# Examining independently switching components of auditory task sets:

# Towards a general mechanism of multicomponent switching

Von der Philosophischen Fakultät der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades einer Doktorin/eines Doktors der Philosophie genehmigte Dissertation

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**Content**

## Abstract

To deal with the flood of information that we are confronted with in daily life, the cognitive system allows to quickly switch between the processing of different tasks. In the present thesis, I examine complex task switching situations in which different components of the task representation switch independently and randomly between trials. In such paradigms, typically, a robust interaction of the components' switches and repetitions is obtained that indicates their integrated processing. It was the aim of the present thesis to identify the general mechanism underlying the component interactions.

I start with a review of findings and theories reported in previous studies, and I identify three different interaction pattern types, which are defined by their interactions' strengths. In the four studies, which are part of this thesis, the component interaction was examined in setups with auditory stimuli. Namely, an auditory attention component and a judgment component led to a rather weakly pronounced interaction pattern. Additional manipulations showed that this interaction pattern was not modulated by modality-specific processing demands and that it even arose when the attention switches were elicited automatically by exogenous cues. Moreover, the component that was cued in the beginning of the trial seemed to dominate the interaction pattern. When there was sufficient time for cue-based preparation of an attention switch, the interaction pattern became more pronounced. Similarly more pronounced patterns were found with instructed dependencies between the components. They allowed a preparation of a component based on the processing of the other component. Dependencies were especially evident in the interaction of a judgment component and a response component. The latter component interaction has elicited a rather separate line of research in the past years (i.e., studies on response repetition effect). As an explanation for the interaction pattern, inhibition of the just executed response was proposed. Yet, the similarities between the interaction of judgment component and response component, and the interactions of other components rather point towards a general mechanism of integrated component processing.

A component interaction seems to be generally elicited to a large part by episodic priming and temporal episodic binding of the components. In component switches, in contrast, active preparation during a sufficiently long interval and facilitated switches due to instructed component dependencies seems to affect performance, too. Altogether, the present thesis points towards a general mechanism of integrated component processing and emphasizes that future

research on multicomponent switching and on response repetition effects may benefit from more exchange.

## Zusammenfassung

Um mit der Informationsflut und den dadurch entstehenden Verarbeitungserfordernissen im täglichen Leben umgehen zu können, erlaubt das kognitive System schnelle Wechsel zwischen Aufgaben. In der vorliegenden Arbeit untersuche ich komplexe Aufgabenwechselsituationen in denen verschieden Komponenten einer kognitiven Aufgabenrepräsentation unabhängig voneinander und unvorhersehbar wechseln. In solchen Paradigmen findet man typischerweise eine Interaktion zwischen den Wechseln und Wiederholungen der jeweiligen Komponenten, welche auf deren integrierte Verarbeitung hinweist.

Es war das Ziel der vorliegenden Arbeit den dem Interaktionsmuster zugrundeliegenden Mechanismus zu untersuchen. Ich beginne damit verschieden Theorien und Befunde früherer Studien zu vergleichen und identifiziere drei prototypische Interaktionsmuster, welche durch ihr verschieden starkes Interaktionsmuster definiert sind. In den vier Studien, die in diese Arbeit eingeschlossen sind, wird die Interaktion der Komponenten in Experimenten mit auditiven Stimuli untersucht.

Eine auditive Aufmerksamkeitskomponente und eine Aufgabenkomponente ergeben ein eher schwaches Interaktionsmuster. Zusätzliche Manipulationen in den Experimenten zeigen, dass die Interaktion der Komponenten nicht durch Modalitäts-spezifische Verarbeitungsanforderungen beeinflusst wird und dass sie auch gefunden werden kann, wenn die Aufmerksamkeitswechsel der Aufmerksamkeitskomponente automatisch (exogen) ausgelöst werden. Die Komponente, die am Anfang eines Durchgangs von einem Hinweisreiz angezeigt wird, scheint zudem das Interaktionsmuster zu dominieren. Das Muster wird außerdem ausgeprägter, wenn die Aufmerksamkeitswechsel basierend auf einem Hinweisreiz während eines genügend langen Zeitintervalls vorbereitet werden können. Selbiges scheint auch aufzutreten, wenn es Abhängigkeiten zwischen den Komponenten gibt, welche basierend auf der Verarbeitung einer Komponente die Vorbereitung der anderen Komponente erlauben.

Letzteres ist sichtbar in der ausgeprägten Interaktion einer Aufgabenkomponente und einer Antwortkomponente. Diese Interaktion wurde in der Vergangenheit in einer relativ unabhängigen Forschungslinie untersucht und als Erklärung für ihr Muster wurde mitunter eine Hemmung der gerade ausgeführten Antwort vorgeschlagen. Die Ähnlichkeiten dieses Interaktionsmusters zu den Interaktionsmustern anderer Komponenten deuten jedoch eher auf einen generellen Mechanismus von integrierter Komponentenverarbeitung hin.

Insgesamt scheint das Interaktionsmuster der Komponenten zu einem großen Teil durch episodische Bahnung und durch vorübergehenden Assoziationen verschiedener der Komponenten eines Durchgangs hervorgerufen zu sein. Bei Komponenten-Wechseln dagegen scheint aktive Vorbereitung zu einem stärker ausgeprägten Interaktionsmuster führen zu können. Insgesamt deuten die Befunde der vorliegenden Arbeit auf einen generellen Mechanismus der integrierten Komponenten-Verarbeitung hin und darauf dass die Forschung in Multikomponenten-Paradigmen als auch die des Forschungszweigs zu Aufgaben- und Antwortkomponenten zukünftig von einem stärkeren gegenseitigen Austausch profitieren könnte.

## List of scientific publications and submitted manuscripts

**Study A**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018a). Intentional preparation of auditory attention-switches: Explicit cueing and sequential switch-predictability. *Quarterly Journal of Experimental Psychology, 71*, 1382-1395.

**Corrigendum A.c**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018). *Corrigendum: Intentional preparation of auditory attention-switches: Explicit cueing and sequential switch-predictability.* Manuscript submitted for publication.

**Study B**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018b). Auditory attention switching and judgment switching – exploring multicomponent task representations. *Attention, Perception, & Psychophysics* (online first, doi: 10.3758/s13414-018-1557-0).

**Study C**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018). *The binding of an auditory attention location and a judgment: A two-component switching approach.* Manuscript submitted for publication.

**Study D**

Seibold, J. C., Koch, I., Nolden, S., Proctor, R. W., Vu, K.-P. L., & Schuch, S. (2018). *Exploring response repetition effects in auditory task switching: Response discriminability and task-set decay.* Manuscript submitted for publication.

