing (Fs < 1).

---------- *Table 3* ----------

Switch-cost contrast. The RT analysis revealed an effect of switching, $F(1, 23) = 164.778$, $p < 0.001$, $\eta^2_p = 0.878$, with higher RT on switches than on repetitions (809 ms vs. 726 ms). There was also an effect of modality compatibility, $F(1, 23) = 6.065$, $p = 0.022$, $\eta^2_p = 0.209$, showing slower responses for the modality-incompatible condition compared to the modality-compatible condition (777 ms vs. 758 ms). Finally, task demand revealed a significant effect as well, $F(1, 23) = 1095.559$, $p < 0.001$, $\eta^2_p = 0.979$, showing higher RT for temporal-duration task demands than for spatial-location task demands (877 ms vs. 658 ms).

We found a significant interaction between task demand and switching, $F(1, 23) = 5.727$, $p = 0.025$, $\eta^2_p = 0.199$, revealing larger switch costs for temporal-duration task demands than for spatial-location task demands (92 ms vs. 74 ms). Note that modality compatibility and switching did not show a significant interaction, $F(1, 23) = 0.011$, $p = 0.916$, $\eta^2_p = 0.000$, but the predicted three-way interaction of modality compatibility, task demand, and switching was significant, $F(1, 23) = 11.122$, $p < 0.003$, $\eta^2_p = 0.326$. The post-hoc t-test showed that for the temporal-duration task demand, switch costs were numerically larger in the modality-incompatible condition compared to the modality-compatible condition, $t(23) = 1.538$, $p = 0.138$, $d = 0.31$ (103 ms vs. 81 ms), but for spatial-location, switch costs were actually larger in the modality-compatible condition than in the modality-incompatible condition, $t(23) = 2.593$, $p = 0.016$, $d = 0.53$ (84 ms vs. 64 ms). The remaining interaction of modality compatibility and task demand was non-significant ($p > 0.10$).

The error analysis in the switch-cost contrast demonstrated a significant effect of switching, $F(1, 23) = 15.521$, $p = 0.001$, $\eta^2_p = 0.403$, showing more errors on switch trials than on repetition trials (6.2% vs. 4.0%). There was a significant effect of task demand, too, $F(1, 23) = 85.443$, $p < 0.001$, $\eta^2_p = 0.788$, revealing more errors for temporal-duration task demands than for spatial-location task demands (6.7% vs. 3.5%).

Unlike in the RT data, there was a significant interaction of modality compatibility and switching, $F(1, 23) = 11.022$, $p = 0.003$, $\eta^2_p = 0.324$, confirming larger switch costs in the modality-incompatible condition compared to the compatible condition (4.1% vs. 0.4%). The interaction of modality compatibility and task demand was also significant, $F(1, 23) = 7.314$, $p = 0.013$, $\eta^2_p = 0.241$, implying a stronger general modality-compatibility effect with spatial-location task demands than with temporal-duration task demands, for which the modality-compatibility effect was reversed (1.7% vs. -0.9%). Yet, the three-way interaction of modality compatibility, task demand, and switching was not significant, $F(1, 23) = 2.292$, $p = 0.144$, $\eta^2_p = 0.091$, suggesting no difference in the size of the modality-compatibility effect on switch costs between temporal-duration task demands and spatial-location task demands. All other effects were non-significant (Fs < 1).

Again, like in Experiment 1, the data of Experiment 2 showed a reasonably clear picture in the mixing cost contrast, but in the switch cost contrast the data of the spatial-location task shows an unclear trade-off, with larger error switch costs in the modality-incompatible condition, which was expected, but unexpectedly smaller RT switch costs in the modality-incompatible condition. Hence, the influence of modality compatibility on switch costs with spatial-

location task demands are again difficult to interpret.[4] For the full overview of the data in each component task, please see Table 4.

---------- *Table 4* ----------

Discussion

In Experiment 2, we found an influence of temporal-duration task demands, in form of a trend for a stronger effect of modality compatibility on mixing costs compared to spatial-location task demands. However, the data suggested a numerically larger influence of modality compatibility on mixing costs with the temporal-duration task only for RT. Again, similarly to Experiment 1, for spatial-location task demands the switch cost contrast showed an unclear speed-accuracy trade-off. The predicted interactions of modality compatibility and transition revealed a modality-compatibility effect on mixing costs for RT, and a modality-compatibility effect on switch costs for errors.

Supplemental Analyses

In order to assess to what extent the auditory-vocal coupling was strengthened by spatial-verbal processing codes and temporal-duration task demands compared to spatial-location processing codes / task demands, we considered performance with the individual modality-incompatible mappings. Therefore, for the auditory-manual mapping and the visual-vocal

[4] We examined whether the order in which the tasks were presented – spatial-verbal vs. spatial-location in Experiment 1; temporal-duration vs. spatial-location in Experiment 2 – might have influenced performance specifically in the spatial-location task. Yet, RT switch costs on the spatial-location task were consistently at least numerically larger with modality-compatible mappings, and error switch costs were larger with modality-incompatible mappings. This means the trade-off was always present, irrespective of the order in which the tasks were presented. Note that participants who started with the spatial-location task were, at the time of performing the spatial-location task, facing the same conditions as subjects in preceding studies that exclusively employed the spatial-location task (e.g. Fintor et al., 2018a; Stephan & Koch, 2010). This leaves no obvious explanation for the trade-off in our study.

mapping separately, we ran 2x2 ANOVAs with the within-subjects variables transition (mixed vs. single in the mixing-cost contrast and switch vs. repetition in the switch-cost contrast) and processing code (spatial-verbal vs. spatial-location) for Experiment 1 or task demand (temporal-duration vs. spatial location) for Experiment 2. For the sake of brevity, we only report the relevant interactions of mixing / switching and processing code / task demand.

Auditory-manual mapping. For Experiment 1, the interaction of mixing and processing code was significant for RT, $F(1, 23) = 6.708$, $p = 0.016$, $\eta^2_p = 0.226$, revealing larger mixing costs with spatial-verbal codes compared to spatial-location codes (159 ms vs. 117 ms); in error rates, the interaction was not significant ($p = 0.263$), but the numerical trend pointed into the same direction (1.0% spatial-verbal vs. -0.1% spatial-location). The interaction of switching and processing code was neither significant for RT, $F(1, 23) = 1.845$, $p = 0.188$, $\eta^2_p = 0.074$, nor for errors, $F(1, 23) = 1.230$, $p = 0.279$, $\eta^2_p = 0.051$, but there were numerically larger switch costs with spatial-verbal processing codes than with spatial-location processing codes (84 ms vs. 65 ms for RT and 3.8% vs. 2.1% for errors).

For Experiment 2, the interaction of mixing and task demand was neither significant for RT, $F(1, 23) = 0.746$, $p = 0.397$, $\eta^2_p = 0.031$, nor for errors, $F(1, 23) = 1.905$, $p = 0.181$, $\eta^2_p = 0.076$. The interaction of switching and task demand however was significant in both RT, $F(1, 23) = 40.251$, $p < 0.001$, $\eta^2_p = 0.636$, and error rates, $F(1, 23) = 15.091$, $p = 0.001$, $\eta^2_p = 0.396$, with larger switching costs for the temporal-duration task demand than for the spatial-location task demand (122 ms vs. 52 ms for RT and 5.4% vs. 0.8% for errors).

Visual-vocal mapping. For Experiment 1, the interaction of mixing and processing code was neither significant for RT, $F(1, 23) = .147$, $p = 0.705$, $\eta^2_p = 0.006$, nor for errors, $F(1, 23) = 0.001$, $p = 0.970$, $\eta^2_p = 0.000$. Switching and processing code, however, revealed a non-significant interaction trend in RT, $F(1, 23) = 3.836$, $p = 0.062$, $\eta^2_p = 0.143$ (120 ms spatial-location vs. 88 ms spatial-verbal), and a significant interaction in error rates, $F(1, 23) = 6.416$, $p = 0.019$,

$\eta^2_p = 0.218$ (8.2% spatial-location vs. 3.9% spatial-verbal), demonstrating consistently higher switch costs for spatial-location codes than for spatial-verbal codes.

For Experiment 2, mixing and task demand did not interact significantly, neither for RT, $F(1, 23) = 0.294$, $p = 0.593$, $\eta^2_p = 0.013$, nor for error rates, $F(1, 23) = 1.438$, $p = 0.243$, $\eta^2_p = 0.059$. Switching and task demand neither showed a significant interaction for RT, $F(1, 23) = 0.003$, $p = 0.960$, $\eta^2_p = 0.000$, nor for errors, $F(1, 23) = 0.868$, $p = 0.361$, $\eta^2_p = 0.036$.

Taken together, these results reveal that mixing costs and switch costs with the modality-incompatible auditory-manual mapping were indeed negatively affected by both spatial-verbal processing codes and temporal-duration task demands compared to spatial-location processing codes / task demands. Specifically, with the auditory-manual mapping spatial-verbal processing codes predominantly affected mixing costs, whereas temporal-duration task demands mainly influenced switch costs. Meanwhile, mixing costs and switch costs with the competing visual-vocal mapping either did not differ based on processing code / task demand, or they were enlarged with the spatial-location processing code / task demand compared to its respective counterpart. This suggests that the increased influence of modality compatibility on mixing costs (and, to a lesser extent, switch costs) which we found in the main analysis with both spatial-verbal processing codes and temporal-duration task demands can be attributed mainly to their effect on the auditory-manual mapping, probably because auditory stimuli are particularly strongly coupled with vocal responses.

We can only speculate why the auditory-manual mapping was only affected in terms of mixing costs by the spatial-verbal processing codes and only in terms of switch costs by the temporal-duration task demands. The absence of an effect of temporal-duration task demands on mixing costs for the auditory-manual mapping might be explained by the smaller similarity between the auditory temporal-duration stimulus and the auditory effect of the response, which was still spatial-verbal (the spoken word “left” or “right”) – compared to Experiment 1, where

the effect of the vocal response and the auditory stimulus were ideomotor compatible. This smaller similarity in Experiment 2 might have led to less between-task crosstalk.

General Discussion

In two experiments, we examined modality compatibility in task switching using visual and auditory stimuli as well as manual and vocal responses. Previous studies demonstrated increased mixing costs and switch costs with incompatible modality mappings compared to compatible modality mappings. In the present study we investigated whether spatial-verbal processing codes (Experiment 1) and/or temporal-discrimination task demands (Experiment 2) would increase the strength of the auditory-vocal coupling and thereby the influence of modality compatibility on mixing and switch costs.

Summary of main findings

We found a consistently larger modality-compatibility effect on mixing costs for both spatial-verbal codes compared to spatial-location codes (Experiment 1) and for temporal-discrimination task demands compared to spatial-location task demands (Experiment 2). The findings with respect to switch costs are less consistent in the spatial-discrimination paradigm because of an unexpected speed-accuracy trade-off, but for both spatial-verbal processing codes and temporal-duration tasks switch costs were always at least numerically larger in the modality-incompatible condition than in the modality-compatible condition.

The analysis of the individual modality mappings supported our account that, compared to spatial-location discrimination tasks (i.e., requiring spatial-location codes), both spatial-verbal codes and temporal-duration task demands indeed strengthened the auditory-vocal coupling. This is suggested by the analysis of the respective counterparts to those couplings, i.e. the individual modality-incompatible mappings: The auditory-manual mapping showed larger mixing costs with spatial-verbal processing codes and larger switch costs with temporal-duration task

demands, as well as numerical trends into the same direction for larger switch costs with spatial-verbal processing codes in Experiment 1 and larger mixing costs with temporal-duration task demands in Experiment 2. Meanwhile, the overall impact of processing codes / task demands on the visual-manual coupling was much less pronounced when assessed in the modality-incompatible counterpart, that is, the visual-vocal mapping.

The role of processing codes in mixing costs

Embedding our findings on mixing costs into the literature, our results are in line with Schacherer and Hazeltine (2019), who also found larger mixing costs with modality-incompatible mappings than with modality-compatible mappings. Our study suggests, more specifically, that both spatial-verbal processing codes and temporal-discrimination task demands increase the impact of modality compatibility on mixing costs.

When two tasks with modality-compatible mappings need to be maintained in working memory, working-memory load should be lower because both tasks can be processed more or less independently in distinct subsystems (Baddeley, 1992, 2010). For example, the auditory-vocal task requires the phonological loop and the visual-manual task requires the visuospatial sketchpad, whereas in the modality-incompatible visual-vocal task, the visual stimulus would refer to the visuospatial sketchpad, but the vocal response (and its anticipated auditory effect) to the phonological loop. Hence, with both tasks referring to distinct subsystems, between-task crosstalk should be lower (see Maquestiaux et al., 2018; Schacherer & Hazeltine, 2019).

The supplemental analysis showed that mixing costs for auditory-manual trials were particularly affected by spatial-verbal processing codes and temporal-discrimination task demands (each compared to spatial-location codes / task demands). That is, when sensory input in different modalities needs to be processed and also reactions in different modalities are required, auditory stimuli tend to require vocal responses (as it is common in conversations in everyday life) and this tendency is even increased when auditory input was also verbal in nature.

This suggests that, as predicted, the auditory-vocal coupling was indeed strengthened by spatial-verbal codes. This pattern is consistent with Wickens (1984), and we can specify that the definition of compatibility of mappings can be derived from ideomotor theorizing proposing a strong role of anticipation of sensory action effects in action selection generally (Greenwald, 1972; Shin et al., 2010).

While there is a similar connection between spatial-location tasks and the visual-manual mapping (Wickens et al., 1984), the similarity in the present study between a manual keypress and a white diamond-shaped stimulus is obviously much smaller than between an auditory stimulus and a vocal response which both produce the exact same word. Thus, the ideomotor linkage between the spatial-location task and the visual-manual coupling should be considerably weaker than the ideomotor linkage between the spatial-verbal task and the auditory-vocal coupling. Hence, spatial-verbal stimuli can be assumed to have strengthened the auditory-vocal coupling to a greater extent than the spatial-location stimuli may have strengthened the visual-manual coupling.

The role of processing codes in switch costs

Regarding switch costs, however, the prediction that interference due to spatial-verbal codes or temporal-duration task demands should be particularly strong on switch trials could not be confirmed: While the modality-compatibility effect was still numerically present in the expected direction for both spatial-verbal codes and temporal-duration task demands, spatial-location codes / task demands yielded a speed-accuracy trade-off that was not observed in earlier studies (Fintor, Poljac, et al., 2018; Fintor, Stephan, & Koch, 2018a, 2018b; Schacherer & Hazeltine, 2019; Stephan & Koch, 2010, 2011, 2015, 2016; Stephan et al., 2013). Specifically with regard to spatial-verbal codes, our results are also not completely in line with the study by Schäffner et al. (2018), who had indeed found larger switch costs with verbal compared to nonverbal stimulus material, and with incompatible modality mappings, while we found larger

switch costs with spatial-location (nonverbal) stimuli and compatible modality mappings in RT, and larger switch costs for incompatible modality mappings in error rates, but with *both* types of processing codes. The important distinction though, as mentioned earlier, is that in the spatial-verbal condition in the study by Schäffner et al. (2018), only the responses actually featured a spatial component, whereas the stimuli referred to semantic categories; in our Experiment 1, both the spatial-verbal stimuli and the required responses were conceptually overlapping, since both referred to the spatial dimension.

Schacherer and Hazeltine (2019) demonstrated how differences in switch costs between compatible and incompatible modality mappings could be made to disappear by reducing conceptual overlap between the tasks. However, since our participants only switched between modality mappings, that is, there were no trial-to-trial switches between spatial-verbal codes / temporal-duration task demands and spatial-location codes / task demands, we would argue that the amount of conceptual overlap within one processing code or task demand was equal: It either always referred to a spatial code (with spatial-verbal and spatial-location stimuli) or duration (with temporal-duration). Note that in the context of dual-task training, Maquestiaux et al. (2018) explained the beneficial effects of modality compatibility in terms of Baddeley's (e.g. 1992, 2010) model of working memory, suggesting that response selection should be easier with compatible modality mappings because both stimulus and response codes referred to the same subsystem. However, this more general approach can explain the effect on mixing costs (see previous section); it is less clear how it could explain the specifically increased between-task crosstalk in task switches relative to repetitions.

Based on our ideomotor approach, we can integrate the notion of distinct working memory subsystems, so that these are not mutually exclusive accounts, even though we believe that our account is more specific. In particular, we propose that in Experiment 1, spatial-location codes may be processed in the visuospatial sketchpad, while spatial-verbal codes would be held

primarily by the phonological loop (because their "spatial" component is merely semantic; their physical location was central / binaural, i.e. neutral). Hence, it would be more difficult to select the proper response code from one working-memory subsystem if both the code for the stimulus modality and the spatial-verbal / spatial-location code are processed in the respective other subsystem. In fact, in the supplemental analyses, the auditory-manual mapping showed larger interference with spatial-verbal codes (because both the auditory stimulus and the spatial-verbal code point towards the phonological loop, while the anticipated effect of the correct manual response should be processed in the visuospatial sketchpad), whereas the visual-vocal mapping showed increased interference, if at all, with spatial-location codes (because both the visual stimulus and the spatial-location code point towards the visuospatial sketchpad, while the anticipated effect of the correct vocal response should be contained in the phonological loop). In turn, auditory-manual spatial-location trials and visual-vocal spatial-verbal trials are "easier" because two of the three relevant codes are contained in the subsystem that features the correct response (spatial-location and manual in the visuospatial sketchpad, spatial-verbal and vocal in the phonological loop). This idea could also be transferred to Experiment 2: While Baddeley (2010) described how a visual verbal stimulus can be transformed into the phonological loop like a spoken word, it is by no means obvious that an analogous translation into the duration of some type of sound would happen to a visual temporal-duration stimulus. If indeed this does not occur, it would explain why, with the visual-vocal mapping, the temporal-duration task was not sufficiently easier than the spatial-location task to yield a significant difference in switch costs, as it was found for the same modality mapping between spatial-verbal and spatial-location processing codes.

Theoretical implications

As noted in the previous section, both multiple resource accounts (Wickens, 1984, 2008) as well as working memory subsystem accounts (Maquestiaux et al., 2018; see also Schacherer

& Hazeltine, 2019) and the between-task crosstalk account that we propose in line with previous studies (e.g. Stephan & Koch, 2011, 2015, 2016) are not mutually exclusive but differ in their degree of specificity. Both could explain modality-compatibility effects in mixing costs (or dual-task costs in dual-task contexts, e.g. Göthe et al., 2016), whereas our ideomotor approach, based on anticipation of response effects (see also Wirth, Steinhauser et al., 2018), can also explain specifically increased interference in switch trials relative to repetition trials.

The present study adds to the body of evidence strengthening the claim that "central" processes, as put forward by both bottleneck accounts (e.g. Pashler, 1994) and resource-sharing approaches (e.g. Kahneman, 1973; Navon & Miller, 2002; Tombu & Jolicoeur, 2003), are affected by modality-specific influences. Specifically, the increased mixing-costs with modality-incompatible mappings, as well as increased switch costs with such mappings in error rates, further strengthen the support for the between-task crosstalk account (Stephan & Koch, 2011; see also Göthe et al., 2016), in line with ideomotor approaches to action control (e.g. Greenwald, 1970, 1972; Shin et al., 2010). In contrast, modality-specific accounts that assume generally preferred mappings, such as visual-spatial-manual and auditory-verbal-vocal, meaning that these combinations of modalities and processing codes should be beneficial even in a single-task setting (Wickens et al., 1983; Wickens et al., 1984), would consequently expect incompatible modality mappings to lead to worse performance in general. However, as shown by the higher RT and error rates for the compatible condition in the single-task analysis of both experiments, this can be ruled out as an explanation for the influence of modality compatibility in multitasking situations. Our findings further extend previous research by demonstrating that the interference in form of between-task crosstalk can be further modulated by varying processing codes and task demands; specifically, such processing codes and task demands that strengthen the auditory-vocal coupling can further increase the already-present interference between mappings. Keep in mind that this between-mapping interference occurs in addition to the

central interference in terms of general mixing costs and switch costs, which were still present with modality-compatible mappings. However, if both task sets feature incompatible modality mappings, spatial-verbal codes and temporal-duration task demands seem to interfere predominantly with the concurrent maintenance of two competing task sets in working memory, and only to a lesser extent with the updating and shifting from one task set to another, as it is required on switch trials.

In sum, our study provides further evidence for a modality-specific influence on cognitive control processes in the form of task-confusion due to crosstalk between two incompatible mappings. Our research extends the earlier work in this field by demonstrating that this influence can be further modulated by introducing both spatial-verbal processing codes and temporal-duration task demands compared to the previously employed nonverbal spatial-location paradigm. We attribute this to a strengthening of the auditory-vocal coupling, resulting from the tight ideomotor binding between audition and verbal content, as well as the modality appropriateness of audition for temporal discrimination.

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Conflict of interest

The authors declare that they have no conflict of interest. They furthermore declare that they are in full control of their data and that the journal has permission to review their data on request.

Ethical standards

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. All individual participants gave their informed consent prior to their inclusion in this study.

References

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559. doi:10.1126/science.1736359

Baddeley, A. (2010). Working memory. *Current Biology, 20*(4), R136-R140. doi:DOI 10.1016/j.cub.2009.12.014

Bell-Berti, F., & Harris, K. S. (1981). A temporal model of speech production. *Phonetica, 38*(1-3), 9-20. doi:10.1159/000260011

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191. doi:10.3758/BF03193146

Fintor, E., Poljac, E., Stephan, D. N., & Koch, I. (2018). Modality compatibility biases voluntary choice of response modality in task switching. *Psychological Research, 84,* 380-388. doi:10.1007/s00426-018-1040-5

Fintor, E., Stephan, D. N., & Koch, I. (2018a). Emerging features of modality mappings in task switching: Modality compatibility requires variability at the level of both stimulus and response modality. *Psychological Research, 82*(1), 121-133. doi:10.1007/s00426-017-0875-5

Fintor, E., Stephan, D. N., & Koch, I. (2018b). The interplay of crossmodal attentional preparation and modality compatibility in cued task switching. *Quarterly Journal of Experimental Psychology, 72*(4), 955-965. doi:10.1177/1747021818771836

Földes, N., Philipp, A. M., Badets, A., & Koch, I. (2017). Exploring modality compatibility in the response-effect compatibility paradigm. *Advances in Cognitive Psychology, 13*(1), 97-104. doi:10.5709/acp-0210-1

Freides, D. (1974). Human information processing and sensory modality: cross-modal functions, information complexity, memory, and deficit. *Psychological Bulletin, 81*(5), 284-310.

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition, 150*, 92-108. doi:10.1016/j.cognition.2016.02.003

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*(2), 73-99. doi:10.1037/h0028689

Greenwald, A. G. (1972). On doing two things at once: time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology, 94*(1), 52-57. doi:10.1037/h0032762

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: evidence for content-dependent central interference. *Cognitive Psychology, 52*(4), 291-345. doi:10.1016/j.cogpsych.2005.11.001

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): a framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849-937. doi:10.1017/s0140525x01000103

James, W. (1890). *The principles of psychology* (Vol. 2). Holt.

Kahneman, D. (1973). *Attention and effort*. Prentice-Hall.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - A review. *Psychological Bulletin, 136*(5), 849-874. doi:10.1037/a0019842

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-An integrative review of dual-task and task-switching research. *Psychological Bulletin, 144*(6), 557-583. doi:10.1037/bul0000144

Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica, 94*(2), 145-188. doi:10.1016/0001-6918(95)00050-X

Lukas, S., Philipp, A. M., & Koch, I. (2010). Switching attention between modalities: Further evidence for visual dominance. *Psychological Research, 74*(3), 255-267. doi:10.1007/s00426-009-0246-y

Lukas, S., Philipp, A. M., & Koch, I. (2014). Crossmodal attention switching: Auditory dominance in temporal discrimination tasks. *Acta Psychologica, 153*, 139-146. doi:10.1016/j.actpsy.2014.10.003

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception, & Psychophysics, 80*(3), 752-772. doi:10.3758/s13414-017-1469-4

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*(3), 134-140. doi:10.1016/S1364-6613(03)00028-7

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*(3), 193-251. doi:10.1006/cogp.2001.0767

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*(2), 220-244.

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Hochenberger, R., Sogo, H., . . . Lindelov, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195-203. doi:10.3758/s13428-018-01193-y

Poljac, E., Koch, I., & Bekkering, H. (2009). Dissociating restart cost and mixing cost in task switching. *Psychological Research, 73*(3), 407-416. doi:10.1007/s00426-008-0151-9

Repp, B. H., & Penel, A. (2002). Auditory dominance in temporal processing: new evidence from synchronization with simultaneous visual and auditory sequences. *Journal of Experimental Psychology: Human Perception & Performance, 28*(5), 1085-1099.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*(2), 207-231. doi:10.1037/0096-3445.124.2.207

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(6), 1477-1491. doi:10.1037/0278-7393.31.6.1477

Schacherer, J., & Hazeltine, E. (2019). How conceptual overlap and modality pairings affect task-switching and mixing costs. *Psychological Research, 83*(5), 1020-1032. doi:10.1007/s00426-017-0932-0

Schacherer, J., & Hazeltine, E (2020). Cue the effects: Stimulus-action effect modality compatibility and dual-task costs. *Journal of Experimental Psychology: Human Perception and Performance, 46*(4)*,* 350-368. doi:10.1037/xhp0000719

Schäffner, S., Koch, I., & Philipp, A. M. (2018). Sensory-motor modality compatibility in multitasking: The influence of processing codes. *Acta Psychologica, 191*, 210-218. doi:10.1016/j.actpsy.2018.09.012

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943-974. doi:10.1037/a0020541

Smith, B. L. (1978). Temporal aspects of English speech production: A developmental perspective. *Journal of Phonetics, 6*(1)*,* 37-67. doi:10.1016/S0095-4470(19)31084-8

Spence, C., Parise, C., & Chen, Y. C. (2012). The Colavita Visual Dominance Effect. In M. M. Murray & M. T. Wallace (Eds.), *The Neural Bases of Multisensory Processes* (pp. 1-25). CRC Press/Taylor & Francis.

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology: Learning, Memory and Cognition, 36*(4), 1075-1081. doi:10.1037/a0019695

Stephan, D. N., & Koch, I. (2011). The role of input-output modality compatibility in task switching. *Psychological Research, 75*(6), 491-498. doi:10.1007/s00426-011-0353-4

Stephan, D. N., & Koch, I. (2015). Tactile stimuli increase effects of modality compatibility in task switching. *Experimental Psychology, 62*(4), 276-284. doi:10.1027/1618-3169/a000291

Stephan, D. N., & Koch, I. (2016). Modality-specific effects on crosstalk in task switching: evidence from modality compatibility using bimodal stimulation. *Psychological Research, 80*(6), 935-943. doi:10.1007/s00426-015-0700-y

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task switching, modality compatibility, and the supra-modal function of eye movements. *Experimental Psychology, 60*(2), 90-99. doi:10.1027/1618-3169/a000175

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences, 14*(9), 400-410. doi:10.1016/j.tics.2010.06.008

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29*(1), 3-18. doi:10.1037/0096-1523.29.1.3

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483-488. doi:10.1016/j.tics.2003.09.002

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin, 88*(3), 638-667. doi:10.1037/0033-2909.88.3.638

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63-101). Academic Press.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors, 50*(3), 449-455. doi:10.1518/001872008X288394

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. *Human Factors, 25*(2), 227-248. doi:10.1177/001872088302500209

Wickens, C. D., Vidulich, M., & Sandrygarza, D. (1984). Principles of S-C-R compatibility with spatial and verbal tasks - the role of display-control location and voice-interactive display-control interfacing. *Human Factors, 26*(5), 533-543. doi:10.1177/001872088402600505

Wirth, R., Janczyk, M., & Kunde, W. (2018). Effect monitoring in dual-task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44*(4), 553-571. doi:10.1037/xlm0000474

Wirth, R., Steinhauser, R., Janczyk, M., Steinhauser, M., & Kunde, W. (2018). Long-term and short-term action-effect links and their impact on effect monitoring. *Journal of Experimental Psychology: Human Perception and Performance, 44*(8), 1186-1198. doi:10.1037/xhp0000524

Figures and Tables

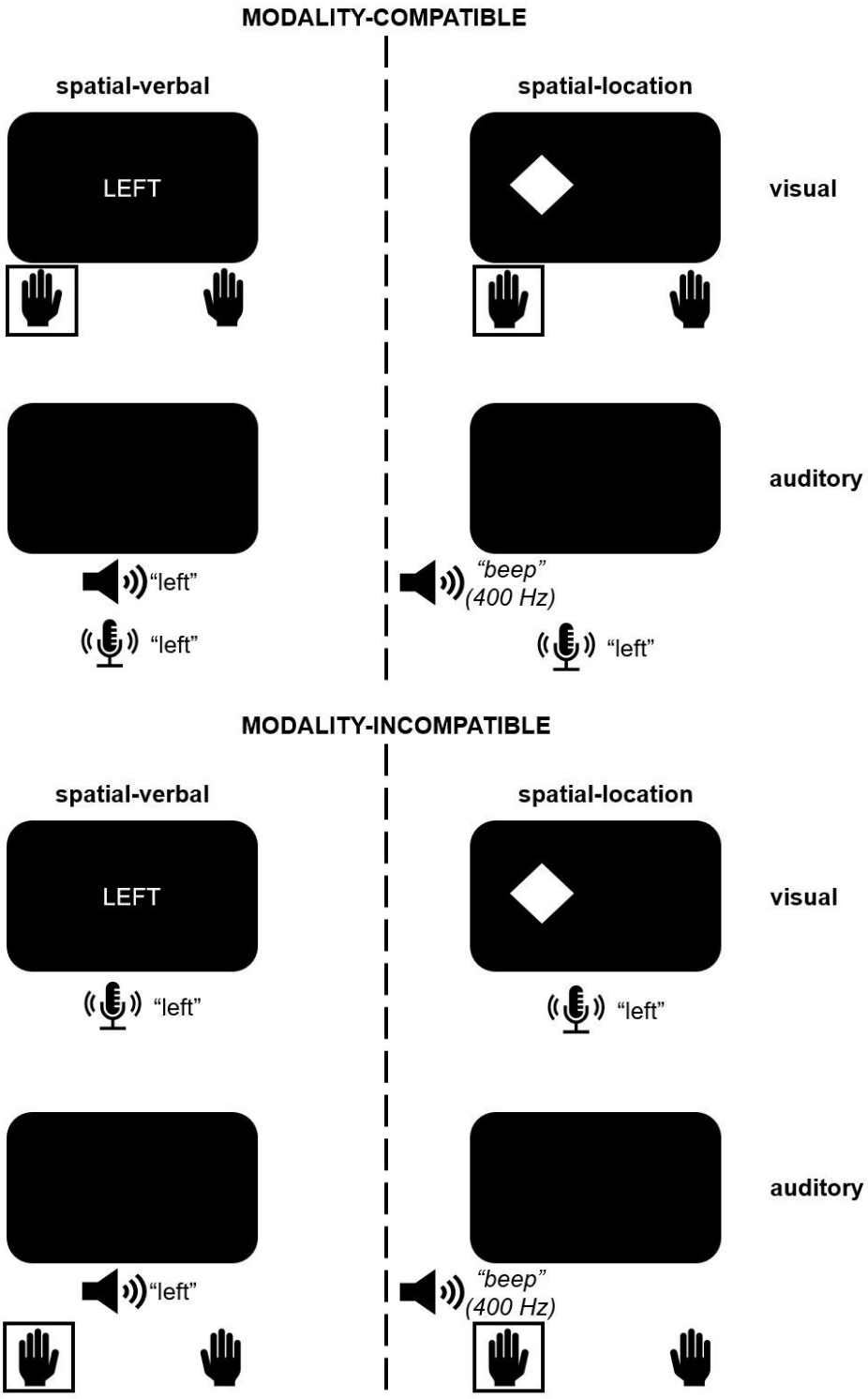


Fig. 1. Overview of stimulus-response mappings in the modality-compatible and modality-incompatible condition for spatial-verbal and spatial-location processing codes (Experiment 1). Spatial-verbal stimuli were presented centrally / binaurally, spatial-location stimuli on one ear / one side of the screen. In Experiment 2, spatial-verbal processing codes were replaced with temporal-duration task demands, while the spatial-location task demands remained the same.

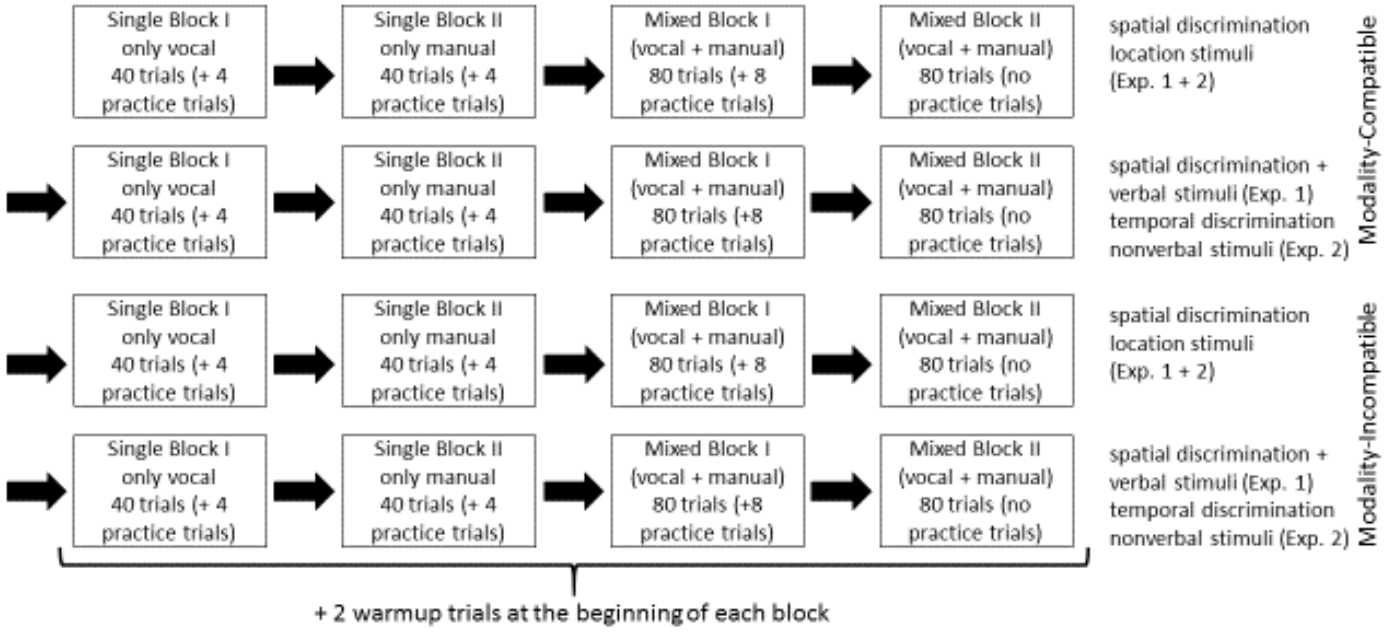


Fig. 2. Example procedure of the whole experiment. Order of modality-compatibility conditions, processing code (spatial-location vs. spatial-verbal) in Experiment 1 / task demand (spatial-location vs. temporal-duration) in Experiment 2, and response modalities in the single-task blocks was counterbalanced across all participants (Exp. 1 + 2 = Experiment 1 and Experiment 2).

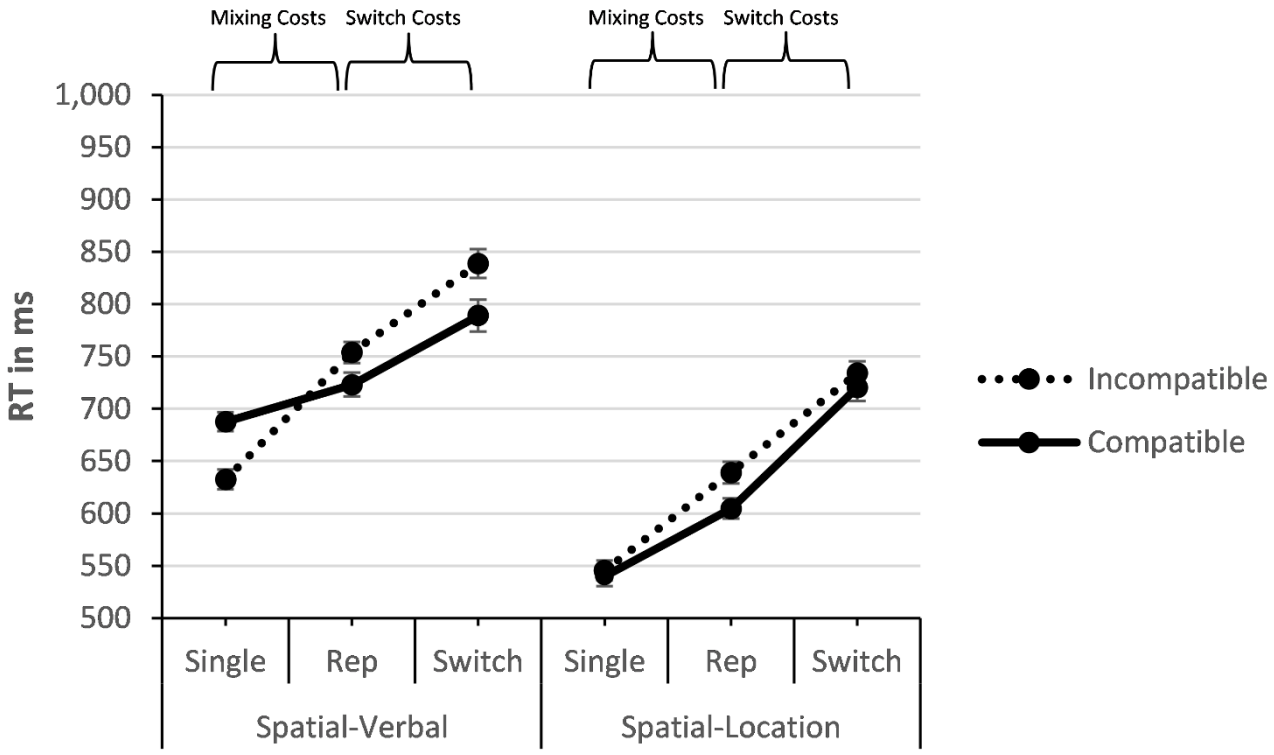


Fig. 3. Mean response times (RTs) in ms in Experiment 1 in the mixing-cost contrast and the switch-cost contrast (Rep = Repetition). Error bars indicate the standard error of the mean.

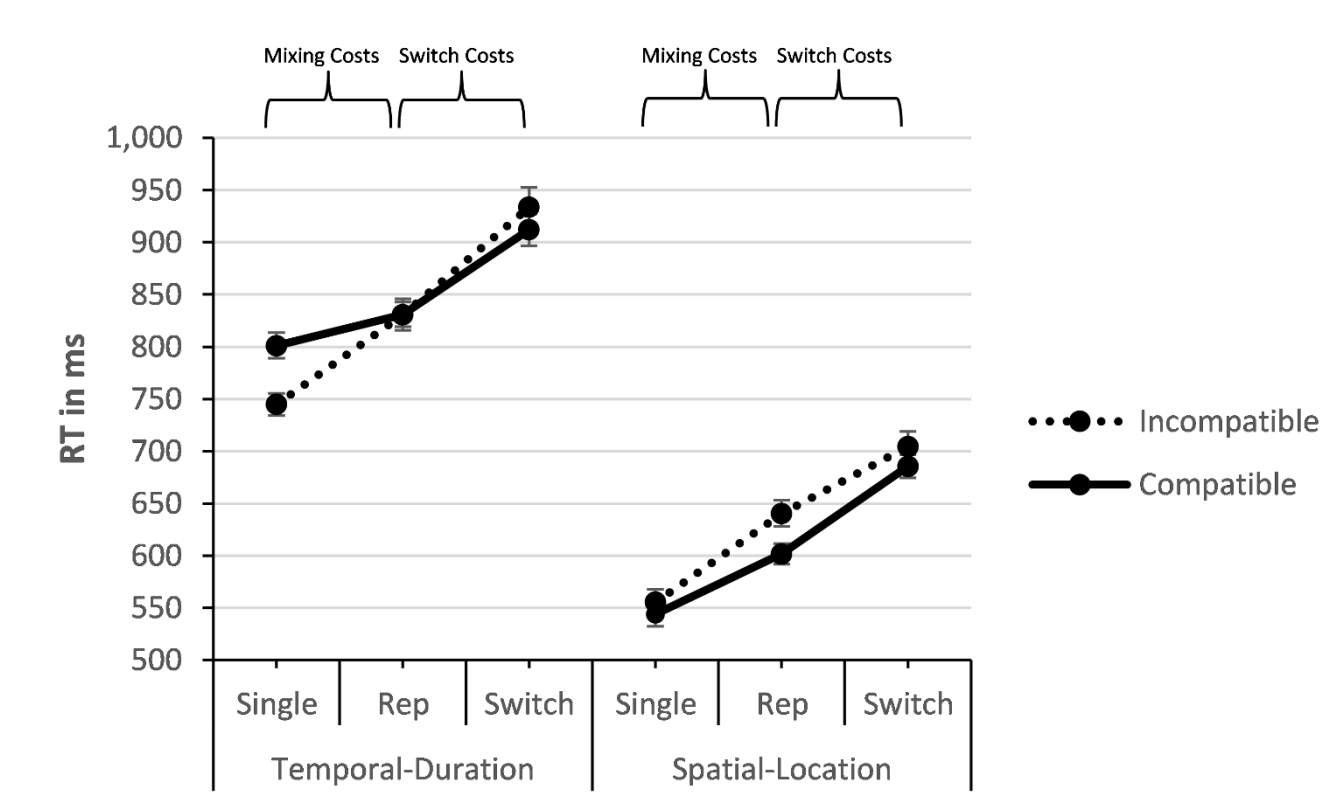


Fig. 4. Mean RTs in ms in Experiment 2 in the mixing-cost contrast and the switch-cost contrast. Error bars indicate the standard error of the mean.

Table 1. Mean PE (percent errors) in Experiment 1 (MC = modality compatibility).

		Spatial-Location		Spatial-Verbal	
MC	Transition	mean PE	SD	mean PE	SD
Modality-Compatible	Switch	5.4	4.7	6.2	5.6
	Repetition	2.6	2.3	3.9	4.0
	Single	1.1	1.3	4.1	2.8
Modality-Incompatible	Switch	7.9	7.1	7.7	7.6
	Repetition	2.5	2.9	3.6	3.2
	Single	1.2	1.7	1.8	2.4

Table 2. Mean RT (in ms) and PE in Experiment 1 for each component task (=with the factor Modality Compatibility split up into Stimulus Modality and Response Modality).

			Spatial-Location		Spatial-Verbal	
Stimulus Modality	Response Modality	Transition	mean	SD	mean	SD
RT						
Visual	Manual	Switch	483.75	59.463	559.00	90.833
		Repetition	380.13	49.519	481.42	57.194
		Single	314.75	30.543	425.96	41.215
Auditory	Vocal	Switch	961.08	87.358	1021.33	78.692
		Repetition	867.42	63.859	990.75	73.844
		Single	784.17	80.180	944.96	76.498
Visual	Vocal	Switch	821.63	87.678	817.63	67.395
		Repetition	701.67	60.507	729.63	59.504
		Single	623.38	58.267	647.17	56.451
Auditory	Manual	Switch	651.13	64.335	860.17	85.798
		Repetition	585.96	75.954	776.42	59.407
		Single	469.25	50.989	617.33	51.270
PE						
Visual	Manual	Switch	3.7171	5.16421	7.7502	4.70865
		Repetition	0.9294	1.62830	4.5419	5.40590
		Single	0.4090	0.93438	6.8457	4.03735
Auditory	Vocal	Switch	7.0014	6.13946	4.6185	9.02277
		Repetition	4.5722	3.92233	3.2810	4.30273
		Single	1.7678	2.63794	1.3849	2.55705
Visual	Vocal	Switch	11.6783	8.16878	7.7129	8.09657

		Repetition	3.4612	3.51095	3.8374	4.58211
		Single	0.5437	1.70025	0.9607	2.28423
Auditory	Manual	Switch	3.9118	6.10283	7.4676	8.20968
		Repetition	1.7895	3.52031	3.6602	4.18811
		Single	1.8706	2.50593	2.6972	3.53486

Table 3. Mean PE in Experiment 2.

		Spatial-Location		Temporal-Duration	
MC	Transition	mean PE	SD	mean PE	SD
Modality-Compatible	Switch	3.0	3.1	7.2	4.9
	Repetition	2.3	2.6	7.1	4.1
	Single	1.1	1.4	5.1	3.3
Modality-Incompatible	Switch	5.9	4.6	8.6	5.5
	Repetition	2.6	2.6	3.8	2.9
	Single	0.7	1.1	3.2	2.6

Table 4. Mean RT (in ms) and PE in Experiment 2 for each component task (=with the factor Modality Compatibility split up into Stimulus Modality and Response Modality).