Please note that these articles do not exactly replicate the final version published in Attention, Perception, and Psychophysics and Quarterly Journal of Experimental Psychology. They are not the versions of record and are therefore not suitable for citation.

## Declaration of Authorship

I hereby certify that this cumulative dissertation has been composed by me and is based on my own work. I conceptualized the studies, conducted the respective experiments and wrote the included publications and manuscripts. My supervisors Prof. Dr. Iring Koch and Dr. Sophie Nolden were involved during conceptualization of the studies and assisted in the preparation of the manuscripts. Prof. Dr. Janina Fels, M. Sc. Josefa Oberem, Prof. Dr. Robert W. Proctor, and Prof. Dr. Kim-Phuong L. Vu collaborated with us in the different studies.

# 1 Introduction

Every day, our cognitive system needs to deal with a flood of information and processing demands. It has to accomplish simple tasks, like “judging the parity of a number stimulus”, but also complex ones, like “grading a student’s exam”, or “finding the way home”. Each task is assumed to be represented cognitively as a task set, which is a set of bindings between the parameters required to successfully perform the task, such as the task’s goal and specific rules, which associate stimuli with responses (see similar definitions e.g., Grange & Houghton, 2014; Kiesel et al., 2010; Koch, Poljac, Müller, & Kiesel, 2018; Logan & Gordon, 2001; Vandierendonck, Liefooghe, & Verbruggen, 2010). It has been demonstrated that the working memory capacity is limited (e.g., Miller, 1956), and therefore we can only deal with a certain amount of information at one time. Yet, we can compensate for that by switching quickly between different tasks.

To accomplish a task switch, a new task set needs to be retrieved and implemented. Thus, longer reaction times (RT) and higher error rates occur in task switches than in task repetitions (Jersild, 1927; for reviews, see e.g., Jost, de Baene, Koch, & Brass, 2013; Kiesel et al., 2010; Koch, Gade, Schuch, & Philipp, 2010; Koch, Poljac, et al., 2018; Monsell, 2003; Vandierendonck et al., 2010). The performance difference between switches and repetitions has been claimed to represent a measure of controlled processing, which is supposed to be conscious and voluntary (e.g., Grange, & Houghton, 2014; Rubinstein, Meyer, & Evans, 2001) and associated with executive functions (e.g., shifting, updating, and inhibition, see Miyake et al., 2000).

Yet, also automatic processes seem to contribute to the performance difference between task switches and repetitions (see Hommel, Ridderinkof, & Theeuwes, 2002; and for further details, see Ach, 1910; Atkinson & Shiffrin, 1968; Ruthruff, Remington, & Johnston, 2001; Shiffrin & Schneider, 1977). In task repetitions, the active task set can be re-used and may even prime the correct response, leading to improved performance (e.g., Altmann, 2005; Dreisbach, Haider, & Kluwe, 2002; Koch, 2001, 2005; Schmidt & Liefooghe, 2016). In task switches, the currently implemented (old) task set may interfere with the new task set (e.g., Wylie & Allport, 2000; Meiran, Chorev, & Sapir, 2000). To demonstrate the impact of such automatic priming and interference, Schneider and Logan (2005) quite successfully attempted to model performance in task switching without implementing any executive control mechanism.

Task switching has been examined many times in laboratory experiments. Usually, very simple tasks are thereby switched and repeated. Performance is, however, more difficult to predict when a task is more complex and consists of several (sub-)components. For example, the difficulty of “finding the way home” strongly depends on one’s current location (e.g., the neighbor’s apartment, or the work place) and the time point (e.g., noon, or midnight). One may need to walk, catch the bus at a certain time, or take a cab when busses don’t run any more. In the present thesis, I will examine how our cognitive system switches between such more complex tasks and their components. It will thereby be of interest how automatic, as well as controlled processes contribute to the performance.

## 1.1 Multicomponent switching

To explore such more complex task switching requirements, multicomponent switching paradigms can be employed. Here, at least two components switch and repeat independently from each other between the trials of the experiment. In the following, I use a very broad definition of a task set component. Namely, a component can be every feature of a task set that switches randomly between trials of the experiment – no matter whether the component is relevant (e.g., a judgment) or irrelevant for response selection (e.g., the cue modality in Koch, Frings, & Schuch, 2018). I will not examine components that are correlated with other components’ switches, like cue switches, which are entirely correlated with judgment switches in a cued judgment switching paradigm. Their contribution to performance cannot be isolated experimentally (Mayr & Kliegl, 2003; but see also transition cues, in Forstmann, Brass, & Koch, 2007).

For example, in a dichotically presented auditory stimulus pair (i.e., one stimulus presented per ear), the participant needs to identify a target by listening to the left or right ear. Thus, switching between left- and right-ear targets between trials of the experiment would be one component of the task set. The identified target can be a number or a letter, and depending on its identity, either a number judgment, or a letter judgment needs to be performed. The second component of the task set would therefore be judgment switches and repetitions. Typically, a robust interaction between the components’ switches and repetitions is found, which indicates that they are not processed independently. In the following, I will describe the general pattern of this component interaction, empirical findings from previous studies, and theoretical accounts that were developed to explain the integrated component processing.

### 1.1.1 The component interaction

Before going into detail about the component interaction pattern, I want to point out that I will report the performance differences between component switches and repetitions in terms of repetition benefits (and costs). In simple switch vs. repeat contrasts, I will use switches as the baseline. To describe the component interaction, I will treat complete switches (trial in which both components switch) as the baseline. Reporting repetition benefits is less common in the task switching literature than reporting switch costs, but there is no obvious baseline in the performance difference between switches and repetitions. Repetition benefits emphasize an episodic retrieval perspective, which may be helpful to understand the pattern of the component interaction and how the experience in the previous trial contributes to performance in a present trial (see similar practices in e.g., Dreisbach et al., 2002; Koch, 2001, 2005; Schmidt & Liefooghe, 2016; Wylie, & Allport, 2000).