			Spatial-Location		Temporal-Duration	
Stimulus Modality	Response Modality	Transition	mean	SD	mean	SD
RT						
Visual	Manual	Switch	439.54	43.738	711.96	82.770
		Repetition	366.50	41.308	656.46	60.433
		Single	303.67	26.249	597.50	54.375
Auditory	Vocal	Switch	931.58	87.036	1112.46	75.790
		Repetition	873.13	76.978	1058.08	83.114
		Single	805.54	97.212	1006.13	85.068
Visual	Vocal	Switch	764.04	86.364	985.50	98.714
		Repetition	693.54	66.753	915.54	87.832
		Single	626.79	54.194	856.79	67.834
Auditory	Manual	Switch	647.13	80.539	882.33	110.135
		Repetition	594.63	74.174	759.50	74.035
		Single	486.04	89.453	639.08	57.989
PE						
Visual	Manual	Switch	2.3107	3.26491	9.7120	7.36968
		Repetition	1.1738	3.56109	6.9496	5.45941
		Single	0.7376	1.75193	7.6382	6.57806
Auditory	Vocal	Switch	3.6720	4.48619	4.3236	4.04629
		Repetition	3.6480	4.13481	7.3511	6.41058
		Single	1.4554	1.94290	2.9853	3.40751

Visual	Vocal	Switch	9.1799	7.40682	8.2989	7.61209
		Repetition	3.8544	4.07643	4.4368	5.23055
		Single	0.2360	0.80804	2.6429	6.10841
Auditory	Manual	Switch	2.4245	2.88267	8.8043	5.23203
		Repetition	1.5701	2.15064	3.3561	2.68115
		Single	1.1489	1.82094	4.0485	3.51741

Study II

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Dissociating stimulus-response compatibility and modality compatibility in task switching

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Abstract

Modality compatibility (MC) describes the similarity between the modality of the stimulus and the modality of the anticipated response effect (e.g., auditory effects when speaking). Switching between two incompatible modality mappings (visual-vocal and auditory-manual) typically leads to larger costs than switching between two compatible modality mappings (visual-manual and auditory-vocal). However, it is unclear whether the influence of MC arises before or after task selection, response selection, or affects both processes. We investigated this issue by introducing a factor known to influence response selection, stimulus-response (S-R) compatibility, examining possible interactions with MC. In Experiment 1, stimulus location was task-irrelevant; participants responded manually or vocally to the meaning of visual and auditory colour words presented left or right (Simon task). In Experiment 2, stimulus location was task-relevant; participants responded manually or vocally, indicating the location (left or right) of visual or auditory stimuli, using a spatially compatible vs. incompatible mapping rule ("element-level" S-R compatibility). Results revealed independent effects of S-R and modality compatibility in both experiments (n = 40 per experiment). Bayes factors suggested moderate but consistent evidence for the absence of an interaction. Independent effects suggest MC effects arise either before or after response selection, or possibly both. We propose that motor response initiation is associated with anticipatory activation of modality-specific sensory effects (e.g., auditory effects when speaking), which in turn facilitates the correct response in case of modality-compatible mappings (e.g., auditory-vocal) or reactivate, at the task-selection level, the incorrect task in case of modality-incompatible mappings (e.g., visual-vocal).

Keywords: task switching, S-R compatibility, modality compatibility

Performance costs arise when switching between tasks. These switch costs, denoting the performance difference between task-repetition trials and switch trials, are assumed to reflect the time required to shift from one task to another (e.g. Kiesel et al., 2010). Task switching can require reconfiguration of the task set for the upcoming task (Monsell, 2003) as well as inhibition of the previously relevant task set (Koch et al., 2010; Vandierendonck et al., 2010). The term "task set" denotes the cognitive representation of the task requirements, which arguably need to include both stimulus- and response features as well as their mappings (Kiesel et al., 2010). However, the idea that modality requirements are specifically represented in the task set only recently started to attract more attention (see Koch et al., 2018, for a review).

Stephan and Koch (2010) introduced the concept of modality compatibility (MC) in task switching. MC is rooted in the ideomotor principle (James, 1890), which states that actions are selected and initiated based on their anticipated effects (see also Hommel et al., 2001). The ideomotor principle is also the basis for the notion of ideomotor compatibility, which refers to the overall similarity between a stimulus and the sensory effect of the response required (Greenwald, 1970, 1972), such as when hearing the stimulus A and responding to it by saying "A". In comparison to ideomotor compatibility, the concept of MC refers more generally to the degree of similarity between the modality of the stimulus and the modality of the anticipated response effect, so that saying "B" would still be modality-compatible with hearing A, because both the stimulus and the corresponding response share the auditory modality (Stephan & Koch, 2010). That is, vocal responses are modality-compatible with auditory stimuli because vocal responses usually lead to auditory effects (see also Földes et al., 2017); manual responses are modality-compatible with visual stimuli because manual actions typically lead to visual changes in the environment. If, however, in a block that requires switching between two tasks, auditory stimuli require manual responses and visual stimuli require vocal

responses, the modality of the anticipated effect of each response is more similar to the stimulus modality of the competing task, resulting in an incompatible mapping. An example of such a modality-incompatible task-switching situation in daily office work would be typing something that another person is telling you on the phone (auditory-manual mapping) while also reporting back to them via the phone about information you are reading off the screen (visual-vocal mapping).

In several studies, Stephan and Koch (2010, 2011) demonstrated that MC affects switch costs, showing larger switch costs in blocks with two modality incompatible mappings than in blocks with two modality compatible mappings (Fintor, Poljac, et al., 2020; Fintor, Stephan, & Koch, 2018a, 2018b; Stephan & Koch, 2010, 2011, 2015, 2016; Stephan et al., 2013, 2021; see also Göthe et al., 2016; Hazeltine et al., 2006, Schacherer & Hazeltine, 2020; Wirth et al., 2020, for related findings in dual-task research). This MC effect on switch costs has been attributed to larger between-task crosstalk with incompatible modality mappings (Stephan & Koch, 2011). Alternatively, MC effects may arise because the processing codes for stimulus and response refer to different working-memory subsystems (Maquestiaux et al., 2018). A recent study (Friedgen et al., 2020) integrated the crosstalk and the working-memory account, suggesting they are not mutually exclusive but merely differ in their degree of specificity. In particular, the crosstalk account was considered more specific, since it could also explain MC effects on switch costs, whereas the working-memory account is more specific to mixing costs.

Note that task switching in MC studies refers to switching between two different stimulus-response *mappings* (e.g., auditory-vocal and visual-manual task), but with the same stimulus-classification rules (e.g., both tasks require spatial discrimination). It does not refer to a switch in the type of *judgement* that is applied to a given stimulus (like, e.g., judging a number in terms of its magnitude vs. parity). When switching between modality mappings, the

increased crosstalk with modality-incompatible mappings is what we assume to increase switch costs. Meanwhile, main effects of MC on single-task performance have rarely been found (e.g. Stephan & Koch, 2011; see also e.g. Hazeltine et al., 2006, for related findings in dual-task research), implying that MC is predominantly a multitasking phenomenon, rather than leading to better performance per se.

However, another type of compatibility does indeed lead to such main effects: Stimulus-response (S-R) compatibility (Fitts & Deininger, 1954; Fitts & Seeger, 1953) describes the degree of overlap between a stimulus and a required response. For example, in a spatial two-choice task, responding to a stimulus presented on the left side (i.e., via earphones) with a left response yields shorter response times (RT) and lower error rates (ER) than responding with a right response. Commonly, this is explained by automatic activation of response codes for overlapping stimulus and response features, which occurs in parallel to an indirect processing route (Kornblum et al., 1990), controlling the connection of stimuli and responses according to the experimental instructions (Eimer et al., 1995). The automatic, direct route is presumed to be fast, allowing for the overlapping stimulus information to be transmitted to later processes in parallel to the task-relevant information.

This way, spatial information can impact performance even when the stimulus location is task-irrelevant, which is the case in the so-called Simon task (Hommel, 2011; Simon & Rudell, 1967). For example, when blue and red coloured stimuli require a left or a right response but are presented left- or right-sided, performance is better if the spatial position of the stimulus corresponds to the required response side. Most theories suggest that the Simon effect, as well as other S-R compatibility effects, influence response-selection processes (Adam, 2000; Hommel, 2011; Kornblum et al., 1990; Proctor & Vu, 2006; Spijkers & Walter, 1985).

However, it remains unclear whether the same is the case for MC effects. Effect anticipation, which has been assumed as a possible source of these effects (e.g., Stephan & Koch,

2011; see also Schacherer & Hazeltine, 2020; Wirth et al., 2020), can be linked to both response selection and response execution (Kunde et al., 2004). Especially previous studies on response-effect (R-E) compatibility, which describes the degree of overlap between properties of the response and those of an induced (i.e., not naturally-occurring) action effect (e.g., Koch & Kunde, 2002; Kunde, 2001), have linked effect anticipation to cognitive control processes responsible for response execution (e.g., Wirth et al., 2015). MC has indeed been shown to increase anticipation effects in such R-E compatibility paradigms, as well (e.g., Földes et al., 2017). However, anticipated effects need to be part of the representation of the task if they already affect response selection, despite the effects themselves not occurring until after response execution (Hommel, 1996). While we attribute effects of MC to crosstalk between task sets (with stimuli, responses, and modality mappings being part of these task sets), rather than responses themselves, we cannot tell yet whether the presumed processes of mapping selection and response selection are actually independent. To examine this question in the present study, we used manipulations of S-R compatibility as a methodological tool. If both types of compatibility effects affect response-selection processes, the effect of S-R compatibility and the effect of MC should be interactive (Hommel, 1993; Sternberg, 1969). We would then assume that both compatibility manipulations affect the same underlying cognitive processes, which most likely refer to response selection.

In contrast, if there is an effect of S-R compatibility and an effect of MC on switch costs, but no interaction between them, this would suggest that effects of S-R and MC affect different processes: Either, crosstalk between mappings might occur already *before* a particular response has been selected according to a mapping; or effects of MC might not occur until *after* response selection has already been completed (note that Kunde et al. (2004) further distinguish between response initiation and response execution). In case of no interaction between MC and S-R compatibility, it could be assumed that the (vocal vs. manual) response

modality has to be known already before anticipatory influences can even occur in the first place (Harrison & Ziessler, 2016; Huestegge & Koch, 2010; Ziessler & Nattkemper, 2011). If response modality (manual or vocal), but not response identity (left or right) is what needs to be known for effect anticipation to arise, this would mean that mapping selection and response selection are independent processes. However, seriality is not a necessary assumption in case of finding such independence: The processes responsible for processing the two different imperative components of the stimulus – stimulus modality instructing the required response modality, and stimulus identity instructing response location – could also run in parallel, as it is assumed by race models (e.g., Logan, 1990).

Determining the locus of the MC effect in task switching is crucial because it would provide more insight into the question to what extent cognitive control processes like response selection can be considered generic and amodal (Koch et al., 2018) – that is, if MC does not affect response selection but for example only later processes – or whether cognitive control processes are at least in part modality-specific (if response selection is indeed affected by MC, i.e. if the effects of S-R and modality compatibility interact).

While several studies examined the effect of spatial S-R compatibility in crossmodal settings, previous research has either focused on stimulus modality (e.g. Castro et al., 2018; Ruzzoli & Soto-Faraco, 2017), or, in cases where there were variations in response modality as well, those were manipulated between blocks (see also Simon & Sudalaimuthu, 1979; Wang & Proctor, 1996). However, as shown by Fintor, Stephan, et al. (2018a), both stimulus modality and response modality need to be varied within the same mixed-task block in order for the typical effects of MC on switch costs to occur – because MC effects seem to arise from competing mappings (and crosstalk between them), rather than from separate neural structures (Wickens, 2008) or preferred mappings (Hazeltine et al., 2006; Stelzel & Schubert, 2011) for vision and manual actions / audition and vocal actions per se. Thus, studies which

only varied stimulus modality or response modality, or did so across blocks rather than within blocks, cannot answer the question of whether S-R compatibility and MC interact. In other words, most studies so far on S-R compatibility did not manipulate MC, and in turn, preceding studies on MC on task switching (Fintor, Poljac, et al., 2020; Fintor, Stephan, et al., 2018a, 2018b; Stephan & Koch, 2010, 2011, 2015, 2016; Stephan et al., 2013, 2021) did not manipulate spatial S-R compatibility in a systematic way. Note though that for dual-tasking, Stelzel and Schubert (2011) varied S-R compatibility, finding no interaction between MC and what they called "categorical crosstalk" (p. 481), that is, congruency effects between the modality mappings, since visual stimuli required a left/right and auditory stimuli a low/high judgment. Furthermore, Huestegge and Koch (2010) used an S-R incompatible mapping in one task and a compatible mapping in the other, thus varying temporal overlap of response selection across tasks, and found evidence for parallel response selection. To our knowledge, the present task-switching study is the first to systematically vary spatial S-R compatibility and MC for the purpose of investigating a possible connection between response selection and mapping selection.

In two experiments, we sought to examine to what extent response selection and mapping selection are independent processes. Specifically, we were interested in whether the increased crosstalk with two modality-incompatible mappings compared to two modality-compatible mappings (Stephan & Koch, 2011) affects response selection or functionally earlier or later processes, like mapping activation or response initiation and response execution (Kunde et al., 2004). For that purpose, we manipulated both S-R and modality compatibility. In the first experiment, stimulus location was task-irrelevant (Simon task); in the second experiment, stimulus location was task-relevant (spatial-discrimination task).

A previous study (Fintor, Stephan, et al., 2018a) found an effect size of $\eta^2_p = .192$ for the interaction of MC and switching. Using GPower 3.1, we calculated that a sample size of N

= 40 would allow us to detect an effect of this size with a power of .84. at an α = .05 (Faul et al., 2007). Note that in another study (Stephan & Koch, 2016), the effect of MC on RT switch costs was even larger at η^2_p = .295. Both of these effect sizes refer to the two-way interaction of MC and switching; since to our knowledge, our current study was the first to examine a possible three-way interaction in a within-subjects design between MC, S-R compatibility, and switching, we had no way to predict the effect size of that interaction specifically.

However, a previous pilot study of ours (unpublished) had varied MC between subjects (N = 8 per group) and S-R compatibility within subjects, finding a significant three-way interaction in RT of MC, S-R compatibility, and switching, $F(1, 14) = 7.616$, $p = .015$, $\eta^2_p = .352$. The post-hoc t-test yielded a non-significant trend for an MC effect on switch costs in the S-R-incompatible condition, $t(14) = 2.097$, $p = .055$, $d = .54$, 95% CI [-0.01, 1.08], with a switch-cost difference of 78 ms, CI [5 ms, 151 ms] between MC conditions, while no significant MC effect on switch costs was observed in the S-R-compatible condition ($t < 1$) (16 ms CI [-31 ms, 63 ms]). Conversely, the mean difference between MC groups for the impact of S-R compatibility on switch costs was significant, $t(14) = 2.760$, $p = .015$, $d = 1.380$, being larger in the modality-incompatible group by 62 ms, CI [14 ms, 110 ms].

Based on our GPower analysis, our sample size of N = 40 per experiment should have allowed us to detect such a three-way interaction effect of $\eta^2_p = .352$ with a power of .99 in a 2x2x2 ANOVA, and an effect of $d = .54$ in a t-test with a power of .91 at an α = .05 (Faul et al., 2007). Note however that, due to the small sample size of said previous pilot study, it is difficult or even impossible to estimate and interpret these effect sizes.

Experiment 1

In the first experiment, we used the Simon effect (Simon & Rudell, 1967) as a tool in a MC paradigm to examine whether S-R compatibility interacts with MC. To this end, we used colour words (“blue” and “red”) as visual or auditory stimuli, which were presented at the left

and right side. Colour words were chosen because they could also be presented as auditory stimuli, with both the auditory and the visual stimuli being verbal in type. As usual in Simon tasks, the spatial location of the stimulus was task-irrelevant, but still expected to affect performance: We predicted a Simon effect in all conditions, that is, higher RT and ER in S-R incompatible trials than in S-R compatible trials.

There was a modality-compatible and a modality-incompatible condition, varied within subjects, with two single-task blocks and two mixed-task blocks in each condition. Specifically, in mixed-task blocks we predicted a three-way interaction between S-R compatibility, MC, and task switching (modality switch vs. repetition): The effect of MC enlarging switch costs should be larger on S-R incompatible trials than on S-R compatible trials, suggesting that increased response-selection difficulty adds to the crosstalk between modality mappings. We also examined the two-way interaction of MC and S-R compatibility, in order to determine, in case of a null effect for the three-way interaction, whether the two forms of compatibility would also be independent from each other in general. However, our hypothesis only specifically predicted a three-way interaction of MC, S-R compatibility, and switching, given that the influence of MC is usually specific to switch costs, whereas main effects of MC, at least in single-task blocks, are an irregularity; such main effects do occur with higher frequency in mixed-task blocks, though, so the question of whether main effects of modality compatibility and S-R compatibility might also interact by themselves was still of interest, even though our primary prediction was indeed specific to the three-way interaction.

Method

Participants. 40 subjects (36 female; 37 right-handed; mean age = 21.97, SD = 3.125) were tested. All gave their informed consent for participation, reported normal or corrected-to-normal vision and hearing, and received partial course credit as compensation.

Stimuli and apparatus. The stimuli were the colour words "BLAU" or "ROT" (German for "blue" or "red"). Visual stimuli were presented in neutral, white font on black background, in capital letters with a height of 1.5 cm, 4 cm to the left or right side of the screen centre. Auditory stimuli were the spoken colour words, presented via headphones on the left or right ear. Thus, stimuli in both stimulus modalities were verbal (rather than using coloured shapes as visual stimuli); recent studies have shown that the question of whether verbal vs. nonverbal stimuli are employed can modulate the effect of MC (Friedgen et al., 2020; Göthe et al., 2016; Schäffner et al., 2018). Manual responses were made via left and right button presses on a custom wooden board, and vocal responses (the German words "links" – "left", "rechts" – "right") via microphone, with the board and the microphone connected to a USB response box.

Error feedback was bimodal, a white exclamation mark presented in the screen centre, together with a "boing" sound, and there was no fixation cross, to prevent priming of one modality over the other, or of the dimensions stimulus location vs. word meaning.

The experiment was programmed and run using PsychoPy2 (Peirce et al., 2019), version 1.83.03, on a computer running Linux. A Samsung flatscreen (diagonal of 59 cm) was used and verbal auditory stimuli were recorded in Logic Pro X inside a non-sound-reflecting portable vocal booth (Isovox 2) using a Shure SM 7B dynamic microphone.

Procedure. At the beginning of each trial, the imperative stimulus was presented for the duration of the spoken word, with the participant having up to 1500 ms to respond. Because stimulus location was task-irrelevant, S-R compatibility varied randomly on a trial-to-trial basis; MC was blocked (i.e., modality-compatible blocks consisted of mappings of a visual stimulus to a manual response and an auditory stimulus to a vocal response; in modality-incompatible blocks, mappings were reversed). The mapping of colour word (blue vs. red) to response side (left vs. right) was counterbalanced among subjects. The response-stimulus

interval (RSI) lasted for 600 ms during which, in case of a vocal response, the experimenter recorded the accuracy of the given response with regard to the correct side (left or right). This was done by recording the experimenter's button presses on a separate keyboard during the constant RSI of 600 ms (i.e., the experimenter's response speed did not affect timing in any way). In case of an error (both after vocal and manual responses), the error feedback was presented after the standard RSI of 600 ms for an additional 400 ms, followed by a 100-ms period of silence with a blank screen, extending the total RSI to 1100 ms.

The experiment lasted about 20 minutes, with counterbalanced order of MC conditions. Each MC condition consisted of two single-task blocks with 40 trials each, followed by two mixed-task blocks with 80 trials each (see Figure 1). Single-task blocks featured only one modality mapping (e.g., only visual-manual or only auditory-vocal), whereas mixed-task blocks contained both mappings of the given MC condition (visual-manual and auditory-vocal or visual-vocal and auditory manual). Each single-task block featured 4 additional practice trials in advance of the proper trials; the first of the two mixed-task blocks in each condition featured 8 such trials. Furthermore, 2 warm-up trials were added at the beginning of each block, following the pause screen which was presented after the practice phase.

Design. We used a 2x2x2 within-subjects design with the independent variables MC (compatible vs. incompatible), S-R compatibility (compatible vs. incompatible), and switching (switch vs. repetition). Switching could only be examined in mixed-task blocks; single-task blocks only featured the variables MC (compatible vs. incompatible) and S-R compatibility (compatible vs. incompatible). The dependent variables were RT and ER. All analyses were calculated at $\alpha = .05$. Data was collapsed across the two modality-incompatible tasks vs. the two modality-compatible tasks, respectively, like in previous studies (e.g., Stephan & Koch, 2010, 2011, 2015, 2016; Stephan et al., 2013, 2021). Since MC is defined as an interaction of stimulus modality and response modality, collapsing the data is necessary to turn MC

into a factor in the first place, rather than analysing trivial influences of different stimulus modalities and response modalities separately.

Results

Practice and warm-up trials were excluded from analysis. We furthermore excluded all trials with an RT < 50 ms or an RT outside +/- 3 z around the mean of the respective block for each participant (0.2% of the data). Trials following an error were excluded as well, and RT analysis also excluded the error trials themselves.

Because a null effect would have been theoretically informative, we decided that, in case of a null effect for an interaction involving MC and S-R compatibility in the main analysis, we would run a Bayesian analysis using the software JASP as a follow-up to determine the strength of evidence for the null hypothesis H_0 (i.e. no interaction between MC, S-R compatibility, and switching): A Bayes factor (BF_{10}) between 1/3 and 1 is considered anecdotal evidence for H_0; a BF_{10} between 1/10 and 1/3 is regarded as moderate evidence for H_0; and a BF_{10} between 1/30 and 1/10 as strong evidence for H_0 (Wagenmakers et al., 2018). The value BF_{10} for a particular interaction was calculated by dividing the BF_{10} of the best-fitting model which includes the interaction of interest by the BF_{10} of the model which includes all the same predictors, *except* for the interaction of interest. Note that for the three-way interaction in a 2x2x2 design, the only predictive model which includes it is the full model (which also includes all main effects and two-way interactions).

Single-task conditions. RT analysis yielded a significant effect of S-R compatibility, $F(1, 39) = 50.074$, $p < .001$, $\eta^2_p = .562$, confirming higher RT on S-R incompatible compared to S-R compatible trials (714 ms vs. 690 ms) and an overall Simon effect of 24 ms. The main effect of MC was non-significant, $F(1, 39) = 2.173$, $p = .149$, $\eta^2_p = .053$, as was the interaction of MC and S-R compatibility, $F < 1$.

The analysis of ER yielded an effect of S-R compatibility, $F(1, 39) = 10.443$, $p = .003$, $\eta^2_p = .211$, showing more errors for S-R incompatible than for the S-R compatible trials (5.9% vs. 4.2%), as well as a "reversed" effect of MC, $F(1, 39) = 18.479$, $p < .001$, $\eta^2_p = .321$, with higher ER for the modality-compatible than for the modality-incompatible condition (7.0% vs. 3.1%). Note that this reversed effect means that any *benefits* of MC in task switching cannot be explained by better single-task performance in modality-compatible blocks. The interaction of MC and S-R compatibility was non-significant, $F(1, 39) = 1.682$, $p = .202$, $\eta^2_p = .041$.

Mixed-task conditions. RT analysis (see Figure 2) yielded a significant effect of switching, $F(1, 39) = 255.130$, $p < .001$, $\eta^2_p = .867$, revealing longer RT on switches compared to repetitions (916 ms vs. 771 ms). The effect of MC was also significant, $F(1, 39) = 120.042$, $p < .001$, $\eta^2_p = .755$, demonstrating longer RT in modality-incompatible than in modality-compatible blocks (892 ms vs. 795 ms). Furthermore, there was an effect of S-R compatibility, $F(1, 39) = 65.773$, $p < .001$, $\eta^2_p = .628$, showing slower responses on S-R incompatible than on S-R compatible trials (860 ms vs. 827 ms).

As predicted, MC interacted with switching, $F(1, 39) = 21.107$, $p < .001$, $\eta^2_p = .351$, indicating larger switch costs for the modality-incompatible compared to the modality-compatible condition (176 ms vs. 115 ms, see Figure 3). There was also a non-significant trend for an interaction of S-R compatibility and switching, $F(1, 39) = 3.791$, $p = .059$, $\eta^2_p = .089$, hinting at a numerically larger Simon effect for switches than repetitions (42 ms vs. 24 ms). The interaction of MC and S-R compatibility was non-significant $F(1, 39) = 1.286$, $p = .264$, $\eta^2_p = .032$. Moreover, the three-way interaction of MC, S-R compatibility, and switching was not significant, $F(1, 39) = .785$, $p = .381$, $\eta^2_p = .020$. Nevertheless, we performed a post-hoc t-test to obtain the effect size (difference in strength of the MC effect on switch costs between S-R compatibility conditions) and its confidence interval, $t(39) = .886$, $p = .381$, $d_z = .14$, 95% CI

[-0.17, 0.45] (14 ms difference, CI [-27 ms, 56 ms]). Because of the significant effect of MC, we also analysed proportional switch costs (RT switch costs divided by RT on repetition trials) to confirm the effect of MC on switch costs was not merely due to higher overall RT in the modality-incompatible condition (see Stephan & Koch, 2011) – and indeed, proportional switch costs were still higher in the modality-incompatible compared to the modality-compatible condition, $F(1, 39) = 10.890$, $p = .002$, $\eta^2_p = .218$ (21.9% vs. 16.0%).

Error analysis demonstrated a significant effect of switching, $F(1, 39) = 36.197$, $p < .001$, $\eta^2_p = .481$, revealing more errors on switches than repetitions (14.8% vs. 6.9%). The effect of MC was also significant, $F(1, 39) = 7.900$, $p = .008$, $\eta^2_p = .168$, indicating higher ER for the modality-incompatible than for the modality-compatible condition (12.0% vs. 9.8%). S-R compatibility yielded a non-significant trend, $F(1, 39) = 3.924$, $p = .055$, $\eta^2_p = .091$, hinting at numerically higher ER for S-R incompatible than for S-R compatible blocks (11.6% vs. 10.2%).

MC interacted with switching, $F(1, 39) = 31.359$, $p < .001$, $\eta^2_p = .446$, demonstrating larger switch costs for the modality-incompatible than for the modality-compatible condition (10.6% vs. 5.2%). The three-way interaction of MC, S-R compatibility, and switching was not significant, though, $F(1, 39) = .082$, $p = .777$, $\eta^2_p = .002$. The post-hoc t-test conducted for reasons stated above yielded $t(39) = .286$, $p = .777$, $d_z = .05$, 95% CI [-0.27, 0.36]. All other effects were non-significant (ps > .10).[5]

[5] Since there were two mixed-task blocks for each MC condition, we also looked for potential improvements in performance on incompatible tasks across time. For this purpose, we compared the first block against the second block of each given condition. This was a 2 x 2 x 2 x 2 ANOVA (from which one subject had to be excluded) with the independent variables MC, S-R compatibility, switching, and time (first vs. second block of the respective compatibility condition). There was no interaction of MC and time ($F < 1$), but a trend for an interaction of S-R compatibility and time, $F(1, 38) = 2.993$, $p = .092$, $\eta^2_p = .073$, indicating a numerical improvement of 25 ms on S-R-incompatible tasks, and an improvement of 12 ms on S-R-compatible tasks, from the first to the second block within each MC condition. There were no significant interactions of MC and time or S-R compatibility and time in error rates (both ps > .12).

Finally, even in a follow-up analysis of inverse efficiency scores (IES, RT per condition divided by 1 minus ER in the same condition), both the three-way interaction of MC, S-R compatibility, and switching, $F(1, 39) = .836$, $p = .366$, $\eta^2_p = .021$, and the interaction of MC and S-R compatibility alone, $F(1, 39) = .622$, $p = .435$, $\eta^2_p = .016$, were still non-significant.

Bayesian analysis. In the follow-up Bayesian repeated-measures ANOVA to assess the probability of the validity of the null hypothesis given the empirical data, for RT, the interaction of MC and S-R compatibility indicated moderate evidence for H_0, $BF_{10} = 0.20$. The three-way interaction of MC, S-R compatibility, and switching showed anecdotal evidence for H_0, $BF_{10} = 0.58$. For ER, again both the interaction of MC and S-R compatibility ($BF_{10} = 0.24$) and the three-way interaction ($BF_{10} = 0.23$) yielded moderate evidence for H_0.

Discussion

Experiment 1 replicated the finding of larger switch costs with incompatible modality mappings, and did so consistently in RT and ER. However, this interaction was not further modulated by S-R compatibility, even though the effect of S-R compatibility was clearly present. Interactions of MC and S-R compatibility remained absent even when looking at IES as a joint measure of speed and accuracy. The evidence for this null effect for the interaction of the two types of compatibility (and switching) was moderate, but consistent in both RT and ER.

Since the locus of the S-R compatibility effect is considered to be response selection (Adam, 2000; Spijkers & Walter, 1985; Sternberg, 1969), this absence of an interaction suggests that the effect of MC either arises before response selection, or after response selection has already been completed, or possibly both. Specifically, the crosstalk (Stephan & Koch, 2011) between the modality of the anticipated effect of the response and the modality of the stimulus would be more likely to arise once the response has already been selected in the first place.

Experiment 2

Searching for converging evidence with findings from Experiment 1, we examined another manipulation of S-R compatibility – specifically in context of the spatial-discrimination paradigm, which, compared to Simon tasks, has been more widely used in our prior studies investigating MC (e.g. Stephan & Koch, 2010). However, these studies used spatially compatible S-R mappings only. In order to gain converging evidence for the conclusion of Experiment 1, we used the spatial-discrimination paradigm in MC research with a systematic variation of spatial S-R compatibility.

Experiment 2 differed from Experiment 1 in that stimulus location was now task relevant. This means that, rather than varying S-R compatibility on a trial-to-trial basis, we did so block-wise. As in Experiment 1, there were modality-compatible and modality-incompatible conditions (first vs. second half of the experiment, order counterbalanced). Thus, each MC condition now consisted of S-R compatible and S-R incompatible blocks.

These differences in element-level compatibility (i.e., whether a left stimulus called for a left vs. a right response) are theorised to affect the duration of response selection (Proctor & Vu, 2006). While we predicted the spatial S-R compatibility effect to be overall larger than the Simon effect, our main predictions were analogous to those from Experiment 1: Of interest was the three-way interaction between MC, S-R compatibility, and switching. A null effect for this interaction would contribute more support for the idea of the MC effect affecting different processes rather than response selection.

Method

Participants. 40 new subjects (33 female; 34 right-handed; mean age = 21.55, SD = 3.328) were tested. Again, all gave their informed consent. They received partial course credit as compensation, and all of them reported normal or corrected-to-normal vision and hearing.

Stimuli and apparatus. This time, we used spatial-location stimuli that had been used in many preceding studies on MC (e.g. Stephan & Koch, 2010). In this setup, visual stimuli consisted of white diamond shapes with a height and width of 1.5 cm – displaced 1.25 cm to either side of the screen centre, and auditory stimuli were 400 Hz beep sounds presented on the left or the right ear via headphones. Manual and vocal responses were identical to Experiment 1.

Procedure. The structure of a trial was analogous to Experiment 1 (see Figure 4). Because stimulus location now was task-relevant, participants were instructed which stimulus location (left vs. right) required which response (left vs. right). Avoiding additional cues, S-R compatibility was blocked, and varied within each MC condition (e.g., modality-compatible + S-R compatible, modality-compatible + S-R incompatible, modality-incompatible + S-R compatible, modality-incompatible + S-R incompatible). The order of modality- and S-R compatibility conditions was counterbalanced across all participants. Within each experiment half, within each S-R compatibility condition, there were four blocks: two single-task blocks, involving one modality mapping (à 40 trials, featuring four practice trials), followed by two mixed-task blocks (à 80 trials, with eight practice trials), featuring both mappings of that respective MC condition. Like in Experiment 1, each block offered two additional warm-up trials after the break that followed the practice trials. With a total of 16 blocks (four in each S-R condition, with two S-R conditions per MC condition), Experiment 2 was roughly twice as long as Experiment 1, varying between 30-45 minutes.

Design. The within-subjects design used the independent variables MC (compatible vs. incompatible), S-R compatibility (compatible vs. incompatible), and switching (switch vs. repetition). The dependent variables were still RT and ER, and once again, all analyses were conducted at $\alpha = .05$.

Results

Data analysis proceeded analogous to Experiment 1, with the same criteria for exclusions, outliers, and levels of significance (0.6% of the data excluded as outliers). Once again, we determined that in case of a null effect, a follow-up Bayesian repeated-measures ANOVA would be calculated to assess the degree of evidence for the null hypothesis.

Single-task conditions. RT analysis revealed a significant effect of S-R compatibility, $F(1, 39) = 44.034$, $p < .001$, $\eta^2_p = .530$, showing higher RT for the S-R-incompatible than for the S-R compatible condition (611 ms vs. 562 ms). Neither the main effect of MC was significant, $F(1, 39) = 2.830$, $p = .101$, $\eta^2_p = .068$ (but RT was numerically longer for the modality-incompatible than for the modality-compatible condition, 593 ms vs. 580 ms), nor the interaction of MC and S-R compatibility, $F < 1$.

The error analysis yielded a significant effect of S-R compatibility, $F(1, 39) = 8.645$, $p = .005$, $\eta^2_p = .181$, showing higher ER for the S-R incompatible than for the S-R compatible condition (2.8% vs. 1.8%). There was also a significant effect of MC, in contrast to RT, $F(1, 39) = 6.851$, $p = .013$, $\eta^2_p = .149$, with higher ER for the modality-compatible than for the modality-incompatible condition (2.8% vs. 1.8%). This means that any effects of MC on ER in task switching cannot be attributed to generally increased ER for the modality-incompatible single-task condition. The interaction of MC and S-R compatibility was not significant, $F < 1$.

Mixed-task condition. The RT analysis (see Figure 5), featuring the independent variables MC, S-R compatibility, and switching, yielded a significant effect of switching, $F(1, 39) = 238.912$, $p < .001$, $\eta^2_p = .860$, showing longer RT for switches than repetitions (780 ms vs. 658 ms). MC also revealed a significant effect, $F(1, 39) = 64.514$, $p < .001$, $\eta^2_p = .623$, with longer RT in modality-incompatible compared to modality-compatible blocks (741 ms vs. 697 ms). The effect of S-R compatibility was also significant, $F(1, 39) = 102.572$, $p < .001$, $\eta^2_p = .725$, revealing longer RT for S-R incompatible than for S-R compatible mappings (749 ms vs. 688 ms).

While the interaction of MC and switching was significant, $F(1, 39) = 6.250$, $p = .017$, $\eta^2_p = .138$, it went into the opposite than the expected direction, with 26 ms larger switch costs in the modality-compatible than in the modality-incompatible condition (135 ms vs. 109 ms). (However, please note that the corresponding interaction in the ER was significant in the expected direction, with larger switch costs in modality-incompatible conditions, so that we have a clear speed-accuracy trade-off pattern for this particular interaction.) S-R compatibility also interacted with switching, $F(1, 39) = 41.149$, $p < .001$, $\eta^2_p = .513$, showing a larger effect of S-R compatibility on switch compared to repetition trials (77 ms vs. 45 ms). Importantly, the interaction of MC and S-R compatibility was not significant, $F(1, 39) = 1.847$, $p = .182$, $\eta^2_p = .045$, nor was the three-way interaction of MC, S-R compatibility, and switching, $F(1, 39) = .031$, $p = .862$, $\eta^2_p = .001$. The post-hoc *t*-test to determine the size of the effect (no difference between S-R compatibility conditions in the size of the MC effect on switch costs) yielded $t(39) = .176$, $p = .862$, $d_z = .03$, 95% CI [-0.28, 0.34] (-2 ms, CI [-34 ms, 30 ms]). The S-R compatibility effect did not differ significantly between MC conditions within switches and repetitions, respectively (modality-incompatible switches: 83 ms; modality-compatible switches: 70 ms; modality-incompatible repetitions: 50 ms; modality-compatible repetitions: 39 ms). Again, since there was a main effect of MC, we analysed proportional RT switch costs, confirming the effect went into the same direction as with regular switch costs, $F(1, 39) = 10.992$, $p = .002$, $\eta^2_p = .220$, i.e. larger proportional switch costs in the modality-compatible than the modality-incompatible condition (21.8% vs. 16.2%).

The error analysis demonstrated a significant effect of switching, $F(1, 39) = 107.027$, $p < .001$, $\eta^2_p = .733$, confirming more errors on switches than repetitions (7.6% vs. 2.6%). The effect of MC was also significant, $F(1, 39) = 6.216$, $p = .017$, $\eta^2_p = .137$, revealing higher ER for the modality-incompatible than for the modality-compatible condition (5.8% vs. 4.5%). There was also an effect of S-R compatibility, $F(1, 39) = 40.539$, $p < .001$, $\eta^2_p = .510$,

showing more errors in the S-R incompatible than in the S-R compatible condition (6.2% vs. 4.1%).

The interaction of MC and switching was clearly significant, $F(1, 39) = 25.018$, $p < .001$, $\eta^2_p = .391$, confirming larger error switch costs in the modality-incompatible than in the modality-compatible condition (6.5% vs. 3.5%). This was the predicted direction of this interaction effect and thus opposed the pattern found in RT, suggesting a speed-accuracy trade-off for this interaction (see Figure 6). Consistent with RT, S-R compatibility interacted with switching as well, $F(1, 39) = 22.596$, $p < .001$, $\eta^2_p = .367$, revealing higher switch costs for the S-R incompatible compared to the S-R compatible condition (6.7% vs. 3.3%). Most critically, neither the interaction of MC and S-R compatibility was significant, $F(1, 39) = 1.240$, $p = .272$, $\eta^2_p = .031$, nor was the three-way interaction of MC, S-R compatibility, and switching, $F(1, 39) = .293$, $p = .591$, $\eta^2_p = .007$. The post-hoc *t*-test to determine effect size (difference of the MC effect on switch costs between S-R compatibility conditions) yielded $t(39) = .541$, $p = .591$, $d_z = .09$, 95% CI [-0.23, 0.40]. The S-R compatibility effect did not differ significantly between MC conditions within switches and repetitions, respectively (modality-incompatible switches: 4.3%; modality-compatible switches: 3.2%; modality-incompatible repetitions: 0.6%; modality-compatible repetitions: 0.3%).

Again, we analysed IES as a follow-up, and again, the three-way interaction of MC, S-R compatibility, and switching was non-significant, $F(1, 39) = .549$, $p = .463$, $\eta^2_p = .014$. The two-way interaction of MC and S-R compatibility was non-significant, too, $F(1, 39) = 3.128$, $p = .085$, $\eta^2_p = .074$, with only a numerical trend for a larger effect of S-R compatibility in the modality-incompatible condition (94 ms) than in the modality-compatible condition (73 ms).[6]

[6] Again, we looked for potential changes in performance on incompatible tasks across time, by comparing the first mixed-task block against the second mixed-task block of each MC and S-R-compatibility condition (note that in Experiment 2, S-R compatibility was varied by block, too). There were no interactions of time with MC ($p = .222$) or S-R compatibility ($F < 1$) in RT, nor were there any such interactions in error rates (both ps > .10).

Bayesian analysis. The follow-up Bayesian repeated-measures ANOVA yielded, for RT, moderate evidence for H_0 concerning both the interaction of MC and S-R compatibility ($BF_{10} = 0.23$) as well as concerning the three-way interaction of MC, S-R compatibility, and switching ($BF_{10} = 0.25$). Error-rate analysis was consistent with this, yielding moderate evidence for H_0 for both the interaction of MC and S-R compatibility ($BF_{10} = 0.31$) as well as for the three-way interaction ($BF_{10} = 0.18$).

Discussion

In Experiment 2, the effects of S-R compatibility were strong and consistent in both single- and mixed-task blocks. Consistent with Experiment 1, both the two-way interaction of S-R compatibility and MC and the three-way interaction of MC, S-R compatibility, and switching was not significant, despite switching interacting with both S-R compatibility and MC individually. Also, in line with Experiment 1, the analysis of the joint measure of speed and accuracy that are IES did not reveal any interactions of S-R compatibility and MC on switch costs either – only a trend for an interaction of S-R compatibility and MC in isolation of switch costs. The Bayesian follow-up analysis once again provided moderate but consistent evidence for the null hypothesis of no interactions between MC and S-R compatibility being present. Note that the category of moderate evidence from $BF_{10} = .33$ to $BF_{10} = .10$ (Wagenmakers et al, 2018) has even been termed substantial evidence for the null hypothesis by others (Jeffreys, 1961).

We found an unexpected speed-accuracy trade-off for the interaction of MC and switching, with ER fully in line with our predictions but with RT showing an opposing pattern. This suggests participants lowered their response threshold somewhat in modality-incompatible switch trials, resulting in faster responses at the expense of accuracy, so that our predicted interaction was even stronger in the ER. It is difficult to interpret this particular trade-off pattern, given that the majority of other studies showed increased switch costs with

modality-incompatible mappings in RT, like in Experiment 1 (e.g. Stephan & Koch, 2010). Most notably though, the effect of MC on switch costs was independent of the effect of S-R compatibility, thus providing converging evidence for the conclusions of Experiment 1.

General Discussion

In two experiments, we examined whether the effects of MC and S-R compatibility would interact in task switching. We did not find such interaction effects, neither in RT nor ER, nor by analysing IES, in either of the two experiments – with Experiment 1 using a Simon-like manipulation of S-R compatibility and Experiment 2 a manipulation of element-level compatibility. The statistical power of our experiments was high enough that we should have detected an effect for any such interaction if there had been one. Support for the null hypothesis of no such interaction in terms of Bayes factors was also consistent (mostly moderate, some anecdotal), for both RT and ER in both experiments. Experiment 1 still replicated the typical effect of MC in terms of larger switch costs with incompatible modality mappings. Experiment 2 also yielded the effect on switch costs in ER, even though there was an unclear speed-accuracy trade-off for RT switch costs (see below for further discussion).

These findings are in opposition to those from our previous unpublished pilot study in which MC was varied between-subjects: That study had found an effect of $d = .54$ for the three-way interaction of MC, S-R compatibility, and switching. However, note that the confidence interval for this effect size was very wide, 95% CI [-0.01, 1.08], whereas confidence intervals for the effect sizes of this same three-way interaction in the present study ranged from $d < 0$ to $d = .45$ at a maximum. The pilot study gave us a plausible justification to expect a three-way interaction initially; however, note that said pilot study had a very small sample size (N = 8 per group), especially for a between-subjects design, so our current results with N = 40 per experiment should be given more weight.

The consistent absence of any interaction between MC and S-R compatibility in the present study suggests these two empirical effects are independent and thus rely on different, dissociable processing mechanisms. Specifically, with S-R compatibility being widely assumed to affect response selection (Adam, 2000; Spijkers & Walter, 1985; Sternberg, 1969), the MC effect could occur either *before* or *after* response-selection processes. That said, at this point we cannot rule out with absolute certainty that at least a "small" interaction effect is still imaginable empirically. Thus, we cannot claim with absolute certainty either that the stages are entirely independent. Rather, since we did not find any evidence of a strong interaction, we suggest that MC and S-R-compatibility effects *primarily* affect different processes. We do not mean to rule out that both might still also affect response selection; but if they do, then they should do so to a much smaller extent.

A recent related dual-task study (Wirth et al, 2020) suggested effector-set priming (i.e. stimulus modality priming response modality) and stimulus-uptake facilitation (i.e. response modality priming stimulus modality) as two possible precentral mechanisms. Effector-set priming would mean that a given stimulus modality (visual or auditory) pre-activates an effector system that produces response effects in the same modality (visual stimuli activate the manual effector system, auditory stimuli activate the vocal effector system), even before stimulus identity (blue/red or left/right, in our case) is known. Stimulus-uptake facilitation (see also Stephan & Koch, 2016) in turn would mean that the anticipation of visible effects from manual responses, or of audible effects from vocal responses, biases the system in favour of stimulus input in those compatible modalities.

For the present task-switching study, however, we suggest a locus after response selection is more likely: Once the response (including its modality) has been selected (but not initiated yet), it is likely that anticipatory codes for the corresponding sensory effect of that response are automatically activated. Ziessler and Nattkemper (2011) presented response-effect-

relevant information before, together with, or after target onset, yet they found no evidence of the information presented before the target activating or priming the response. Therefore, they argued that effect anticipation occurs after the selection of a response, and that this serves the purpose of monitoring its motor execution (see also Harrison & Ziessler, 2016). According to our crosstalk account of the effects of MC (Stephan & Koch, 2011), anticipating a sensory response effect in the same sensory modality as the stimulus in the competing task, now that the response modality has been selected and its anticipated effect modality is activated, leads to greater between-task crosstalk and thus to task confusion.

Additionally, though, there should also have been a different kind of task conflict, more akin to that in the Stroop task (e.g., Entel et al., 2015; Kalanthroff et al., 2017): The stimuli from Experiment 1 featured similarity to Stroop experiments, given that they were colour words with two properties each (location left/right and meaning blue/red), one of which had to be ignored while attending to the other. While in contrast to most Stroop paradigms, word meaning was task-relevant in Experiment 1, the required vocal responses were not those colour words themselves, but the words "left" and "right"; consequently, the automatised tendency to read a word on sight can still be expected to have created task conflict for participants (Should they read the word out loud, or respond with a location word instead?). In both experiments, there was conflict in terms of crosstalk between mappings, that is, which stimulus modality should be responded to in which response modality. The danger of activating a wrong task set could be based on ideomotor effect-anticipation mechanisms (as we suggest), but potentially also on pre-existing associations between stimulus (i.e., verbal code) and vocal vs. manual response requirements of the task.

Note that a difference between Experiment 1 and 2 is that S-R compatibility varied on a trial-by-trial basis in Experiment 1 while being blocked in Experiment 2. Varying S-R compatibility on a trial-by-trial basis in Experiment 2 as well (i.e., with stimulus location being

task relevant) would have required additional cues to instruct which spatial S-R mapping to use on any given trial. However, this would have reduced comparability between the two experiments to a much greater extent than the trial-by-trial vs. block-wise manipulation of S-R compatibility. Because there were no interactions of S-R compatibility and MC to begin with, we also do not think it is plausible to assume this difference in the way S-R compatibility was manipulated between experiments might be the source of the speed-accuracy trade-off for the effect of MC on switching in Experiment 2. It is important to note that the influence of MC in Experiment 2, notwithstanding the particular RT-error rate trade-off pattern in modality-incompatible switch trials, was completely independent of the influence of S-R compatibility.