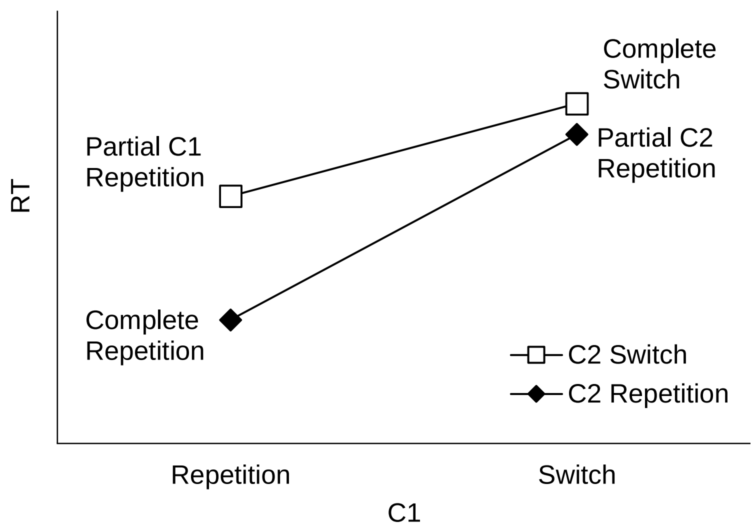


*Figure 1.* Example of an interaction between the components C1 and C2. Complete repetitions lead to the shortest reaction times (RT), whereas complete switches lead to similarly prolonged RT as partial C1 repetitions and partial C2 repetitions.

The components in a multicomponent switching setup usually interact and the following pattern is obtained in reaction times (RT) and error rates: When taking performance in complete switches as a baseline, large performance benefits are present in complete repetitions. In partial repetitions, in which one component repeats and the other component switches, small but systematic repetition benefits are frequently obtained, but sometimes also costs with respect to complete switches (see Figure 1 above for an exemplary interaction pattern).

The component interaction was obtained across many different component combinations in multicomponent switching setups. It was, for example found with a judgment component and a stimulus dimension component (Allport, Styles, & Hsieh, 1994; Hübner, Futterer, & Steinhauser, 2001; Kleinsorge, 2004; Vandierendonck, Christiaens, & Liefooghe, 2008), a cue modality component (Koch, Frings & Schuch, 2018), a stimulus modality component (Sandhu & Dyson, 2013; Murray, De Santis, Thut, & Wylie, 2009), a response modality component (Philipp & Koch, 2010), a response set component (Hahn, Anderson, & Kramer, 2003; Kieffaber, Kruschke, Cho, Walker & Hetrick, 2013), and a response-compatibility mapping component (Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001, 2002). A similar pattern was also present between a stimulus dimension component and a visual search component (Rangelov, Töllner, Müller, & Zehetleitner, 2013), and even when one of the components was entirely irrelevant for response selection (e.g., an auditory attention component and an irrelevant target location component in Koch & Lawo, 2014).

Moreover, there is the specific interaction of a judgment component and a response component that leads to a quite pronounced interaction pattern in which partial response repetitions systematically lead to costs with respect to complete switches (for a review and overview over so-called “response repetition effects”, see Altmann, 2011; Druey, 2014b). It has been examined in a relatively independent line of research and only rarely been linked to multicomponent switching (Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001, 2002). To my understanding, and as I will discuss later in more detail (2.4), this separation is not necessarily justified. Many similarities can be found between the empirical findings and the respective theoretical accounts of both lines of research. I will discuss multicomponent switching and these response repetition effect interactions therefore in an integrated way in the present thesis.

### 1.1.2 Theoretical accounts of multicomponent switching

When examining different components that switch independently between trials, it becomes evident that the traditional definition of a task set cannot be employed. The component interaction indicates that the components may be rather different subsets of the same task set than separate, independent task sets (see Philipp & Koch, 2010; Rangelov et al., 2013; Vandierendonck et al., 2008; see the similar idea of a “task file” in Hazeltine & Schumacher, 2016; see a “task space” in Kleinsorge & Heuer, 1999).

Moreover, the similar component interaction patterns across very different component combinations suggest that their supposedly integrated processing may be due to a rather general (i.e., a component-independent) underlying mechanism. Various theoretical accounts were proposed to explain this mechanism. The reason for the variety of theoretical accounts seems to be that they stem from and therefore predict differently pronounced component interaction patterns. To anticipate, all the theoretical accounts acknowledge that the performance benefits in complete repetitions are due to some sort of episodic priming from the previous trial's episode. Yet, for performance in partial repetitions and complete switches, very different mechanisms have been proposed and these mechanisms can be categorized by predicting roughly the following three differently pronounced interaction patterns: ordinal, flat, and disordinal interaction patterns (see examples in Figure 2). I will outline the most important theoretical accounts organized by the strength of the interaction pattern that they can explain.

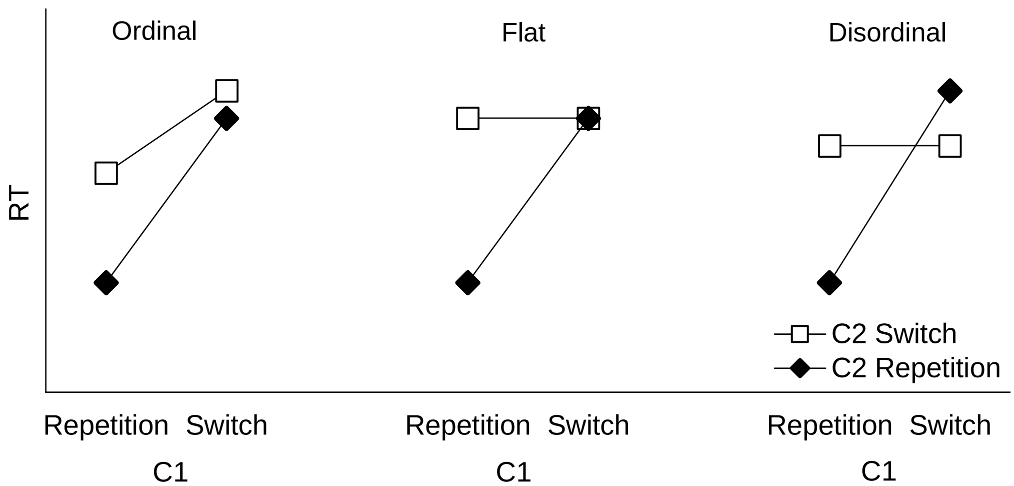


*Figure 2.* Examples of component interactions between the components C1 and C2. The left interaction shows an ordinal pattern with the longest RT in complete repetitions. The interaction in the middle shows a flat pattern with equally long RT in all trials containing a switch. The interaction on the right shows a disordinal pattern, in which partial C2 repetitions lead to the longest RT.

The least pronounced interaction finding is an *ordinal interaction pattern*, in which complete switches led to the longest RT and highest error rates (see the left pattern in Figure 2). Here, partial repetitions elicit systematic benefits with respect to complete switches.

Vandierendonck et al. (2008) proposed the componential account based on an idea of Hübner et al. (2001), due to which all components are processed independently. The component interaction supposedly arises because an additional cost of coordination of the independent switch process occurs in partial repetitions and in complete switches. No joint task set or integrated processing is proposed in this account.