In summary, effect anticipation can be associated with both response selection and response execution (Kunde et al., 2004), so that it was a plausible starting point for us to hypothesize that these two forms of compatibility effects might interact to affect response selection. However, the evidence presented in this study suggests that such an interaction of S-R compatibility effects and MC effects did not occur, so that it is more likely that these two effects influence different processes of action production. Because response selection is typically assumed as the functional locus of S-R compatibility effects based on additive-factors logic (Adam, 2000; Spijkers & Walter, 1985; Sternberg, 1969), this leaves the post-selection processes of response initiation and response execution as the more probable locus of MC effects. In conclusion, we suggest that MC effects in task switching only occur after response selection has already been completed by activating the competing modality mappings based on sensory effect anticipations associated with response initiation.

Declarations

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Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article. They furthermore declare that they are in full control of their data and that the journal has permission to review their data on request.

Ethical standards

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. All individual participants gave their informed consent prior to their inclusion in this study.

Open Practices Statement

The data for all experiments are available at https://osf.io/gykbr/?view_only=6de5a7d065b14c75a686ef63212ec387. Neither of the experiments was preregistered.

References

Adam, J. J. (2000). The additivity of stimulus-response compatibility with perceptual and motor factors in a visual choice reaction time task. *Acta Psychologica*, *105*(1), 1-7. https://doi.org/10.1016/S0001-6918(00)00042-1

Castro, L., Soto-Faraco, S., Fernandez, L. M., & Ruzzoli, M. (2018). The breakdown of the Simon effect in cross-modal contexts: EEG evidence. *European Journal of Neuroscience*, *47*(7), 832-844. https://doi.org/10.1111/ejn.13882

Eimer, M., Hommel, B., & Prinz, W. (1995). S-R compatibility and response selection. *Acta Psychologica*, *90*(1-3), 301-313. https://doi.org/10.1016/0001-6918(95)00022-M

Entel, O., Tzelgov, J., Bereby-Meyer, Y., & Shahar, N. (2015). Exploring relations between task conflict and informational conflict in the Stroop task. *Psychological Research, 79,* 913-927. https://doi.org/10.1007/s00426-014-0630-0

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175-191. https://doi.org/10.3758/BF03193146

Fintor, E., Poljac, E., Stephan, D. N., & Koch, I. (2020). Modality compatibility biases voluntary choice of response modality in task switching. *Psychological Research, 84*, 380-388. https://doi.org/10.1007/s00426-018-1040-5

Fintor, E., Stephan, D. N., & Koch, I. (2018a). Emerging features of modality mappings in task switching: Modality compatibility requires variability at the level of both stimulus and response modality. *Psychological Research*, *82*(1), 121-133. https://doi.org/10.1007/s00426-017-0875-5

Fintor, E., Stephan, D. N., & Koch, I. (2018b). The interplay of crossmodal attentional preparation and modality compatibility in cued task switching. *The Quarterly Journal*

of Experimental Psychology, *72*(4), 955-965. https://doi.org/10.1177/1747021818771836

Fitts, P. M., & Deininger, R. L. (1954). S-R Compatibility - Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*(6), 483-492. https://doi.org/10.1037/h0054967

Fitts, P. M., & Seeger, C. M. (1953). S-R Compatibility - Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*(3), 199-210. https://doi.org/10.1037/h0062827

Földes, N., Philipp, A. M., Badets, A., & Koch, I. (2017). Exploring modality compatibility in the response-effect compatibility paradigm. *Advances in Cognitive Psychology*, *13*, 97-104. https://doi.org/10.5709/acp-0210-1

Friedgen, E., Koch, I., & Stephan, D. N. (2020). Modality compatibility in task switching depends on processing codes and task demands. *Psychological Research*, 1-18. https://doi.org/10.1007/s00426-020-01412-2

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition*, *150*, 92-108. https://doi.org/10.1016/j.cognition.2016.02.003

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*(2), 73-99. https://doi.org/10.1037/h0028689

Greenwald, A. G. (1972). On doing two things at once: time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*(1), 52-57. https://www.ncbi.nlm.nih.gov/pubmed/5032213

Harrison, N. R., & Ziessler, M. (2016). Effect anticipation affects perceptual, cognitive, and motor phases of response preparation: Evidence from an event-related potential (ERP)

study. *Frontiers in Human Neuroscience*, *10*, 1-16. https://doi.org/10.3389/fnhum.2016.00005

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291-345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Hommel, B. (1993). The relationship between stimulus processing and response selection in the Simon task: Evidence for a temporal overlap. *Psychological Research*, *55*(4), 280-290. https://doi.org/10.1007/BF00419688

Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*(2), 189-202. https://doi.org/10.1016/j.actpsy.2010.04.011

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849-937. https://doi.org/10.1017/s0140525x01000103

Huestegge, L., & Koch, I. (2010). Crossmodal action selection: Evidence from dual-task compatibility. *Memory & Cognition*, *38*(4), 493-501. https://doi.org/10.3758/MC.38.4.493

James, W. (1890). *The principles of psychology* (Vol. 2). Henry Holt and Co.

Jeffreys, H. (1961). *Theory of probability.* Clarendon Press.

Kalanthroff, E., Davelaar, E. J., Henik, A., Goldfarb, L., & Usher, M. (2017). Task conflict and proactive control: A computational theory of the Stroop task. *Psychological Review, 125*(1), 59-82. https://doi.org/10.1037/rev0000083

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - A review. *Psychological Bulletin*, *136*(5), 849-874. https://doi.org/10.1037/a0019842

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review*, *17*(1), 1-14. https://doi.org/10.3758/PBR.17.1.1

Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory & Cognition, 30*(8), 1297-1303. https://doi.org/10.3758/BF03213411

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking – An integrative review of dual-task and task-switching research. *Psychological Bulletin, 144*(6), 557-583. http://dx.doi.org/10.1037/bul0000144

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility - A model and taxonomy. *Psychological Review*, *97*(2), 253-270. https://doi.org/10.1037/0033-295X.97.2.253

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 387-394. https://doi.org/10.1037//0096-1523.27.2.387

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology*, *57A*(1), 87-106. https://doi.org/10.1080/02724980343000143

Logan, G. D. (1990). Repetition priming and automaticity : Common underlying mechanisms? *Cognitive Psychology 22*(1), 1-35. https://doi.org/10.1016/0010-0285(90)90002-L

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception, & Psychophysics*, *80*, 752-772. https://doi.org/10.3758/s13414-017-1469-4 29285603

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134-140. https://www.ncbi.nlm.nih.gov/pubmed/12639695

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Hochenberger, R., Sogo, H., Kastman, E., & Lindelov, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195-203. https://doi.org/10.3758/s13428-018-01193-y

Proctor, R. W., & Vu, K.-P. L. (2006). *Stimulus-response compatibility principles: Data, theory, and application*. CRC/Taylor & Francis.

Ruzzoli, M., & Soto-Faraco, S. (2017). Modality-switching in the Simon task: The clash of reference frames. *Journal of Experimental Psychology: General*, *146*(10), 1478-1497. https://doi.org/10.1037/xge0000342

Schacherer, J., & Hazeltine, E. (2020). Cue the effects: Stimulus-action effect modality compatibility and dual-task costs. *Journal of Experimental Psychology: Human Perception and Performance, 46*(4), 350-368. http://dx.doi.org/10.1037/xhp0000719

Schäffner, S., Koch, I., & Philipp, A. M. (2018). Sensory-motor modality compatibility in multitasking: The influence of processing codes. *Acta Psychologica*, *191*, 210-218. https://doi.org/10.1016/j.actpsy.2018.09.012

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*(3), 300-304. https://doi.org/10.1037/h0020586

Simon, J. R., & Sudalaimuthu, P. (1979). Effects of S-R mapping and response modality on performance in a Stroop task. *Journal of Experimental Psychology: Human Perception and Performance*, *5*(1), 176-187. https://doi.org/10.1037/0096-1523.5.1.176

Spijkers, W. A. C., & Walter, A. (1985). Response processing stages in choice reactions. *Acta Psychologica*, *58*(2), 191-204. https://doi.org/10.1016/0001-6918(85)90007-1

Stelzel, C., & Schubert, T. (2011). Interference effects of stimulus-response modality pairings in dual tasks and their robustness. *Psychological Research*, *75*(6), 476-490. https://doi.org/10.1007/s00426-011-0368-x 21811837

Stephan, D. N., Josten, J., Friedgen, E., & Koch, I. (2021). Crossmodal Effects in Task Switching: Modality Compatibility with Vocal and Pedal Responses. *Journal of Cognition, 4*(1), 1–14. https://doi.org/10.5334/joc.129

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *36*(4), 1075-1081. https://doi.org/10.1037/a0019695

Stephan, D. N., & Koch, I. (2011). The role of input-output modality compatibility in task switching. *Psychological Research*, *75*(6), 491-498. https://doi.org/10.1007/s00426-011-0353-4

Stephan, D. N., & Koch, I. (2015). Tactile stimuli increase effects of modality compatibility in task switching. *Experimental Psychology*, *62*, 276-284. https://doi.org/10.1027/1618-3169/a000291

Stephan, D. N., & Koch, I. (2016). Modality-specific effects on crosstalk in task switching: Evidence from modality compatibility using bimodal stimulation. *Psychological Research*, *80*(6), 935-943. https://doi.org/10.1007/s00426-015-0700-y

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task switching, modality compatibility, and the supra-modal function of eye movements. *Experimental Psychology*, *60*, 90-99. https://doi.org/10.1027/1618-3169/a000175

Sternberg, S. (1969). Discovery of processing stages - Extensions of Donders' method. *Acta Psychologica*, *30*, 276-315. https://doi.org/10.1016/0001-6918(69)90055-9

Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin*, *136*(4), 601-626. https://doi.org/10.1037/a0019791

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q. F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van

Kesteren, E. J., van Doorn, J., Smira, M., Epskamp, S., Etz, A., Matzke, D., de Jong, T., van den Bergh, D., Sarafoglou, A., Steingroever, H., Derks, K., Rouder, J. N., & Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, *25*(1), 58-76. https://doi.org/10.3758/s13423-017-1323-7

Wang, H. F., & Proctor, R. W. (1996). Stimulus-response compatibility as a function of stimulus code and response modality. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1201-1217. https://doi.org/10.1037/0096-1523.22.5.1201

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449-455. https://doi.org/10.1518/001872008X288394

Wirth, R., Koch, I., & Kunde, W. (2020). Localizing modality compatibility effects: Evidence from dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 46(12)*, 1527-1537. https://doi.org/10.1037/xhp0000873

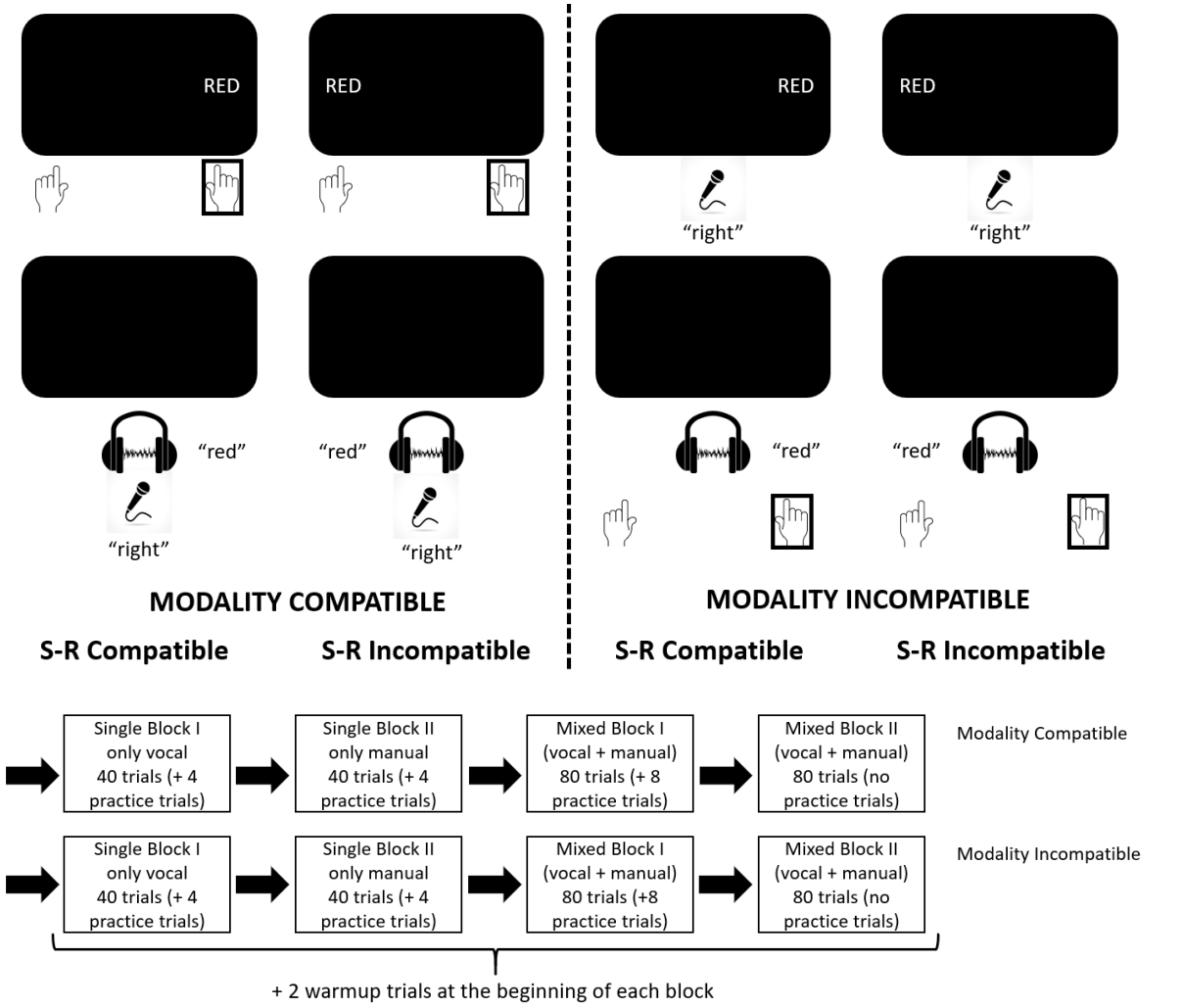
Wirth, R., Pfister, R., Janczyk, M., & Kunde, W. (2015). Through the portal: Effect anticipation in the central bottleneck. *Acta Psychologica*, *160*, 141-151. https://doi.org/10.1016/j.actpsy.2015.07.007

Ziessler, M., & Nattkemper, D. (2011). The temporal dynamics of effect anticipation in course of action planning. *The Quarterly Journal of Experimental Psychology*, *64*(7), 1305-1326. https://doi.org/10.1080/17470218.2011.553067

Figures and Tables

Figure 1

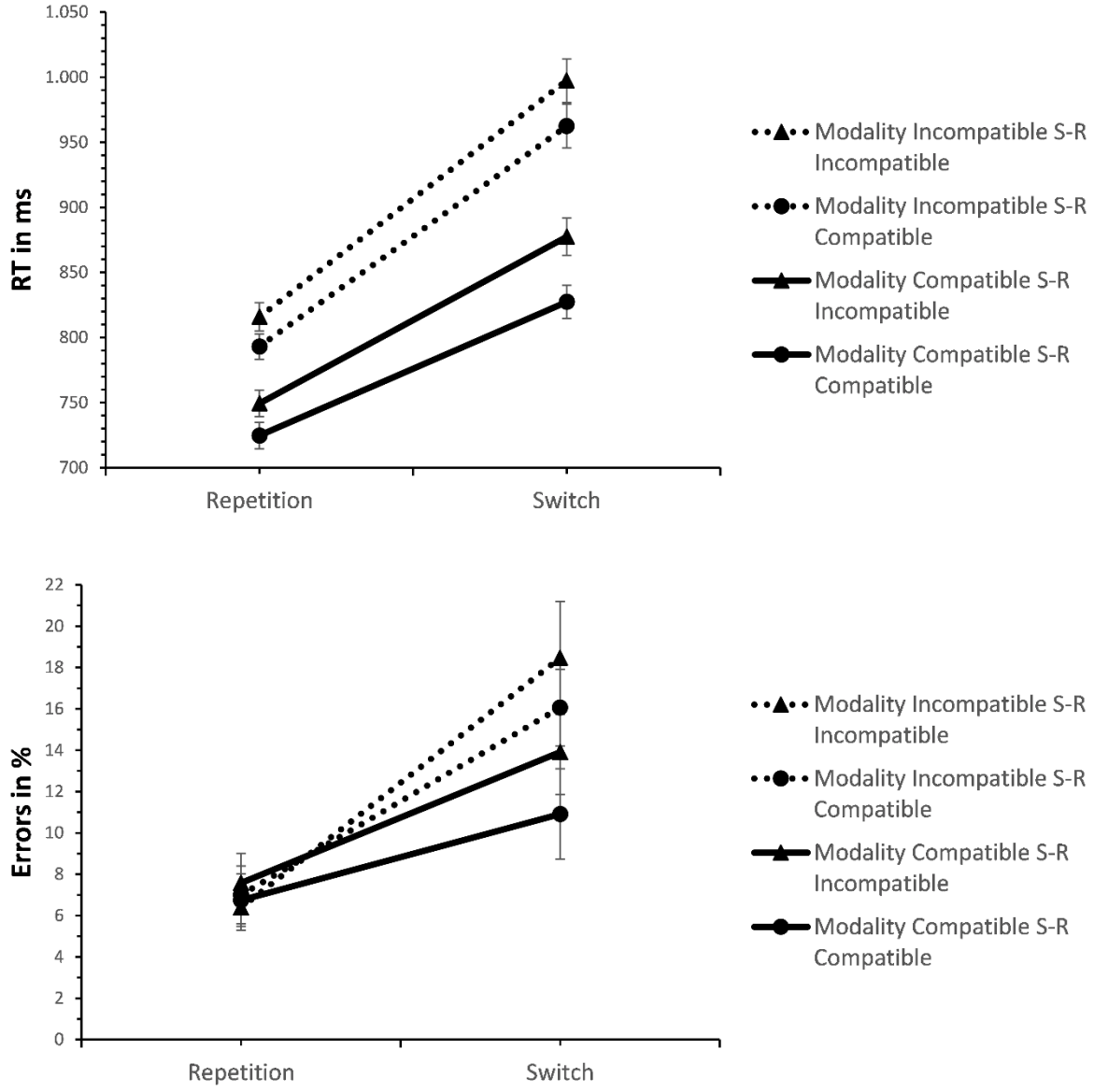
Stimuli and responses (top) and example experimental structure (bottom) for Experiment 1



The stimulus examples use the word "red"; the other stimulus was "blue". The mapping of colour (red/blue) to response side (left/right) as well as the order of conditions were counter-balanced.

Figure 2

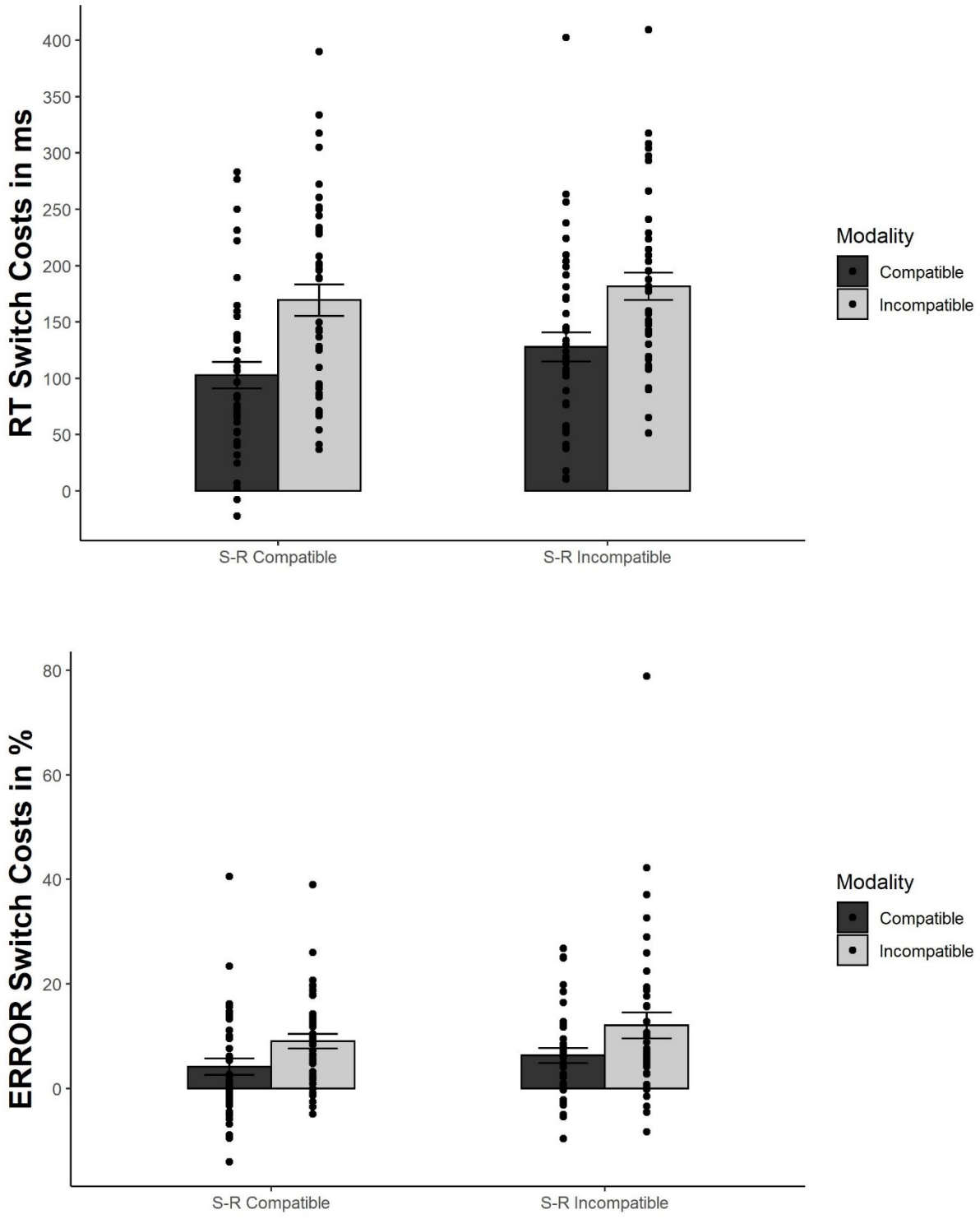
Mean RT and errors in the task-switching analysis in Experiment 1 (S-R = stimulus-response)



Error bars represent the standard error of the mean.

Figure 3

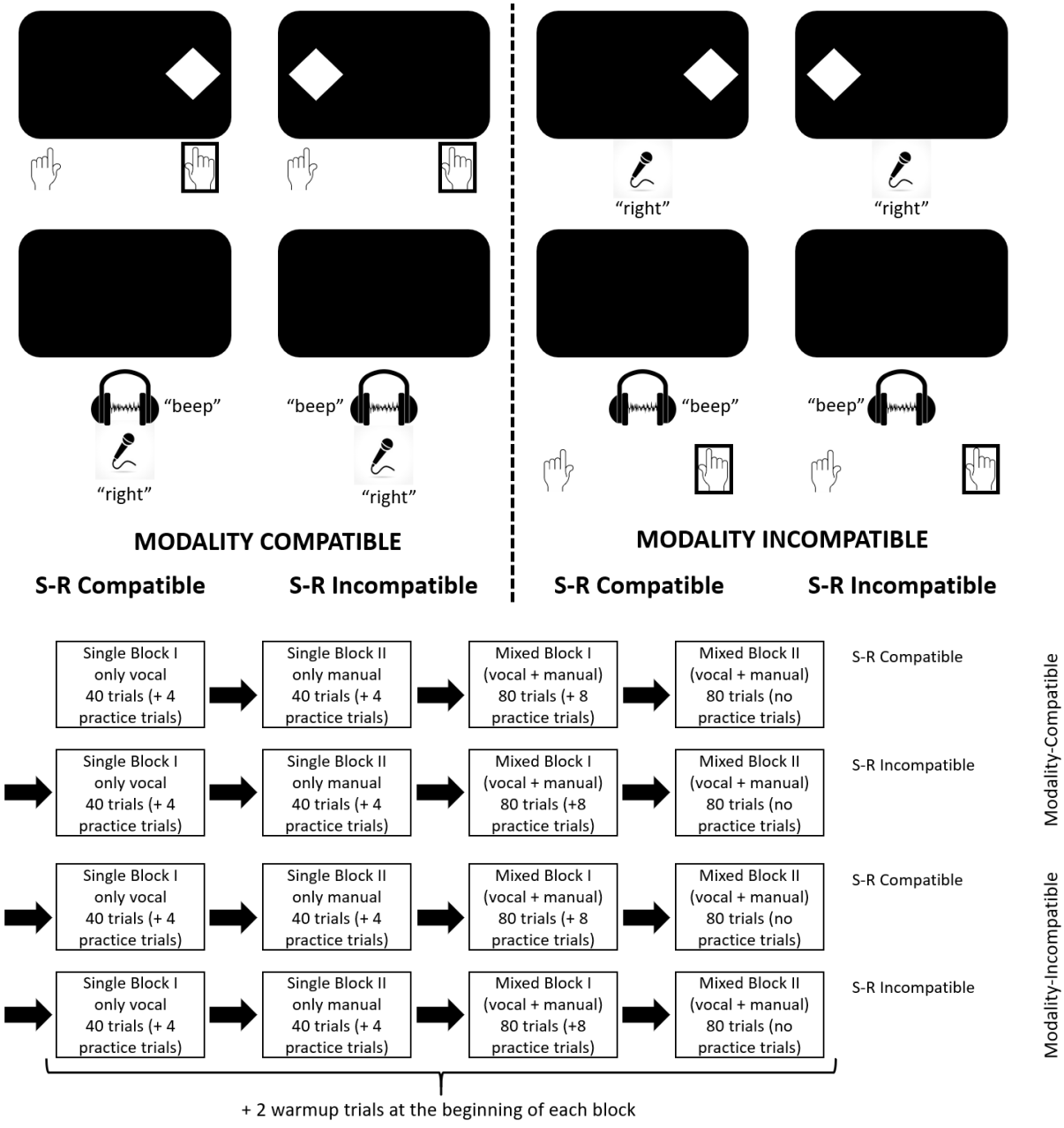
Mean RT and error switch costs in Experiment 1 (S-R = stimulus-response)



Error bars represent the standard error of the mean.

Figure 4

Stimuli and responses (top) and example experimental structure (bottom) for Experiment 2.

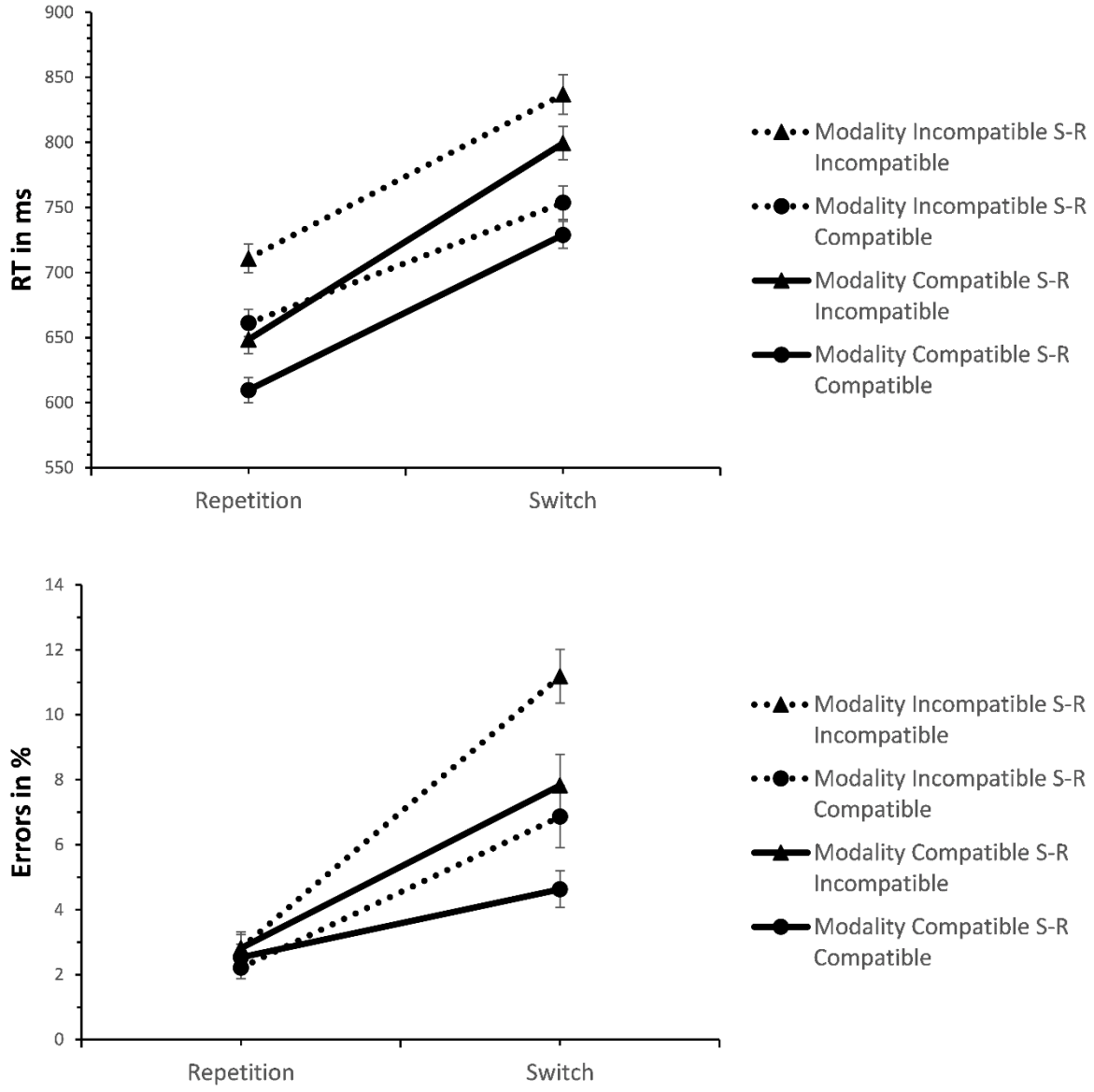


Experiment 2: S-R Compatibility Varied by Block

The stimulus examples use the stimuli that required a right response; the other stimuli required left responses. The order of conditions was counterbalanced.

Figure 5

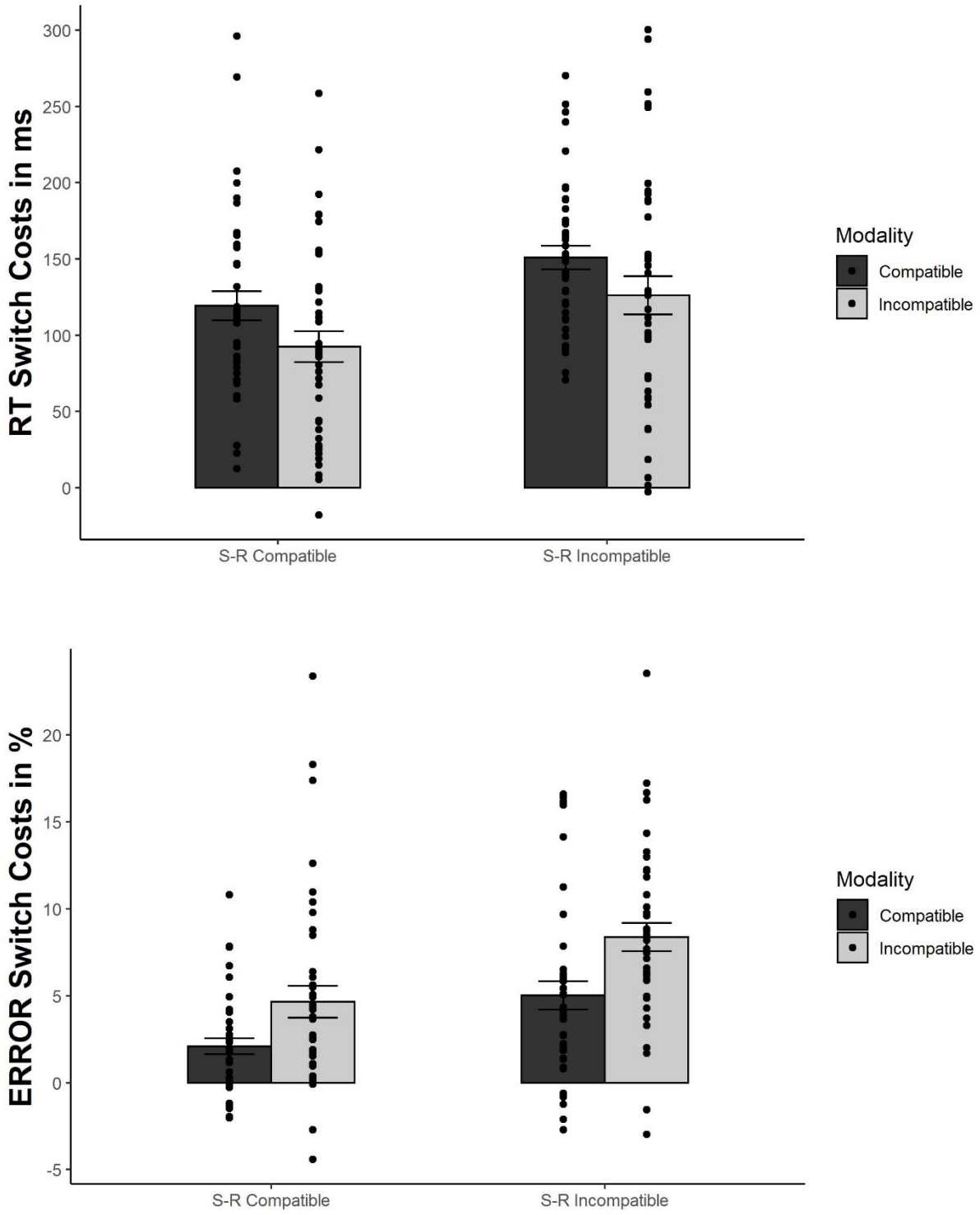
Mean RT and errors across conditions in Experiment 2 (S-R = stimulus-response)



Error bars represent the standard error of the mean.

Figure 6

Mean RT and error switch costs in Experiment 2 (S-R = stimulus-response)



Error bars represent the standard error of the mean.

Study III

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Voluntary Task Switching is affected by modality compatibility, set size, and response-stimulus interval

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Abstract

In task switching, some stimulus-response modality mappings (visual-vocal and auditory-manual) have been shown to elicit larger switch costs than others (visual-manual and auditory vocal), suggesting a role of modality compatibility in task switching. In a previous study, it has been found that such modality compatibility biases can also influence task choice rates in voluntary task switching (VTS): When instructed to use manual and vocal discrimination responses equally often in a setup with two visual and auditory spatial stimuli, participants formed a higher share of compatible than incompatible modality mappings. The present study assessed modality-compatibility effects on choice rates using verbal four-choice tasks: number words 1-4 in visual or auditory modality as stimuli and four horizontally aligned manual keypresses or vocal letters A-D as responses. In two experiments, we found a bias to preferentially create modality-compatible mappings by the response choice. We also found a bias to repeat the response modality just performed, as well as a bias to repeat entire stimulus-response modality mappings. In Experiment 2, we manipulated the response-stimulus interval (RSI). Short RSIs led to generally increased reaction times and an increase in both the response-modality repetition bias and the mapping repetition bias. Together, these findings show that VTS is biased by modality compatibility, suggesting that modality-specific variations induce bias in flexible task choice. However, in contrast to the other common biases in VTS, this modality-compatibility bias itself was equally strong with short and long RSI.

Keywords: task switching, voluntary task switching, modality compatibility

Multitasking research can be subdivided into two major branches: Dual tasking and task switching (see Koch et al., 2018, for a recent review). In both fields, performing two tasks, either simultaneously (dual task) or successively (task switching), leads to performance costs, in form of higher response times (RT) and error rates, compared to performing just a single task. Moreover, within task-switching blocks, there are additional costs on task-switch trials compared to task-repetition trials, which are known as switch costs. Switch costs have been explained as either reflecting the need to reconfigure a task set by retrieving it from long-term memory or the need to overcome interference from the task set from the previous task (see Kiesel et al., 2010; Koch et al., 2018; Monsell, 2003; Vandierendonck et al., 2010, for reviews).

A phenomenon that has repeatedly been shown in the past decade to affect both dual-task costs (e.g., Hazeltine et al., 2006; Stelzel & Schubert, 2011) and switch costs is that of modality compatibility (Stephan & Koch, 2010, 2011). Modality compatibility describes the match between the modality of the sensory input (visual or auditory) and the modality of the anticipated sensory effect of the response: Manual responses usually lead to visible effects, whereas vocal responses lead to auditory effects. As per the ideomotor principle, actions are initiated based on their anticipated effects (James, 1890), so that the anticipation of a visual effect arguably becomes part of the representation of a manual response, and the anticipation of an auditory effect becomes part of the representation of a vocal response. It is notable that modality compatibility, which requires overlap only at the level of the stimulus- and the response-effect modalities, is a less restrictive version of ideomotor compatibility (Greenwald, 1972), which requires overlap even at the level of stimulus and response identity (see Shin et al., 2010, for a review of contemporary ideomotor theory).

In task switching, smaller switch costs have been found when switching between two tasks with modality-compatible mappings in the same task-switching block (visual-manual

and auditory-vocal) than when switching between two tasks with modality-incompatible mappings (visual-vocal and auditory-manual). One proposed explanation for this finding is increased between-task crosstalk with incompatible modality mappings (Stephan & Koch, 2010, 2011, 2015, 2016). This increased crosstalk is assumed to occur because, with incompatible modality mappings, the anticipated response effect refers to the same input modality as the stimulus of the competing task: In a visual-vocal task, the expected effect of the vocal response is still auditory, which is the stimulus modality of the competing auditory-manual task; and on an auditory-manual trial, the expected effect of the manual response is still visual, which in turn refers to the stimulus modality of the competing visual-vocal task. Because there is no systematic effect of modality compatibility on single-task performance, it is evident that modality-compatibility effects on switch costs cannot be the result of modality-incompatible tasks simply being more difficult overall. Rather, it is the between-task crosstalk that only occurs in mixed-task blocks that seems to be influenced by *combinations* of mappings, specifically (since the sets of stimuli and responses are identical in both modality-compatible and modality-incompatible blocks) (Fintor et al., 2018).

In addition to the ideomotor learning and crosstalk account (Stephan & Koch, 2016), models of multitasking that include modality as a factor (Wickens, 2008), as well as modality-specific accounts of working memory (Baddeley, 1992), can explain these different levels of interference. In particular, the working-memory account suggests that response selection with compatible modality mappings is facilitated because both stimulus codes and response codes refer to the same subsystem (Maquestiaux et al., 2018). Note that the crosstalk account and the working-memory account are not necessarily mutually exclusive (Friedgen et al., 2021): If both stimulus and response codes refer to the same subsystem, each modality-compatible task would be contained within one subsystem, whereas crosstalk between two subsystems would be present when switching between tasks with modality-incompatible mappings.

However, modality compatibility does not merely affect multitasking costs in terms of RT and error rates, but also task choice: A study by Fintor et al. (2020) demonstrated that, in a voluntary-task switching (VTS) paradigm (Arrington & Logan, 2004, 2005), participants chose to form a higher share of compatible modality mappings than of incompatible modality mappings (see Table 1 for an overview of all possible choices). This happened even though participants were asked to use both tasks equally often without resorting to any kind of regularity.

Note that VTS research has revealed that there is a general bias for the participant to repeat the task they have just performed, which is therefore called the task-repetition bias (Arrington & Logan, 2005; Mittelstädt et al., 2018). Arrington and Logan (2005) explained this task-repetition bias in form of competing heuristics: A bottom-up process based on (stimulus) availability (Arrington, 2008) can override the top-down mental representation that is trying to generate a random sequence of task choices (see also Mittelstädt et al., 2018). Note that in modality-compatibility studies, a "task" is usually defined as an individual modality mapping (visual-manual, auditory-vocal, visual-vocal, auditory-manual). Accordingly, in the study by Fintor et al. (2020), because stimulus modality was random, only the response modality could be freely chosen by the participant, so that this task-repetition bias equated a response-modality repetition bias.

Studies showed that the task-repetition bias is increased by shortening the response-stimulus interval (RSI), which gives participants less time to choose which task to perform once the subsequent stimulus appears (see Arrington et al., 2014, for a review). This effect of RSI on the task-repetition bias has been found irrespective of whether RSI was varied by block (Arrington & Logan, 2004) or by trial (Arrington & Logan, 2005). Perseverations like these can also be found with greater response conflict: This triggers a top-down enhancement of the working-memory representation of a task, and then bottom-up processes pick the most

activated representation from working memory (Botvinick et al., 2001; Orr et al., 2012). Usually, the most recently activated task set is the most active one, and hence, the task is repeated. But in case modality-compatible mappings have stronger working-memory representations (as suggested by Fintor et al., 2020) – for example, due to both the modality of the stimulus and of the anticipated response effect being processed in the same subsystem (Friedgen et al., 2021; Maquestiaux et al., 2018) – this same conflict-monitoring mechanism could also be responsible for biasing choice behaviour in their favour.

Aside from choice rates, RT and error rates of course remain important measures in VTS, too: Despite participants selecting the tasks themselves, switch costs can still be found (see Kiesel et al., 2010; Vandierendonck et al., 2010, for reviews). Consequently, also the typical effect of modality compatibility on switch costs (larger switch costs with incompatible modality mappings) was still found by Fintor et al. (2020). Because by definition, all four mappings (visual-manual, auditory-vocal, visual-vocal, auditory-manual) occurred within each block, since participants are instructed to vary the response modality (and thus the S-R modality mapping) randomly, Fintor et al. (2020) only compared trials of pure switches (both stimulus modality and response modality change) to trials of pure repetitions (both stimulus and response modality repeat), not to partial switches (only stimulus modality or only response modality changes), as shown in Table 1. This allowed them to approximate the conditions from the previous modality-compatibility studies, in which there had always been fixed mappings of stimulus modality and response modality for each block.

In the present study, we examined in two experiments the influence of modality compatibility on choice rates in VTS. Compared to the study by Fintor et al. (2020), we doubled the number of S-R alternatives in each task to increase the difficulty of response selection (four possible stimuli for each stimulus modality, and four possible responses for each response modality). We assumed that the necessity of maintaining a larger stimulus set and a

larger response set in working memory would increase cognitive load (Demanet et al., 2010), so that the VTS bias, the modality-compatibility effect on choice rates, could be replicated and extended to different materials and tasks. In Experiment 2, we investigated how RSI affects modality compatibility effect in VTS, because a shorter RSI would allow for less decay of the previous task set, or provide less time to prepare for the upcoming choice, and should thus lead to a stronger task-repetition bias. Specifically, we examined whether the bias to form more compatible modality-mappings would get even stronger with short RSI.

Experiment 1

The Experiment 1 we aimed at replicating Fintor et al.'s (2020) finding of the modality-compatibility effect on choice rates. Moreover, we wanted to extend it to different stimulus material and tasks.

Method

Participants. 32 participants (19 female, 29 right-handed, mean age = 24.56, SD = 3.307) were tested, 8 more than Fintor et al. (2020). In their study, the modality-compatibility effect on RT switch costs had an effect size of $\eta^2_p = .331$. According to a power analysis with G*Power 3 (Faul et al., 2007), with alpha = 0.05, a sample size of 30 participants would have been sufficient to find a modality-compatibility effect of this size with a power of 95%. Increasing the sample size to 32 participants raised the power for this effect to over 96%. For the effect of modality compatibility on choice rates, in particular, as said above, Fintor et al. (2020) found an effect size of $\eta^2_p = .249$. The power to find such an effect with the present sample size was over 87%.

All participants had normal or corrected-to-normal vision and hearing and gave their informed consent for participating in the study, receiving either 5 € or partial course credit for their participation.

Stimuli and apparatus. The experiment was programmed using PsychoPy2 (Peirce et al., 2019). Stimuli were the visual and auditory number words “EINS”, “ZWEI”, “DREI”, and “VIER” (German for “one”, “two”, “three”, and “four”). For visual stimuli we chose number words instead of digits so that stimuli in both modalities would consist of verbal material; this was done for consistency and to avoid confounds between stimulus modality and processing codes (since the auditory stimuli had to be verbal for practical reasons, processing codes for visual stimuli should not be systematically different).

Visual stimuli were presented centrally on a 4:3 screen in white letters on a black background; auditory stimuli were presented binaurally via headphones. Manual responses were made using the middle- and index fingers of both hands via four horizontally arranged keys on a wooden board. Vocal responses were made by speaking the letters “A”, “B”, “C”, and “D” into a microphone positioned in the centre of the wooden board and in front of the screen.

Both the wooden board and the microphone were connected to the same response box, which was connected to the computer via a USB cable. Because neither the horizontal spatial locations for the manual responses nor the letters for the vocal responses featured direct dimensional overlap with the centrally / binaurally presented numbers one, two, three, and four, we assumed that both response modalities would require a comparable amount of sensory-motor transformation. The stimulus “one” required the vocal response “A” or the leftmost manual keypress; the stimulus “two” the vocal response “B” or the centre-left manual keypress; the stimulus “three” the vocal response “C” or the centre-right manual keypress; and the stimulus “four” the vocal response “D” or the rightmost keypress. Participants had a maximum time of 1500 ms to respond. The RSI was 600 ms, during which the experimenter recorded the accuracy in case the participant chose a vocal response. This was done to enable instant error feedback for both response modalities, rather than just measuring response time for

vocal responses and determining accuracy in hindsight (accuracy of manual responses was coded automatically from the participants' keypresses). If the participant made an error, bimodal error feedback (a central red exclamation mark and a "boing" sound) was presented for 400 ms, followed by 100 ms of silence and a black screen, thereby extending the total RSI after an error to 1100 ms.