Rangelov et al. (2013) developed the agglomerated task set account in which the task set is defined as consisting of dissociable component representations that are connected by the "stimulus-response chain" (p.2). It is assumed that the components are processed relatively sequentially within a trial and that a switch in one component triggers the independent switches and repetitions of the subsequent components.

In other studies, a *flat interaction pattern* was obtained (e.g., Vandierendonck et al., 2008; Philipp & Koch, 2010), in which the RT and error rates were very similar in all conditions containing a component switch (see middle interaction pattern in Figure 2). In other words, no reliable partial repetition benefits or costs with respect to complete switches are present in the flat component interaction pattern.

Vandierendonck et al. (2008) suggested the flat representation account and assumed that in each trial the components are integrated into a joint representation (i.e., a task set), in which the components are equally weighted. If any mismatch (i.e., a component switch) is detected in the subsequent trial, the whole representation gets discarded and must be newly re-built. Philipp and Koch (2010) extended the flat representation account by proposing that the integration of the components into a joint task set takes time and therefore can only be accomplished with sufficient time for component integration (i.e., a long cue-stimulus-interval after cueing both components).

Finally, there are some multicomponent switching studies that obtained a *disordinal interaction pattern*. This pattern is qualified by performance in complete switches being superior to performance in at least one partial repetition condition (see right interaction pattern in Figure 2). In other words, one partial repetition condition elicits performance costs with respect to complete switches.

Kleinsorge and Heuer (1999) obtained such an interaction pattern and proposed the hierarchical account, according to which the components are hierarchically organized within the task set. A higher-level component switch elicits a switch of all subordinated, lower-level components, but not vice versa. In a later study, in which different components were examined, Kleinsorge (2004) obtained a less pronounced, rather ordinal interaction pattern and therefore mitigated the hierarchical account by revising that a higher-level component switch only facilitates lower-level component switches, but not necessarily elicits them.

As indicated above, a disordinal component interaction pattern can also be found between a judgment component and a response component (called “response repetition effects”) and respective theoretical accounts were developed. The following two of them may also be applicable to two-component interactions in general.

In the feature integration account, Hommel, Proctor, and Vu (2004) proposed that the previous trial’s episode (called “event file”, see Hommel, 1998; Hommel, Müsseler, Aschersleben, & Prinz, 2001) is re-used in complete repetitions. In complete switches, a complete component mismatch with the episode is perceived, which facilitates the retrieval of the alternative response. In partial repetitions, the repeated component retrieves the episode, but it is in conflict with the other component’s switch. The resolution of this conflict (e.g., the “un-binding” of the episode’s components) can be time-consuming and lead to errors, which outweighs the performance benefits of the individual repeated component.

Schuch and Koch (2004) proposed the relatively similar binding account, which proposes that the judgment-specific response code is bound to the motor response after response execution in each trial (e.g., the code “odd” is bound to the left response). Importantly, though, this binding must be overcome when the judgment switches and the response repeats (partial response repetitions), because a new code needs to be bound to the response (e.g., “smaller than five”). Such “unbinding” of the response code is not necessary in the partial judgment repetitions, in which only the response switches. Hence, Schuch and Koch proposed a mechanism like that of the feature integration account and added hierarchical dependencies between the components.

In sum, the variety of theoretical accounts reflects the debate about the mechanism producing the component interaction pattern in multicomponent switching studies. Notably, many studies focused on complete switches and whether their performance was superior to partial switches to distinguish between theoretical accounts (see e.g. Kleinsorge, 2004; Philipp & Koch, 2010; Vandierendonck et al., 2008). It has only been discussed on the sidelines in studies on multicomponent switching whether and how the performance in the two partial repetitions differs (e.g. in Kleinsorge & Heuer, 1999; Rangelov et al., 2013). In the empirical studies, which are included in the present thesis, I will especially focus on the partial repetition conditions, since they seem to provide important information about the relation of the components and their representation within the task set.

## 1.2 Aim of the thesis

The present thesis' aim was to investigate the presumed general mechanism underlying integrated multicomponent switching. I want to discuss how especially episodic priming, but also controlled processing may contribute to this mechanism. Existing theories will be tested and evaluated with respect to our empirical findings. We tested the generalizability of the component interaction by using an auditory multicomponent paradigm, since the above reported multicomponent switching studies mainly used visual stimulus material (except for those, which used a stimulus modality component, e.g., Murray et al., 2009; Sandhu & Dyson, 2013).

Moreover, we examined which experimental manipulations could modulate the component interaction pattern to identify moderators of the mechanism. We included perceptual, modality-specific manipulations that should affect automatic processing, but also more "structural" manipulations that altered the cue-stimulus-response chain of a trial (e.g., the component processing order and the preparation interval).

## 2 Summary and discussion of the empirical contributions in this thesis

First, I will outline the differences between auditory and visual processing and potential modality-specific influences that could modulate auditory attention switches, because the size of the auditory attention repetition benefits could also have an impact on component interactions with the attention component. Consequently, in our first Study A, we examined the auditory attention component in isolation. In Studies B and C, we then combined the attention component with a judgment component to obtain an auditory two-component switching setup. The results and theoretical implications of Study B and Study C will be reported and discussed in an integrated way. In Study D, we examined the interaction of a judgment component and a response component (the interaction is also known as "response repetition effects", e.g., Druey, 2014b). I will discuss its results with respect to those of Studies B and C (for an overview of the analyzed components, and main findings in each study, see Table 1).

Table 1.

*Overview of the four studies of this thesis, the components that were analyzed, and the respective main findings.*

| Study | Authors (Year) | Analyzed Components | Main Findings |
|---|---|---|---|
| A | Seibold, Nolden, Oberem, Fels, & Koch (2018a) | Attention | No evidence for cue-based preparation of auditory attention switches |
| A.c | Seibold, Nolden, Oberem, Fels, & Koch (2018a.c) | | Corrigendum: Re-analysis with constant RSI does not change the interpretation |
| B | Seibold, Nolden, Oberem, Fels, & Koch (2018b) | Attention Judgment | The cued component dominated the component interaction pattern; dependencies between the components may allow more integrated component processing |
| C | Seibold, Nolden, Oberem, Fels, & Koch (2018c) | Attention Judgment | Component interaction arises with exogenously triggered attention switches; cue-based preparation led to a more pronounced component interaction pattern |
| D | Seibold, Koch, Nolden, Vu, Proctor, & Schuch (2018) | Judgment Response | No reliable impact of spatial response distance on the response component; a long RSI led to a more pronounced component interaction pattern in the error rates |

## 2.1 Differences between auditory and visual processing

Using auditory stimuli instead of visual stimuli changes the processing demands in many ways. Visual stimuli can be explored by strategic fixations and saccades to assess the relevant features, whereas an auditory stimulus develops over time and is characterized more by its temporal dynamics, pitch, and continuity than by its spatial features (Shinn-Cunningham, 2008).

Some earlier findings show that spatial relations are more salient in vision than in audition in multi-modal judgment situations (see e.g., Aschersleben & Bertelson, 2003; Lukas, Philipp & Koch, 2010; Shams, Kamitani, & Shimojo, 2000). These findings are supported by neuroimaging studies which suggest that the neuronal structures of auditory and visual spatial processing are quite different. Visual spatial relations are relatively directly projected to the primary visual cortex, whereas this seems to be less evident for spatial relations in the primary auditory cortex. The latter are assumed to be processed more subcortically (King & Nelken, 2009).

Despite the "visual dominance" in multi-modal spatial judgments, spatial auditory attentional filtering seems to be very efficient. In situations with dichotic stimulus presentation in which participants are supposed to attend to a message on one ear, while ignoring the message presented to the other ear, only very salient features from the unattended ear can be reported by the participants. Such salient features were, for example, the speaker's sex, a language switch, or the participant's own name (see e.g., Cherry, 1953; Moray, 1959; for a review, see Bronkhorst, 2015).

Auditory attention switching studies, in which participants switched between a male and a female target-speaker, or between the left and the right ear, revealed performance differences between attention switches and repetitions (e.g., Koch, Lawo, Fels, & Vorländer, 2011), like switching between visual attention foci (Logan, 2005), or switching between judgments. In line with the finding of efficient filtering, auditory spatial attention appears to be relatively inert. The attention repetition benefits were larger for switching between ears than for switching between male and female speakers, whose position varied unpredictably between the ears from trial to trial. Neuroimaging studies suggested that switching between spatial attention criteria recruits different cortical areas than switching between non-spatial cortical areas (Larson & Lee, 2013, 2014), which could account for the different sizes of attention repetition benefits.

### 2.2 The auditory attention component

Due to the above-mentioned differences between visual and auditory stimulus processing, and since we intended to include auditory attention switches as one component in our auditory two-component switching setup of Studies B and C, we conducted Study A. In this study, we examined auditory attention switches in isolation first. The paradigm was very similar to that of the study of Lawo, Fels, Oberem, and Koch (2014) on auditory attention switching. Namely, two number stimuli were presented dichotically (i.e., one to each ear, respectively) in each trial. One of the numbers was always spoken by a male speaker and one by a female speaker. The mapping of the speakers to the ears varied randomly from trial to trial. In the beginning of each trial, a cue indicated the attention criterion based on which the target number had to be identified. In blocks with ear cues, a left-ward pointing arrow, for example, indicated that the target was presented to the left ear of the participant. In blocks with speaker-sex cues, for example the word “Mann” (German for “man”) indicated that the target number was presented by the male speaker. When the target was identified, participants had to judge whether the number was smaller or larger than five and press a left or right response key accordingly (see an example in Figure 3).

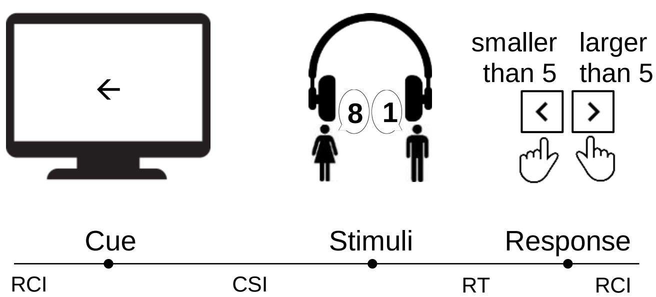


*Figure 3.* Example of a trial of Study A in a block with ear cues. The arrow cue indicated that the target would be presented to the participant’s left ear. On the target (8), a magnitude judgment required a right key press response (larger than five).

We replicated the auditory attention repetition benefits that were obtained in previous studies (Koch, Lawo, et al., 2011; Koch & Lawo, 2014, 2015; Lawo & Koch, 2014a, 2014b, 2015; Lawo et al., 2014). Moreover, similar performance in attention switches and repetitions was found across ear-based and speaker-sex based target selection. Besides that, we examined whether participants engaged in preparation for attention switches during the cue-stimulus interval (CSI). Therefore, the CSI was manipulated to provide a short (e.g., 100 ms) or long (e.g., 1000 ms) interval for preparation.[1]

A long CSI in judgment switching studies typically leads to improved performance in judgment switches – more than in judgment repetitions. This finding is often interpreted as evidence for preparatory judgment selection and implementation, thereby indicating preparatory controlled processing (Arrington & Logan, 2004; Koch, 2001; Logan & Bundesen, 2003; Logan & Schneider, 2006; Meiran, 2000b). However, in previous auditory attention switching studies, a preparatory switch-specific performance improvement was not a robust finding (Koch, Lawo, et al., 2011; Lawo & Koch, 2015; Lawo et al., 2014). Like in previous studies, we found no signs for switch-specific cue-based attention preparation. Only general preparatory RT reduction was obtained.

### 2.3 The interaction of the auditory attention component with a judgment component

In Studies B and C, we combined the attention component with a judgment component to create an auditory two-component switching paradigm. Like in the attention switching paradigm, two stimuli spoken by a male and a female speaker, respectively, were presented dichotically via headphones. A cue in the beginning of the trial indicated the attention criterion to identify the target in the upcoming stimulus pair (attention component).[2] The stimuli were a number and a

[1] The original version of Study A contained a programming error in Experiment 1 and Experiment 2. Therefore, we wrote a corrigendum (Corrigendum A.c). Namely, CSI and response-cue interval (RCI) were inversely varied (as intended), but due to a programming error, this referred to CSI and RCI across trials rather than within one trial. Thus, a short CSI always led to a subsequent long RCI (or a long CSI to a short RCI). This led to three-different possible response-stimulus interval (RSI) lengths (i.e., RCI+CSI: short + short [short], short + long [medium], long + short [medium], long + long [long]). Due to this programming error, the influence of the CSI manipulation was not separable from RSI effects. Hence, we conducted a re-analysis of the data using only those 50% of the trials with medium RSI. The results of the re-analyses in the Corrigendum A.c confirmed the interpretation of Study A.