Procedure. The experiment began with a short practice block of 16 trials in which participants were instructed to try all possible combinations of stimulus- and response modalities at least once. After that, six experimental blocks followed. These six experimental blocks consisted of 80 trials with two additional warm-up trials at the beginning of each block (since the first two trials of each block were going to be dropped from the analysis). This added up to 480 experimental trials plus 12 warm-up trials in total. All blocks in this experiment were mixed-task blocks, that is, they featured both visual and auditory stimuli, and participants were asked to respond both manually and vocally. Participants were instructed to vary the response modality randomly while also trying to use both response modalities equally often; to facilitate this, they were told to imagine they were flipping a coin on every trial.

Design. The within-subjects independent variables were modality compatibility (incompatible vs. compatible) and switching (switch vs. repetition). The dependent variables were RT, error rates, and choice rates. Note that we only manipulated stimulus modality, while modality compatibility and switching were created as a result of the participants' choices. Hence, modality compatibility was not an independent variable of the experimental setup itself, but rather an independent variable for data analysis. All analyses were conducted at $\alpha = .05$.

Results

The practice block and the first two trials of each block were excluded from all analyses. Like in the study by Fintor et al. (2020), for the analysis of RT and error rates, z values

for RT were formed for each participant, with all trials outside +/-3 z for a given participant being excluded, as well as all responses following error trials. RT analysis also excluded the error trials themselves.

Choice probability. First, we examined whether participants would form more compatible modality mappings than incompatible modality mappings. The ANOVA on choice rates as a function of modality compatibility revealed a significantly larger proportion of modality-compatible mappings than of modality-incompatible mappings, $F(1, 31) = 6.505$, $p = .016$, $\eta^2_p = .173$ (52.5% vs. 47.5%). The more detailed overview over the proportion of choices for the individual stimulus-response modality mappings can be seen in Table 2.

Next, we ran a *t* test comparing the proportion of vocal responses and manual responses in order to examine whether participants managed to use both response modalities with about equal frequency. This *t* test indicated significantly more manual responses (60.8%) than vocal responses (39.2%), $t(31) = 6.344$, $p < .001$, $d_z = 1.121$. A second *t* test comparing the proportion of response modality switches and response modality repetitions demonstrated more repetitions (68.8%) than switches (31.2%), $t(31) = 7.217$, $p < .001$, $d_z = 1.276$, confirming the general response-modality repetition bias.

We also looked at transitions between stimulus-response modality mappings (visual-manual, auditory-vocal, visual-vocal, auditory-manual). For the analysis of choice probability, only a "complete" repetition of both stimulus modality and response modality counted as a repetition, while all full switches (both stimulus modality and response modality switching) and partial switches (either stimulus modality or response modality remaining constant while the other one switches) counted as switches. This means that the expected value of randomness for mapping repetitions was 25%, not 50%. The *t* test indicated a significant upward

deviation from 25%, $t(31) = 9.852$, $p < .001$, $d_z = 1.742$ (38.5% mapping repetitions, 61.5% mapping switches), that is, a mapping repetition bias.[7]

Response time and error rates. For the ANOVA, only complete repetitions of both stimulus modality and response modality counted as repetitions (like visual-manual, visual-manual), and only complete switches of both stimulus modality and response modality counted as switches (like visual-manual, auditory-vocal) (see Figure 1). As explained before, the theoretically expected share of complete repetitions in case of randomness would have been 25%, and the same is true for complete switches. Given this, it is not surprising that 57.4% of the data qualified for this analysis of complete stimulus-response modality switches and repetitions in RT and error rates (since this is slightly above 50% of the data: the expected share of complete repetitions, about 25%, plus the expected share of complete switches, another 25%). Modality compatibility was coded by collapsing the data across the two modality-compatible and the two modality-incompatible mappings, since modality compatibility is defined by the interaction of stimulus- and response modality. Thus, just like in the analysis of choice rates, potential effects of individual stimulus- and response modalities were not relevant for our research question.

The 2 x 2 ANOVA for RT with the within-subjects factors modality compatibility (incompatible vs. compatible) and switching (switch vs. repetition) revealed a significant effect of modality compatibility, $F(1, 31) = 43.100$, $p < .001$, $\eta^2_p = .582$, with higher RT for modality-incompatible trials than for modality-compatible trials (955 ms vs. 904 ms). There was also an effect of switching, $F(1, 31) = 156.762$, $p < .001$, $\eta^2_p = .835$, confirming larger RT on switch trials than on repetition trials (1004 ms vs. 855 ms). Finally, the interaction of modality

[7] Note that repeating the entire mapping means two consecutive trials with the same combination of stimulus modality and response modality, like auditory-vocal, auditory-vocal. In contrast, auditory-vocal, visual-vocal would be a response-modality repetition, but not a mapping repetition.

compatibility and switching was significant, too, $F(1, 31) = 11.868$, $p = .002$, $\eta^2_p = .277$. However, the direction was inverted relative to the standard effect of modality compatibility on switch costs: Larger switch costs were found in the modality-compatible condition compared to the modality-incompatible condition (183 ms vs. 115 ms). Post-hoc *t* tests revealed that this inversion was due to a distinct benefit for modality-compatible mappings in repetition trials, $t(31) = 7.451$, $p < .001$, $d_z = 1.317$ (897 ms incompatible vs. 813 ms compatible), whereas performance on switch trials did not differ significantly between modality-compatibility conditions, $t(31) = 1.183$, $p = .246$, $d_z = .209$ (1012 ms incompatible vs. 996 ms compatible).

In the corresponding ANOVA for error rates, the main effect of modality compatibility was not significant, $F(1, 31) = 2.716$, $p = .109$, $\eta^2_p = .081$. The effect of switching was significant, $F(1, 31) = 30.085$, $p < .001$, $\eta^2_p = .493$, with more errors on switch trials than on repetition trials (14.5% vs. 6.6%). Finally, the interaction of modality compatibility and switching was not significant, $F(1, 31) = 1.171$, $p = .288$, $\eta^2_p = .036$, but the pattern was numerically opposite to that found in RT: switch costs were higher for the modality-incompatible condition than for the modality-compatible condition (9.3% vs. 6.5%). Post-hoc *t* tests showed that performance did not differ between modality-compatibility conditions on switch trials, though, $t(31) = .002$, $p = .999$, $d_z = .000$ (14.5% in both conditions); rather, there were more errors on modality-compatible repetitions trials than on modality-incompatible repetition trials, $t(31) = 2.129$, $p = .041$, $d_z = .376$ (8.0% vs. 5.2%).

Note that RT and error rates did not differ as a function of modality compatibility in the switch trials, suggesting that there is a specific speed-accuracy trade-off in repetition trials. Since modality-compatibility effects on switch costs can often be found in both RT and error rates, such a pattern of effects trending in opposite directions required further clarification. Hence, to address this trade-off, we performed a post-hoc analysis based on inverse

efficiency scores (IES), which represent an integrated speed-accuracy measure (Liesefeld & Janczyk, 2019; Vandierendonck, 2017, 2018) by dividing RT in each condition by accuracy (1 – percentage of error rates). In this analysis, there was a significant effect of modality compatibility, $F(1, 31) = 10.627$, $p = .003$, $\eta^2_p = .255$ (1080 ms modality-incompatible vs. 1037 ms modality-compatible). There was also an effect of switching, $F(1, 31) = 96.667$, $p < .001$, $\eta^2_p = .757$ (1194 ms on switch trials vs. 923 ms on repetition trials). However, using IES, the interaction of modality compatibility and switching was no longer significant ($F < 1$), suggesting that the unexpected direction of the interaction in the RT data can be fully accounted for by a speed-accuracy trade-off in the mapping repetitions.

Discussion

In Experiment 1, we replicated the bias to create more modality-compatible mappings than modality-incompatible mappings, although this bias was slightly smaller in our present setup (N = 32) with four responses per modality (52.5% vs. 47.5%, $\eta^2_p = .173$), compared to the previous study by Fintor et al. (2020) (N = 24) (53.2% vs. 46.8%, $\eta^2_p = .249$), despite our larger sample size. However, a direct comparison across studies is not possible, since our study differed from Fintor et al. (2020) both with regards to the number of S-R alternatives *and* the type of stimulus material (spatial vs. verbal). We also found a mapping-repetition bias, where Fintor et al. (2020) had found a mapping-switch bias. We speculate that this may have been due to increased response conflict in our study, with four alternatives instead of two, leading to a stronger perseveration bias: A perseveration bias that resulted in participants not only repeating the response modality, but the entire S-R modality mapping. In Experiment 2, we examined whether the effect of modality compatibility on choice rates in VTS would be affected by a variation of the RSI.

Experiment 2

The RSI represents the time between the free response modality choices. Previous studies have shown that the bias to repeat the just-performed task is stronger with short RSIs than with long RSIs (see Arrington et al., 2014, for a review), suggesting a stronger influence of bottom-up processes when participants have less time to choose. Based on the assumption that modality-compatibility effects also reflect bottom-up processes during the response process[8], we expected them to behave similarly: Hence, Experiment 2 tested whether the bias to form compatible modality mappings is stronger with a short RSI compared to a long RSI.

Method

Participants. 32 further participants who had not taken part in Experiment 1 (23 female, 31 right-handed, mean age = 23.31, SD = 3.225) were tested. All of them gave their informed consent, receiving the same amount of compensation as the participants in Experiment 1. The power analysis was analogous to Experiment 1, regarding the effect of modality compatibility on switch costs and on choice rates.

Stimuli, Apparatus, and Procedure. The experimental setup was the same as in Experiment 1, except for the additional manipulation of the RSI, which was varied randomly trial-by-trial, either being short (400 ms) or long (1200 ms), compared to the standard RSI of 600 ms we used in Experiment 1. Note that the RSI was the interval in which the experimenter coded vocal responses whenever they occurred. Thus, the RSI needed to be sufficiently long for the experimenter to react; a shorter RSI than 400 ms would not have been possible in a modality-compatibility study with instant error feedback. In the first VTS studies by Arrington and Logan (2004, 2005), which used only manual responses, both the short and the long RSI were shorter, with 100 ms vs. 1000 ms, respectively. However, 400 ms have been

[8] Anticipation of the effect (and its modality) by definition is a top-down process, since it forms the basis for intentional, goal-based action. However, the interaction of the modality of the anticipated response effect and the modality of the stimulus is what we regard as a bottom-up process.

used as the comparatively shorter RSI in other VTS studies (e.g., Arrington, 2008) and still demonstrated the increased involvement of bottom-up processes. The procedure was identical to Experiment 1, again except for the trial-by-trial random variation of the RSI.

Design. The independent within-subjects variables for data analyses were modality compatibility (incompatible vs. compatible), switching (switch vs. repetition), and RSI (short vs. long). The dependent variables were RT, error rates, and choice proportion. Like in Experiment 1, we only manipulated stimulus modality, and now additionally RSI; modality compatibility and switching resulted from the participants' choices. All analyses were conducted at $\alpha = .05$.

Results

Data analysis for Experiment 2 followed the same procedure as for Experiment 1, only that now, RSI (short vs. long) was an additional factor. Four participants were excluded from the analysis for having error rates larger than 50% in at least one condition.

Choice probability. Given the additional independent variable RSI, we conducted a series of 2 x 2 ANOVAs to examine potential interactions with RSI on choice rates for modality compatibility, response modality, response modality transition, and mapping transition. Separate ANOVAs were required here, since the factors just listed were different dependent measures that we generated. For example, modality compatibility is defined by the interaction of stimulus modality and response modality; therefore, choice rates of response modality by itself cannot be analysed within the same ANOVA as choice rates of modality compatibility.

Only potential interactions with RSI were relevant in the context of choice rates (since RSI duration was manipulated by us, not chosen by the participants, a main effect of RSI on choice rates was impossible). The overview of choice rates for the individual modality mappings, split up by RSI, can be seen in Table 3.

To examine modality compatibility, the ANOVA with modality compatibility and RSI as independent variables yielded a significant effect of modality compatibility on choice rates, $F(1, 27) = 6.714$, $p = .015$, $\eta^2_p = .199$, confirming a higher share of modality-compatible mappings than of modality-incompatible mappings (52.6% vs. 47.4%). However, this effect was not further modulated by RSI, and there was no main effect of RSI either (Fs < 1). A follow-up Bayesian analysis for the interaction of modality compatibility and RSI revealed a $BF_{10} = 0.29$, which can be seen as substantial evidence for the null hypothesis (Jeffreys, 1961), that is, no difference in the size of the modality-compatibility effect on choice rates depending on RSI.

To examine response-modality preference, we ran an ANOVA on choice rate with response modality and RSI as independent variables. This yielded an effect of response modality, $F(1, 27) = 28.832$, $p < .001$, $\eta^2_p = .516$, with more manual responses than vocal responses (60.7% vs. 39.3%). This effect was not modulated by RSI either. The analysis also revealed no main effect of RSI (Fs < 1), since that would have been conceptually implausible to begin with (see above).

The ANOVA for response modality transition and RSI confirmed the response-modality repetition bias, $F(1, 27) = 78.033$, $p < .001$, $\eta^2_p = .743$ (70.5% repetitions vs. 29.5% switches). There was no (impossible) main effect of RSI (Fs < 1), but importantly, RSI interacted with response modality transition, $F(1, 27) = 42.167$, $p < .001$, $\eta^2_p = .610$, indicating the novel finding of a stronger response-modality repetition bias after the short RSI (72.8% repetitions, 27.2% switches) than after the long RSI (68.2% repetitions vs. 31.8% switches).

To examine the mapping switch vs. repetition bias as in Experiment 1, the ANOVA for mapping transition and RSI yielded an effect of mapping transition, $F(1, 27) = 103.903$, $p < .001$, $\eta^2_p = .794$, with more mapping switches than mapping repetitions overall (61.4% vs. 38.6%). However, keep in mind the decisive threshold to distinguish a mapping switch bias

from a mapping repetition bias was the expected value of randomness for repetitions, 25%: The *t* test confirmed the overall rate of mapping repetitions (38.6%) was significantly higher than 25%, $t(27) = 12.170$, $p < .001$, $d_z = 2.300$, indicating a mapping repetition bias, consistent with Experiment 1. Again, there was no main effect of RSI ($F < 1$). However, the interaction of mapping transition and RSI was significant, $F(1, 27) = 13.348$, $p = .001$, $\eta^2_p = .331$, showing a greater share of mapping repetitions after a short RSI (40.1% repetitions, 59.9% switches) than after a long RSI (37.1% repetitions, 62.9% switches). Post-hoc *t* tests confirmed this second novel finding, with a larger effect size for the mapping repetition bias after the short RSI, $t(27) = 14.043$, $p < .001$, $d_z = 2.654$, than after the long RSI, $t(27) = 9.324$, $p < .001$, $d_z = 1.762$.

Response time and error rates. The 2 x 2 x 2 ANOVA (see Figure 2) for RT with the within-subjects independent variables modality compatibility (incompatible vs. compatible), switching (switch vs. repetition), and RSI (short vs. long) yielded a significant effect of modality compatibility, $F(1, 27) = 47.039$, $p < .001$, $\eta^2_p = .635$, with overall slower responses on modality-incompatible trials than on modality-compatible trials (948 ms vs. 888 ms). There was also an effect of switching, $F(1, 27) = 200.372$, $p < .001$, $\eta^2_p = .881$, showing higher RT on switch trials compared to repetition trials (996 ms vs. 840 ms). The effect of RSI was significant, too, $F(1, 27) = 22.462$, $p < .001$, $\eta^2_p = .454$, with higher RT after a short RSI than after a long RSI (935 ms vs. 901 ms). RSI yielded a trend for an interaction with switching, $F(1, 27) = 3.372$, $p = .077$, $\eta^2_p = .111$, showing numerically larger switch costs after a short RSI than after a long RSI (171 ms vs. 142 ms). The two-way interaction of modality compatibility and RSI was not significant ($F < 1$). Finally, we did not find a three-way interaction of modality compatibility, switching, and RSI ($F < 1$).

Yet, the interaction of modality compatibility and switching was significant, $F(1, 27) = 11.981$, $p = .002$, $\eta^2_p = .307$. Consistent with Experiment 1, the interaction effect showed

the unexpected pattern, with larger switch costs on modality-compatible trials than on modality-incompatible trials (187 ms vs. 125 ms). Again, post-hoc *t* tests suggested this inversion was based on a particular 91 ms advantage for modality-compatible repetition trials over modality-incompatible repetition trials, $t(27) = 7.712$, $p < .001$, $d_z = 1.457$ (885 ms modality-incompatible vs. 794 ms modality-compatible), whereas the performance difference on switch trials was 29 ms smaller between modality-compatibility conditions, but still significant, $t(27) = 2.156$, $p = .040$, $d_z = .407$ (1010 ms modality-incompatible vs. 981 ms modality-compatible).

In the ANOVA for error rates, there was no main effect of modality compatibility, $F(1, 27) = 1.215$, $p = .280$, $\eta^2_p = .043$. The effect of switching was significant, $F(1, 27) = 31.740$, $p < .001$, $\eta^2_p = .540$, showing more errors on switch trials than on repetition trials (14.0% vs. 6.6%). There was no effect of RSI ($F < 1$), and there were no interactions with RSI: Neither between RSI and switching ($F < 1$), nor between RSI and modality compatibility ($F < 1$), nor the three-way interaction of modality compatibility, switching, and RSI ($F < 1$).

The interaction of modality compatibility and switching was not significant, $F(1, 27) = 1.641$, $p = .211$, $\eta^2_p = .057$. But like in Experiment 1, in contrast to RT analysis, for errors the trend went into the expected direction, with numerically larger switch costs on modality-incompatible trials than on modality-compatible trials (8.9% vs. 6%). Therefore, different directions of the influence of modality compatibility on switch costs in RT and error rates again suggest a speed-accuracy trade-off. To account for this trade-off, we again conducted a post-hoc analysis of IES. In this analysis of IES, the main effect of modality compatibility was significant, $F(1,27) = 18.642$, $p < .001$, $\eta^2_p = .408$ (1249 ms incompatible vs. 1152 ms compatible). The effect of switching was significant, too, $F(1, 27) = 137.309$, $p < .001$, $\eta^2_p = .836$ (1503 ms on switch trials vs. 898 ms on repetition trials). There was also the effect of RSI, $F(1,27) = 5.771$, $p = .023$, $\eta^2_p = .176$, with higher IES after the short RSI than after the long

RSI (1255 ms vs. 1146 ms). However, the interaction of modality compatibility and switching was not significant ($F < 1$), nor was the interaction of modality compatibility and RSI ($F < 1$), nor the three-way interaction of modality compatibility, switching, and RSI ($F < 1$). Hence, when taking the speed-accuracy trade-off into account by calculating IES, the surprising interaction pattern in RT disappeared.

Discussion

In Experiment 2, we varied the RSI (400 ms vs. 1200 ms) randomly from trial to trial. While the very first VTS study manipulated RSI by block (Arrington & Logan, 2004), the effect of a stronger task-repetition bias with short RSIs has been found with trial-wise manipulation, too (Arrington & Logan, 2005). With the latter type of manipulation, we replicated this influence of RSI on the task-repetition bias (response-modality repetition bias in our case) and also found such an RSI influence on the mapping-repetition bias: Both types of repetition biases were more pronounced after short RSIs. However, there was no additional influence of RSI on the proportion of modality-compatible mappings formed, with substantial evidence from the Bayes factor supporting the absence of the effect.

Independent from the RSI, we confirmed the novel mapping-repetition bias first found in Experiment 1, whereas Fintor et al. (2020) had reported a mapping-switch bias. Also, we once more replicated both the response-modality repetition bias and the bias to form a greater share of compatible modality mappings, consistent with Fintor et al. (2020).

General Discussion

In two experiments, we examined the effects of modality compatibility in VTS. We found evidence for a bias to form more modality-compatible mappings in both experiments. This effect was about the same size as found by Fintor et al. (2020), who used a much simpler spatial-discrimination task with just two alternatives (52.5% vs. 47.5%, $\eta^2_p = .173$ in

Experiment 1; 52.6% vs. 47.4%, η^2_p = .199 in Experiment 2, compared to Fintor et al. (2020) with 53.2% vs. 46.8%, η^2_p = .249). Compared to that earlier study, in both experiments, we found a mapping-repetition bias as opposed to a mapping-switch bias, and a preference for manual responses, that is, manual dominance rather than vocal dominance. As expected, we also found a bias to repeat the just-performed response modality, which in our design represents a task-repetition bias (Arrington & Logan, 2004, 2005; Arrington et al., 2014; Mittelstädt et al., 2018). Both the task-repetition bias and the mapping-repetition bias were stronger after a short RSI. In contrast, crucially, the tendency to form a greater share of modality-compatible mappings was *not* amplified after a short RSI.

The Influence of RSI

The short RSI led to slower responses overall, suggesting that our manipulation was indeed effective in increasing task difficulty, due to less time for preparing the next choice (in case any preparation occurred), as well as less time for the decay of the working-memory representation of the previous choice. Furthermore, a short RSI also provides less time for response-effect monitoring. In line with previous VTS studies (e.g., Arrington & Logan, 2004, 2005; Mittelstädt et al., 2018), the duration of the RSI further influenced choice rates – however, not with regards to the share of modality-compatible mappings formed, but concerning the rate at which response modalities and stimulus-response mappings were repeated. This suggests the modality-compatibility bias on choice rates is different in nature from the task-repetition bias.

The task-repetition bias is assumed to arise because bottom-up processes select the most active task representation from working memory (Botvinick et al., 2001; Orr et al., 2012); overcoming this perseveration bias consequently requires engaging top-down processes (Arrington & Logan, 2005; Mayr & Bell, 2006). Since in modality-compatibility studies, we define “task” as synonymous with “modality mapping”, this explanation for the task-

repetition bias holds true for both the response-modality repetition bias and the mapping-repetition bias. Participants could of course only select the response modality, but in doing so, they formed compatible or incompatible S-R modality mappings as a result. One potential cause of the mapping-repetition bias in our present study, as opposed to the mapping-switch bias reported by Fintor et al. (2020), might be the presumed greater response conflict with our setup: Having four instead of two alternatives for each stimulus modality and each response modality requires the maintenance of larger task sets (that is, more numerous response alternatives) in working memory.

These task-repetition biases increase with a short RSI because, presumedly, either there is less time to reconfigure the task set if the participant is intending a switch (Arrington & Logan, 2004; Rogers & Monsell, 1995), or because there is less time to allow the persisting activation of the previous task set to decay (Allport et al., 1994; see Vandierendonck et al., 2010, for a review). In either case: With a short RSI, there is less time to resolve the conflict between the current and the previous task set. This would make the bottom-up processes more likely to pick the most active task representation from working memory. Conversely, with a long RSI, there should be more time to engage top-down processes to overcome not only the perseveration bias, but also the bias to form more modality-compatible mappings.