[2] Please note that also in Study B and in two experiments of study C the programming error reported in footnote 1 was present. As the effect of the CSI manipulation could not be separated from RSI effects, we refrained from an analysis and interpretation of the CSI effects in terms of active preparation in these experiments. However, the temporal intervals were manipulated entirely independently from the attention component, the judgment component, and the other examined variables so that the effects of these variables could still be interpreted. Importantly, in Study C's Experiment 3, the programming was corrected so that the RSI was constant and an interpretation of CSI in terms of active preparation was possible. The experiment is reported under 2.3.2.

letter. When the target was a letter, a judgment about whether this letter was a consonant or a vowel was required. When the target was a number, a judgment about whether the number was even or odd was required (judgment component). The responses of both judgments were assigned to two response keys operated by the respective left and right index finger of the participant (see an example trial in Figure 4).

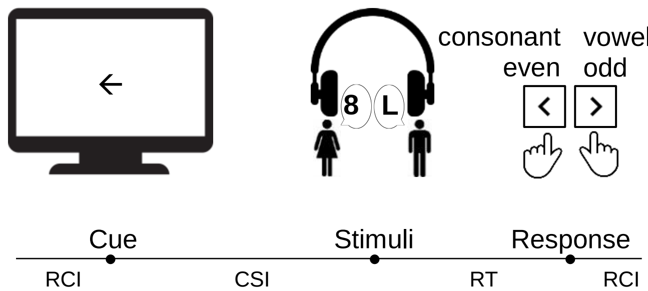


*Figure 4.* Example of a trial of Studies B and C in a block with ear cues. On the target (8) a number judgment had to be executed. As a response, the left key (even) needed to be pressed.

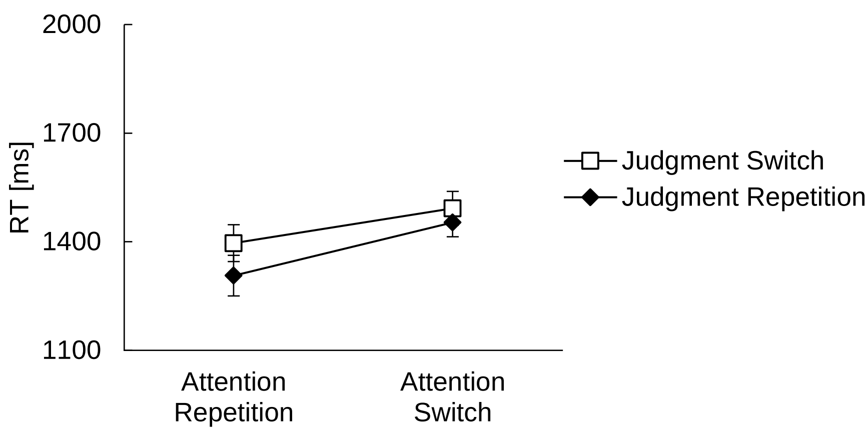


*Figure 5.* Ordinal interaction pattern of attention component and judgment component in the RT of Study B’s Experiment 1. The error bars reflect 95% Cousineau-Morey confidence intervals (Morey, 2008).

As anticipated, an interaction of attention component and judgment component was obtained, indicating that the component interaction generalizes to setups with auditory stimuli. The interaction showed up as an ordinal interaction pattern, which means that the longest RT and highest error rates were obtained in complete switches. Complete repetitions elicited large repetition benefit with respect to complete switches and partial attention repetitions somewhat smaller ones. Partial judgment repetitions only led to very small numerical repetition benefits (see Figure 5).

The ordinal component interaction pattern clearly rules out the flat representation account (Vandierendonck et al., 2008), as well as accounts that can only predict disordinal interaction patterns (e.g., the binding account of Schuch & Koch, 2004). The larger partial attention repetition benefits compared to partial judgment repetition benefits are compatible with the predictions of the componential account (Hübner et al., 2001; Vandierendonck et al., 2008), but even more so with those of the agglomerated task set account (Rangelov et al., 2013). I prefer the agglomerated task set account, because it assumes that the components are at least partly processed sequentially within the trial, which the componential account does not specify. Namely, in our setup, the cue allowed preparatory processing of the attention criterion before the onset of the stimuli and, thus, before judgment processing. The cued attention component could benefit from its repetition in partial attention repetitions. In partial judgment repetitions, the preceding attention switch could have caused that the subsequent judgment was processed without, or only little access to the previous trial's episode.

The hierarchical account (Kleinsorge, 2004) could also predict the ordinal interaction pattern by assuming that the attention component is more dominant than the judgment component. A switch of the dominant attention criterion would be capable of disrupting or even eliminating the partial judgment repetition benefit, whereas this would not possible vice versa. Plus, the attention switch would facilitate the judgment switch, but not vice versa. The finding of a dominant attention component is compatible with a post-hoc explanation of Kleinsorge (2004), who proposed that the component hierarchy arises naturally – because it is necessary to identify the target to know which judgment is required.

Hence, different theoretical accounts could explain our component interaction pattern. To enclose the mechanism underlying the component interaction, we included several manipulations in the five experiments of Studies B and C. The manipulations were supposed to affected auditory modality-specific processing and the structure of the trial. In the following, I will summarize whether and how these manipulations affected the attention component, the judgment component, and their interaction pattern.

### 2.3.1 Automaticity

The manipulations that were supposed to affect auditory attentional processing, were block-wise manipulations of the attention criterion (spatial vs. nonspatial), of the cue modality (visual vs. auditory cues), and of the cue type (exogenous vs. endogenous spatial cues). Cue modality and cue type modulated the size of the attention repetition benefits. Especially auditory exogenous cues led to very fast, possibly automatic attention switches. However, none of these three manipulations also modulated the component interaction pattern. This indicates that the size of the attention repetition benefits did not critically affect the component interaction, confirming that the presumed mechanism underlying the component interaction does not involve any modality-dependent processing (see additive factors logic of Sternberg, 1969). Moreover, the findings from blocks with auditory exogenous attention cues imply that the attention criterion did not have to be switched voluntarily to elicit the interaction with the judgment component. This may indicate that the component interaction arises to some extent automatically.

We also examined whether the component interaction pattern could be attenuated or even eliminated deliberately by the participant. Namely, we interspersed 'pure' attention blocks, in which auditory selective attention had to be kept constant on one ear while the judgment switched randomly between trials. These pure attention blocks could be regarded as judgment switching training, emphasizing that attention component and judgment component were entirely independent in the subsequent blocks with switching attention criterion. Hence, participants might not want to process them in an integrated way. The component interaction, however, did not differ from those of the other experiments. Perhaps, the component independence was already evident to the participants without the interspersed pure attention blocks. Either way, the finding might speak in favor of a rather automatically arising component interaction.

### 2.3.2 Cue-based component preparation

Two of our manipulations led to a reliable modulation of the interaction pattern. One of them was the manipulation of the CSI, which provided time for cue-based preparation of the attention criterion (in Study C). In Study A, we found no switch-specific preparatory RT reduction of the attention repetition benefits when the CSI was prolonged. This was also not the case in the multicomponent switching setup of Study C. Instead, a prolonged CSI led to reduced judgment repetition benefits and at the same time to a more pronounced, disordinal component interaction pattern (see Figure 6). Similarly, Murray et al. (2009) obtained a disordinal interaction pattern with a cued judgment component and a stimulus modality component after a CSI of over one second.

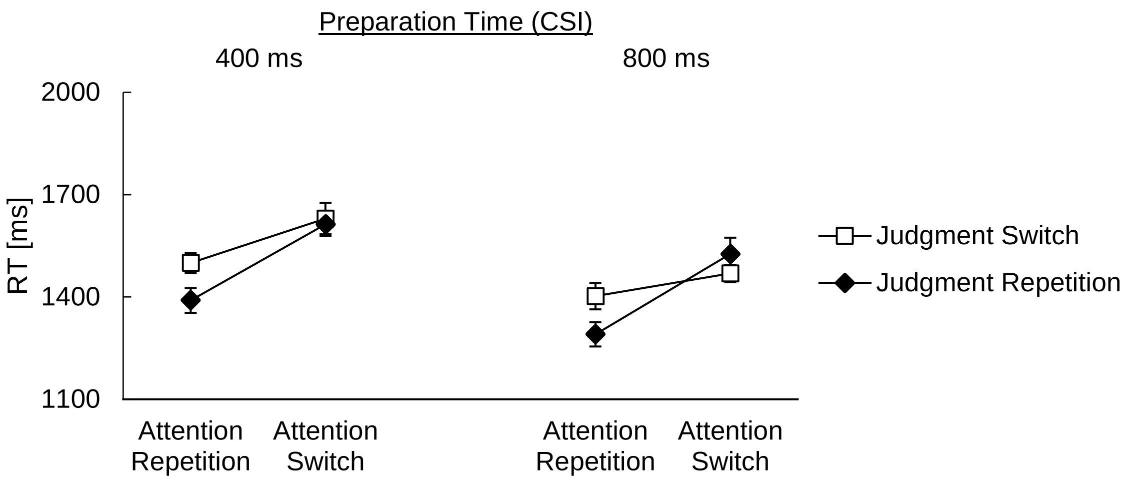


*Figure 6.* Attention component and judgment component as a function of preparation time (CSI: 400 ms vs. 800 ms) in the RT of Study C's Experiment 3. With short CSI, the component interaction pattern is ordinal, and with long CSI, it is disordinal. The error bars reflect 95% Cousineau-Morey confidence intervals (Morey, 2008).

We did not expect reduced judgment repetition benefits after a long CSI, because the cue was entirely uninformative about the judgment. Inserting uninformative warning signals to a random judgment sequence usually produces very weak preparation effects, at best (Meiran et al., 2000; see also Meiran & Chorev, 2005). Moreover, the RSI was constant between trials and therefore passive processes during the RSI, such as task set dissipation (Allport et al., 1994), should not have affected the judgment processing.

Earlier findings of Philipp and Koch (2010) indicate that such reduced repetition benefits of the second component in a trial's processing chain may be a general characteristic outcome of the component interaction. In Philipp and Koch's study (2010), both components were indicated by separate cues, which appeared randomly and independently – either at a CSI of 1000 ms or at a CSI of 100 ms. Cueing the response modality with a long CSI and the judgment with a short CSI led to a reduction of the judgment repetition benefits. Cueing the judgment with a long CSI and the response modality with a short CSI led to a reduction of the response modality repetition benefits. Hence, the reduction of the repetition benefits of the later processed component may be a general result of cue-based preparation of switches in component interaction patterns.

In Philipp and Koch's (2010) study randomly either the judgment or the response modality was cued, which led the authors to speculate that knowing about the first cued component made it possible to expect the specification of the second cued component. In our experiment, the cueing was manipulated block-wise, while only the CSI switched on a trial-by-trial basis, which makes Philipp and Koch's explanation not applicable to our data.

The inspection of the interaction pattern of the RT showed that especially the performance in complete switches benefitted from the long CSI. A similar numerical trend was also visible in Philipp and Koch's (2010) findings. Hence, cue-based attention switch preparation may somehow also have prepared for complete switches, too. This is compatible with the idea of hierarchical switch facilitation of Kleinsorge (2004). Yet, it remains unclear why switch preparation should arise when it is only beneficial in half of cued component's switch trials (complete switches) and potentially deteriorating for the other half. Similar to assumptions in the feature integration account by Hommel et al. (2004), one could suggest that due to current episodic binding of the previous trial's components, cue-based preparation for an attention switch could have also retrieved the remaining judgment that is not bound to the previous trial's episode (i.e. the complete mismatch of the previous trial's episode). In trials with a long CSI, simply more time for a mismatch retrieval could have been available.

### 2.3.3 Component processing order

The ordinal interaction pattern and the thereby implied asymmetry in the performance of partial attention repetitions and partial judgment repetitions could indicate that the attention component was more dominant in the task set. The hierarchy could be due to a "natural" requirement to process the attention criterion before the judgment (see Kleinsorge, 2004). Yet, the explicit cueing of the attention component could be critical as well. To answer this question, we compared blocks, in which the attention criterion (speaker-sex) was cued, to blocks in which the judgment was cued. To make the distinction clear, the components will be named the "cued" and the "uncued" component in the following. Comparing the performance in the judgment cueing block to that in the attention cueing block required an extension of the response rules. Namely, speaker sex had to be similarly relevant for response selection in the judgment cueing block like it was in the attention cueing block: When the target was spoken by a male speaker, participants now had to respond with two response keys operated by their left hand. When the target was spoken by a female speaker, participants had to press one of two keys operated by right hand (see an example trial in Figure 7).

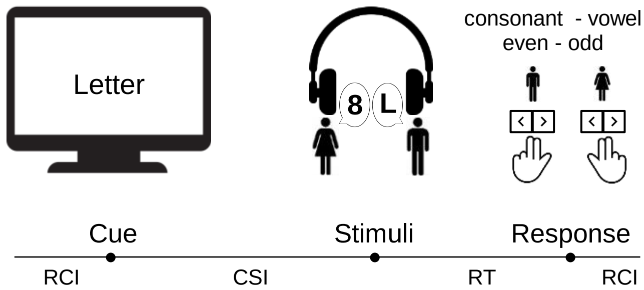


*Figure 7.* Example of a trial of Study B's Experiment 2 in a block with judgment cues. The letter cue indicated the target (L), which required a left response (consonant) with the left hand (male speaker).