Yet, since we found no difference in the share of compatible modality mappings between short and long RSIs, this is not in line with the suggestion by Fintor et al. (2020) that modality-compatible mappings have stronger working-memory representations in general. Even though, with compatible modality mappings, both the stimulus modality and the modality of the anticipated response effect refer to the same working-memory subsystem (Friedgen et al., 2021; Maquestiaux et al., 2018), this would then not imply locally stronger working-memory representations of those mappings within the respective subsystem – meaning, the phonological loop or visuospatial sketchpad (Baddeley, 1992).

Instead, if there is no such locally stronger working-memory representation creating a performance benefit for compatible modality mappings, the issue might instead lie with incompatible modality mappings being represented in both subsystems – specifically, with *both* modality-incompatible tasks partially referring to *both* subsystems, so that the modalities of the stimuli and the anticipated response effects overlap *between* subsystems, rather than within. In short: If the present results can be interpreted as evidence against stronger working-memory representations of modality-compatible mappings, this instead lends further credence to the crosstalk account (Friedgen et al., 2021; Schacherer & Hazeltine, 2020, 2021; Stephan & Koch, 2010, 2011), attributing modality-compatibility effects to greater between-task interference with incompatible modality mappings.

That said, note that we cannot rule out the possibility that modality-compatibility effects on choice rates might still increase if the RSI is even shorter than 400 ms – for example, in the studies by Arrington and Logan (2004, 2005), the short RSI was only 100 ms long. A minimum RSI duration of 400 ms was required in our experiment, though, to enable the experimenter to code the participant's vocal responses and thereby provide instant error feedback. Even though in VTS, only errors of response identity are possible, not errors of task choice (which are usually the more common type of error in forced-choice modality-compatibility experiments), our paradigm still required this instant error feedback – among others, because of the increased number of S-R alternatives.

Manual Dominance

The finding of manual dominance – relative to vocal dominance in Fintor et al. (2020) – could be explained by an easier sensory-motor transformation from the number stimuli to four horizontally aligned keys, going along with the mental number line from left to right, compared to the transformation required from number words to the spoken letters. Thus, numerical-spatial associations may produce SNARC-like compatibility (Dehaene et al., 1993)

that might have created stronger dimensional overlap (Kornblum et al., 1990) than the numerical-alphabet associations for the vocal responses. Moreover, the fact that both experiments in the present study were conducted during the COVID-19 pandemic, with participants being required to wear masks in the lab, may also have contributed to this shift in preferred response modality; Fintor et al. (2020) attributed vocal dominance in their study specifically to the effort involved in producing vocal responses, and the masks may have increased this physical effort in our case. Note though that this general preference for one respective response modality, in both our study and theirs, cannot explain how choice rate is influenced by modality compatibility, which is defined by the interaction of stimulus modality and response modality and is thus independent of the main effect of modality (i.e., vocal vs. manual dominance bias).

Speed-Accuracy Trade-Off

In both experiments, the effect of modality compatibility on switch costs was reversed in RT, but the analysis of IES indicated a speed-accuracy trade-off, which, if taken into account, no longer revealed an effect of modality compatibility on switch costs. Note that the trade-off was restricted to the mapping-repetition condition, suggesting no generally better performance with modality-compatible conditions. This suggests the possibility of an adjustment of response threshold (=a lower response threshold when repeating modality-compatible mappings, resulting in faster responses at the cost of accuracy). This hypothetical threshold adjustment was not evident in Fintor et al. (2020).

The trade-off could be due to the differences to forced-choice modality-compatibility studies with fixed modality mappings: The free task choice allowed participants to switch between all four possible mappings (visual-manual, auditory-vocal, visual-vocal, auditory-manual) within the same block, rather than just between two compatible or two incompatible modality mappings within the same block. Even though, in line with previous research (Fintor et al., 2018), the ANOVA only compared switches within modality-compatibility conditions, not

between modality-compatibility conditions (e.g., not a switch from visual-manual to visual-vocal), this necessary exclusion of partial switch trials of course reduced the overall number of switch trials that could be contrasted in the analysis of RT and error rates. A different explanation for the unclear modality-compatibility effect on RT and error switch costs is the lower conceptual overlap (Schacherer & Hazeltine, 2019, 2021) between stimuli and responses in our present study compared to the strong spatial compatibility and thus dimensional overlap in Fintor et al. (2020)'s setup: Schacherer and Hazeltine (2019) demonstrated that reducing conceptual overlap in both tasks can make the modality-compatibility effect on switch costs disappear. In either case: This trade-off should not detract from the main findings, which refer to the choice rates in VTS.

Conclusion

This study examined modality compatibility in task switching, using a VTS design. Participants created more modality-compatible mappings than modality-incompatible mappings if given free choice. They also were more likely to repeat not only response modalities, but entire stimulus-response modality mappings – especially so after short RSIs. Yet, importantly, the tendency to create more compatible modality mappings was not increased by those same RSI manipulations. These findings extend previous research by showing that modality compatibility affects voluntary task choices, but not in the same way that perseveration biases do. Hence, in contrast to perseveration biases, we do not attribute modality-compatibility effects on choice rates to stronger working-memory representations for compatible modality mappings, but to greater between-task crosstalk with incompatible modality mappings.

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Conflict of interest

The authors declare that they have no conflict of interest. They furthermore declare that they are in full control of their data and that the journal has permission to review their data on request.

Ethical standards

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This research has been approved by the ethics committee of department 7.3 Empirical Human Sciences of RWTH Aachen University. All individual participants gave their informed consent prior to their inclusion in this study.

Open Practices Statement

The data for all experiments is available at https://osf.io/q7e4p/?view_only=ca0ec13ed2074077a412d33c79be3153. Neither of the experiments was preregistered.

References

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance series. Attention and performance 15: Conscious and nonconscious information processing* (pp. 421–452). The MIT Press.

Arrington, C. M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory & Cognition*, *36*(5), 991-997. https://doi.org/10.3758/mc.36.5.991

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, *15*(9), 610-615. https://doi.org/10.1111/j.0956-7976.2004.00728.x

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *31*(4), 683-702. https://doi.org/10.1037/0278-7393.31.4.683

Arrington, C. M., Reiman, K. M., & Weaver, S. M. (2014). Voluntary task switching. In J. Grange & G. Houghton (Eds.), *Task switching* (pp. 117-136). Oxford University Press.

Baddeley, A. (1992). Working memory. *Science*, *255*, 556-559. https://doi.org/10.1126/science.1736359

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624-652. https://doi.org/10.1037/0033-295x.108.3.624

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371-396. https://doi.org/10.1037/0096-3445.122.3.371

Demanet, J., Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2010). Voluntary task switching under load: Contribution of top-down and bottom-up factors in goal-

directed behavior. *Psychonomic Bulletin & Review*, *17*(3), 387-393. https://doi.org/10.3758/PBR.17.3.387

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175-191. https://doi.org/10.3758/BF03193146

Fintor, E., Poljac, E., Stephan, D. N., & Koch, I. (2020). Modality compatibility biases voluntary choice of response modality in task switching. *Psychological Research*, *84*(2), 380-388. https://doi.org/10.1007/s00426-018-1040-5

Fintor, E., Stephan, D. N., & Koch, I. (2018). Emerging features of modality mappings in task switching: Modality compatibility requires variability at the level of both stimulus and response modality. *Psychological Research*, *82*(1), 121-133. https://doi.org/10.1007/s00426-017-0875-5

Friedgen, E., Koch, I., & Stephan, D. N. (2021). Modality compatibility in task switching depends on processing codes and task demands. *Psychological Research*, *85*(6), 2346-2363. https://doi.org/10.1007/s00426-020-01412-2

Greenwald, A. G. (1972). On doing two things at once: time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*(1), 52-57. https://doi.org/10.1037/h0032762

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291-345. https://doi.org/10.1016/j.cogpsych.2005.11.001

James, W. (1890). *The principles of psychology* (Vol. 2). Dover.

Jeffreys, H. (1961). *Theory of probability* (3d ed.). Clarendon Press.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - A review. *Psychological Bulletin*, *136*(5), 849-874. https://doi.org/10.1037/a0019842

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557-583. https://doi.org/10.1037/bul0000144

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility - A model and taxonomy. *Psychological Review*, *97*(2), 253-270. https://doi.org/10.1037/0033-295X.97.2.253

Liesefeld, H. R., & Janczyk, M. (2019). Combining speed and accuracy to control for speed-accuracy trade-offs(?). *Behavior Research Methods*, *51*(1), 40-60. https://doi.org/10.3758/s13428-018-1076-x

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception, & Psychophysics*, *80*, 752-772. https://doi.org/10.3758/s13414-017-1469-4 29285603

Mayr, U., & Bell, T. (2006). On how to be unpredictable: Evidence from the voluntary task-switching paradigm. *Psychological Science*, *17*(9), 774-780. https://doi.org/10.1111/j.1467-9280.2006.01781.x

Mittelstädt, V., Dignath, D., Schmidt-Ott, M., & Kiesel, A. (2018). Exploring the repetition bias in voluntary task switching. *Psychological Research*, *82*(1), 78-91. https://doi.org/10.1007/s00426-017-0911-5

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134-140. https://www.ncbi.nlm.nih.gov/pubmed/12639695

Orr, J. M., Carp, J., & Weissman, D. H. (2012). The influence of response conflict on voluntary task switching: A novel test of the conflict monitoring model. *Psychological Research*, *76*(1), 60-73. https://doi.org/10.1007/s00426-011-0324-9

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Hochenberger, R., Sogo, H., Kastman, E., & Lindelov, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195-203. https://doi.org/10.3758/s13428-018-01193-y

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks [Peer Reviewed]. *Journal of Experimental Psychology: General*, *124*(2), 207-231. https://doi.org/10.1037/0096-3445.124.2.207

Schacherer, J., & Hazeltine, E. (2019). How conceptual overlap and modality pairings affect task-switching and mixing costs. *Psychological Research*, *83*(5), 1020-1032. https://doi.org/10.1007/s00426-017-0932-0

Schacherer, J., & Hazeltine, E. (2020). Cue the effects: Stimulus-action effect modality compatibility and dual-task costs. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(4), 350-368. https://doi.org/10.1037/xhp0000719

Schacherer, J., & Hazeltine, E. (2021). Crosstalk, not resource competition, as a source of dual-task costs: Evidence from manipulating stimulus-action effect conceptual compatibility. *Psychonomic Bulletin & Review*, *28*(4), 1224-1232. https://doi.org/10.3758/s13423-021-01903-2

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943–974. https://doi.org/10.1037/a0020541

Stelzel, C., & Schubert, T. (2011). Interference effects of stimulus-response modality pairings in dual tasks and their robustness. *Psychological Research*, *75*(6), 476-490. https://doi.org/10.1007/s00426-011-0368-x 21811837

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *36*(4), 1075-1081. https://doi.org/10.1037/a0019695

Stephan, D. N., & Koch, I. (2011). The role of input-output modality compatibility in task switching. *Psychological Research*, *75*(6), 491-498. https://doi.org/10.1007/s00426-011-0353-4

Stephan, D. N., & Koch, I. (2015). Tactile stimuli increase effects of modality compatibility in task switching. *Experimental Psychology*, *62*(4), 276-284. https://doi.org/10.1027/1618-3169/a000291

Stephan, D. N., & Koch, I. (2016). Modality-specific effects on crosstalk in task switching: Evidence from modality compatibility using bimodal stimulation. *Psychological Research*, *80*(6), 935-943. https://doi.org/10.1007/s00426-015-0700-y

Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods*, *49*(2), 653-673. https://doi.org/10.3758/s13428-016-0721-5

Vandierendonck, A. (2018). Further tests of the utility of integrated speed-accuracy measures in task switching. *Journal of Cognition*, *1*(1), 1-16. https://doi.org/10.5334/joc.6

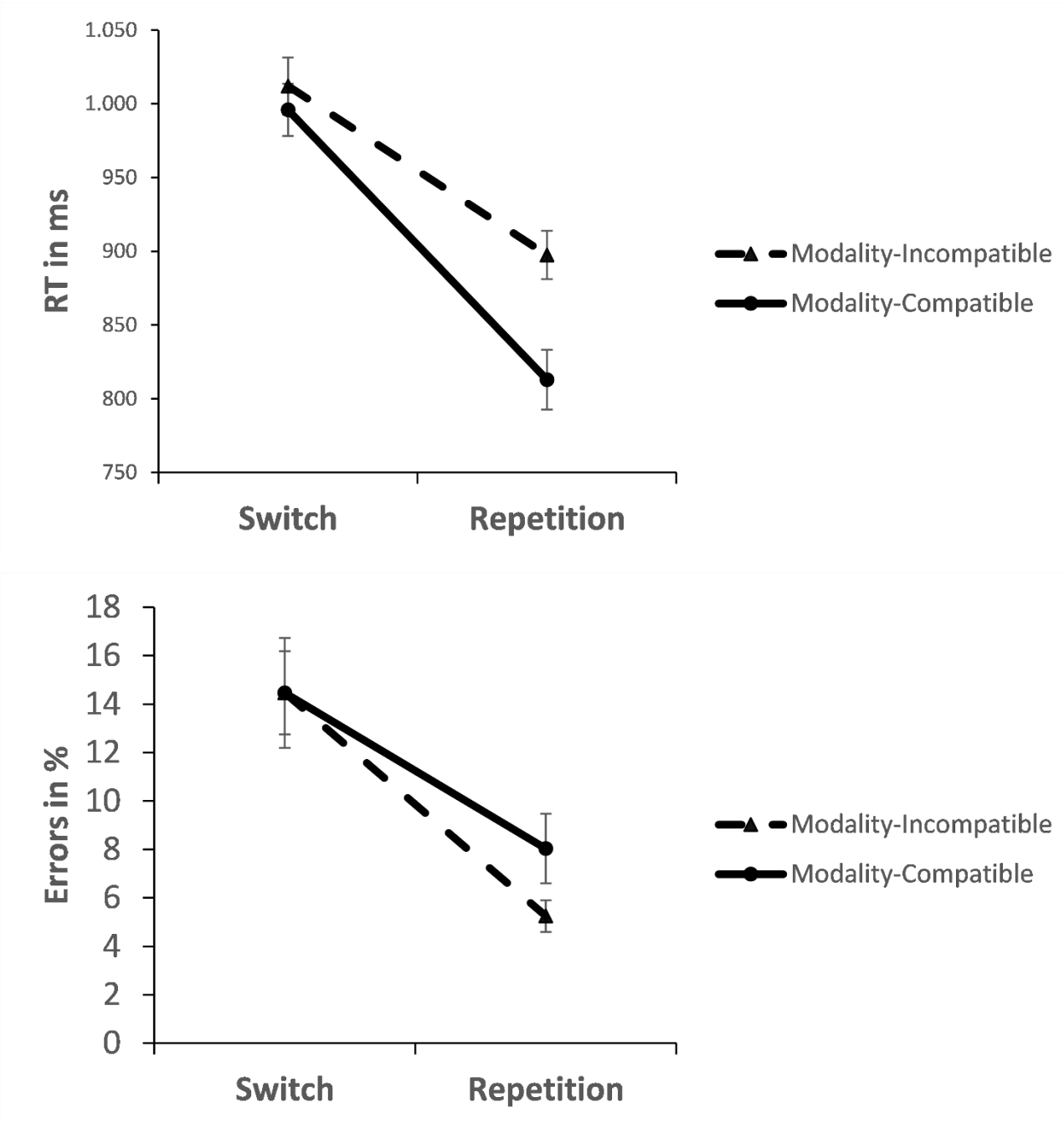
Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin*, *136*(4), 601-626. https://doi.org/10.1037/a0019791

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449-455. https://doi.org/10.1518/001872008X288394

Figures and Tables

Figure 1

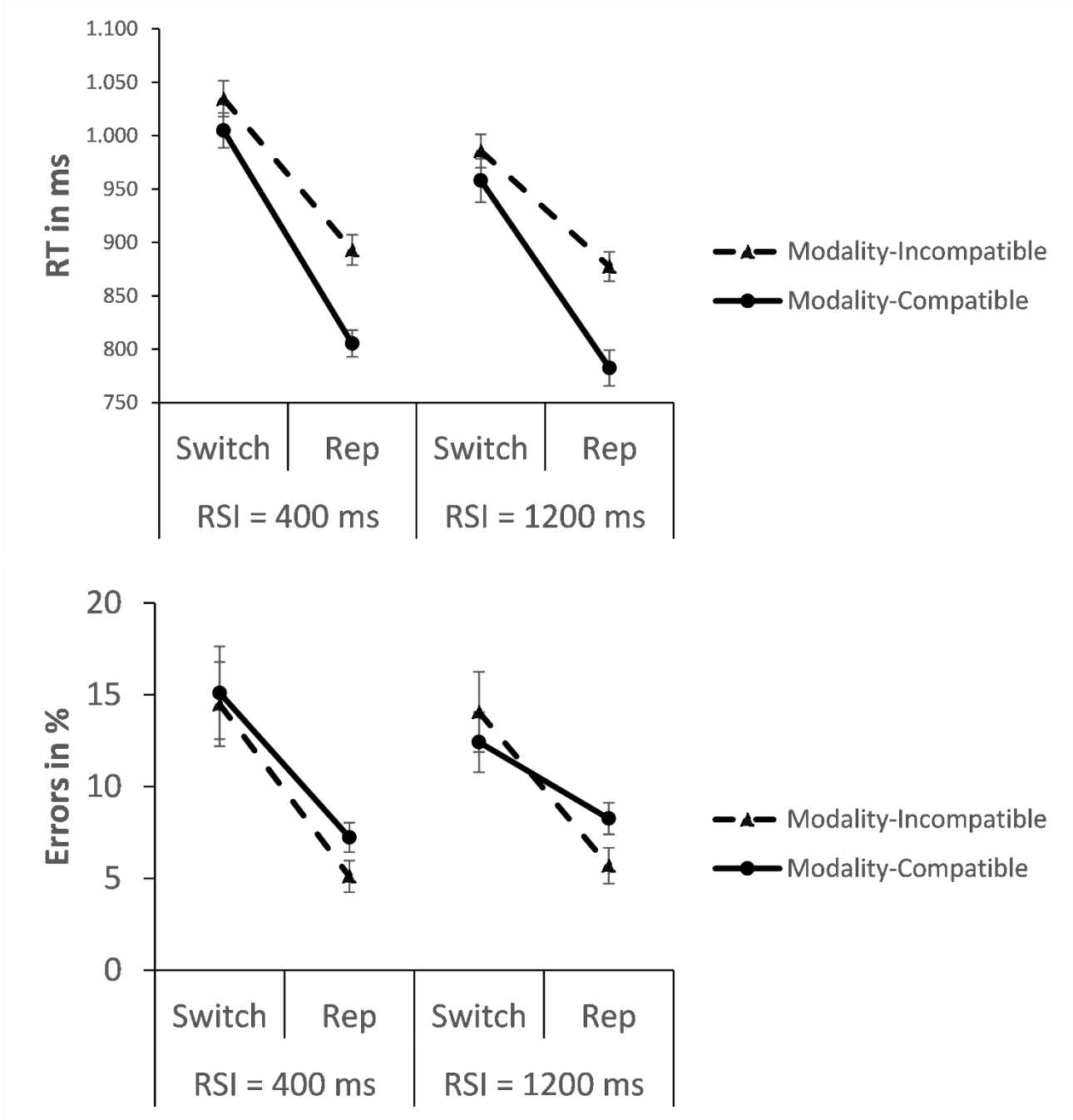
Mean response times (RT) for the modality-incompatible and the modality-compatible condition on switch trials vs. repetition trials in Experiment 1. A speed-accuracy trade-off can be seen in the repetition condition.



Error bars represent the standard error of the mean.

Figure 2

Mean RT and error rates for the modality-incompatible and the modality-compatible condition on switch trials vs. repetition trials (Rep) in Experiment 2, split up by RSI (400 ms = short; 1200 ms = long)



Error bars represent the standard error of the mean.

Table 1

Overview of Possible Stimulus-Response Transitions (adapted from Fintor et al., 2020).

Stimulus-Response Modality Mapping		Transition Type		
Trial N-1	Trial N	Stimulus Modality	Response Modality	Stimulus-Response Mapping
Complete Repetition				
Auditory-Vocal	**Auditory-Vocal**	Repetition	Repetition	Repetition
Auditory-Manual	Auditory-Manual	Repetition	Repetition	Repetition
Visual-Vocal	Visual-Vocal	Repetition	Repetition	Repetition
Visual-Manual	**Visual-Manual**	Repetition	Repetition	Repetition
Partial Switches				
Auditory-Vocal	Auditory-Manual	Repetition	Switch	Switch
Auditory-Manual	**Auditory-Vocal**	Repetition	Switch	Switch
Visual-Vocal	**Visual-Manual**	Repetition	Switch	Switch
Visual-Manual	Visual-Vocal	Repetition	Switch	Switch
Auditory-Vocal	Visual-Vocal	Switch	Repetition	Switch
Auditory-Manual	**Visual-Manual**	Switch	Repetition	Switch
Visual-Vocal	**Auditory-Vocal**	Switch	Repetition	Switch
Visual-Manual	Auditory-Manual	Switch	Repetition	Switch
Complete Switches	**Visual-Manual**	Switch	Switch	

Auditory-Vocal				Switch
Auditory-Manual	Visual-Vocal	Switch	Switch	Switch
Visual-Vocal	Auditory-Manual	Switch	Switch	Switch
Visual-Manual	**Auditory-Vocal**	Switch	Switch	Switch

Note: Modality-compatible conditions are written in bold.

Table 2

Mean Probability of Mapping Choices in Percent in Experiment 1

	Response Modality	
	Vocal	Manual
Stimulus Modality	M (SD)	M (SD)
Visual	19.39 (5.24)	**32.64 (5.22)**
Auditory	**19.83 (5.79)**	28.13 (6.10)

Note: Modality-compatible conditions are written in bold. M = mean, SD = standard deviation. The proportion of manual responses to visual stimuli was significantly higher than to auditory stimuli, $t(1, 31) = 4.225$, $p < .001$. The proportion of vocal responses did not differ significantly between visual and auditory stimuli ($t < 1$).

Table 3

Mean Probability of Mapping Choices in Percent in Experiment 2

	Response Modality			
	RSI = 400 ms		RSI = 1200 ms	
Stimulus Modality	Vocal M (SD)	Manual M (SD)	Vocal M (SD)	Manual M (SD)
Visual	19.08 (6.1)	**32.23 (6.8)**	19.32 (5.9)	**32.87 (4.9)**
Auditory	**20.63 (6.5)**	28.06 (6.3)	**19.54 (6.5)**	28.27 (7.5)

Note. Modality-compatible conditions are written in bold. The proportion of manual responses to visual stimuli was significantly higher than to auditory stimuli, $t(1, 27) = 4.102$, $p < .001$. The proportion of vocal responses did not differ significantly between visual and auditory stimuli ($t < 1$), but numerically, there were more vocal responses to auditory than to visual stimuli. The 3-way interaction of stimulus modality, response modality, and RSI on choice rates was not significant ($F < 1$).