The results clearly indicated that the presumed component hierarchy within the task set depended on the explicit cueing. In the attention cueing block, the previous ordinal interaction pattern with large partial attention repetition benefits and small judgment repetition benefits was replicated. Yet, this partial repetition benefit asymmetry was reversed in the judgment cueing block, in which larger judgment repetition benefits were obtained. Thus, the cued component benefitted more from its partial repetition than the uncued component.

When interpreting this within the hierarchical account (Kleinsorge, 2004), I could conclude that the trial structure determined the component hierarchy. Also related areas in the multi-tasking literature revealed trial-structure-based hierarchies. For example, when two judgments were presented in pairs, not only judgment repetition benefits could be obtained but also repetition benefits when the complete judgment pair repeated (e.g., Lien & Ruthruff, 2004; Luria & Meiran, 2003; Hirsch, Nolden & Koch, 2017; Hirsch, Nolden, Philipp, & Koch, 2017).

However, a performance asymmetry in partial repetitions must not necessarily be due to an actual component hierarchy. Schneider and Anderson (2011) proposed a computational model for task switching that, I apply to multicomponent switching. The cue is understood as a retrieval context, which elicits the retrieval of the associated stimulus-response rule. When the cue of the previous trial repeats, the retrieval of the required response rule is skipped and the previous episode, which is still within an episodic buffer, is re-used. This would lead to strong episodic priming in complete repetitions and in partial repetitions for the cued component (a similar idea can be found in Rangelov et al., 2013).

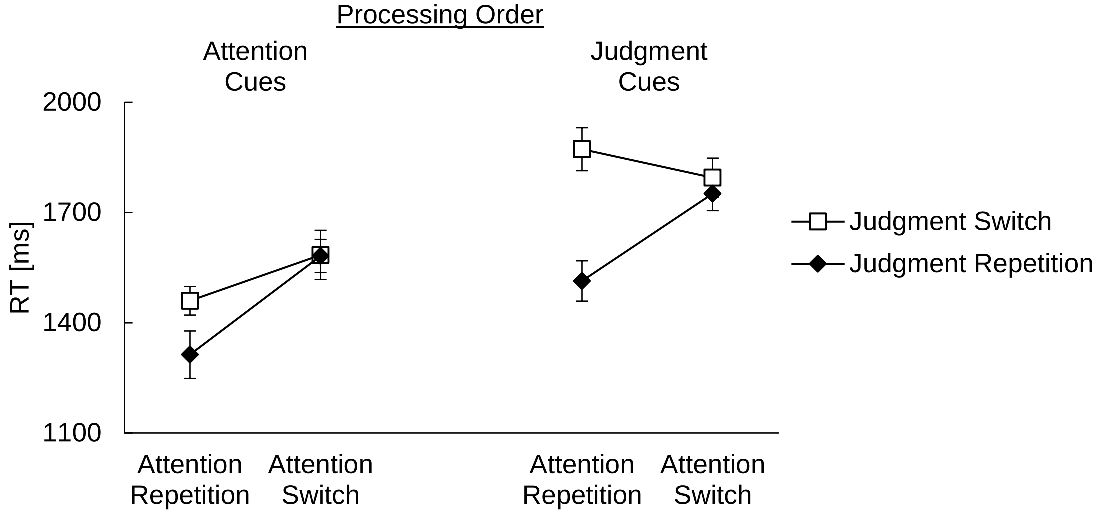


*Figure 8.* Attention component and judgment component as a function of processing order (attention [speaker-sex] cues vs. judgment cues) in the RT of Study B's Experiment 2. The repetition benefits of the cued component are larger than those of the uncued component. The component interaction pattern is ordinal with attention cues and disordinal with judgment cues. The error bars reflect 95% Cousineau-Morey confidence intervals (Morey, 2008).

The attention cueing block and the judgment cueing block differed also by the strength of their component interaction pattern. In the attention cueing block the pattern was ordinal, whereas in the judgment cueing blocks, it was more pronounced and numerically even disordinal (see Figure 8). In Study B, we proposed that in the judgment cueing blocks, judgment preparation could not be fully accomplished when participants did not know whether they had to link the judgment-specific response codes to the left or right hand's responses. The resulting more simultaneous processing of the judgment and the attention criterion could have led to more integrated component processing and thereby to a more pronounced, even disordinal component interaction. Yet, the outcome of the CSI manipulation speaks against the latter idea. Here, more sequential component processing due to preparation during a long CSI led to a more pronounced component interaction pattern (see 2.3.2).

When inspecting the differences between the component interaction patterns in both cueing blocks, one may notice that the RT are generally longer in the judgment cueing block, but that the performance of partial repetitions of the respective uncued component is especially deteriorated. In other words, in the judgment cueing block, no partial judgment repetition benefits with respect to complete switches were present. A repeated judgment cue may not only have elicited priming of the judgment-specific response codes, but also of the speaker-sex that was bound to it in the previous trial's episode. This led participants to (automatically) attend to the incorrect speaker during stimulus presentation and thereby also to a stimulus indicating the opposite of the primed judgment (e.g., the stimulus was a number instead of the anticipated letter). Such a confusion could have eliminated the cue-based judgment repetition priming benefit on performance. In the attention cueing block, cue-based speaker-sex priming should, in contrast, have prevented that the participant attended to the incorrect stimulus.

#### 2.3.4 Interim summary and interim conclusion

In sum, the findings in Studies B and C showed that the component interaction generalized to our setup with auditory stimuli and was not modulated by modality-specific manipulations. The resulting ordinal interaction pattern indicated a strong contribution of episodic priming, elicited by the cue. Large performance benefits were present in complete repetitions and somewhat smaller, yet reliable benefits in the partial repetitions of the cued component. The component interaction, furthermore, was obtained regardless of whether the attention switches were voluntary or triggered by exogenous cueing.

We also seem to have obtained evidence for the binding of the components in the episode. In the judgment cueing condition, a cued judgment repetition seemed to automatically retrieve the attention criterion that was associated with it in the previous trial. The resulting automatic attention criterion (i.e., speaker-sex) priming deteriorated performance in partial judgment repetitions, because it led participants to attend to the incorrect speaker-sex first. Hence the results indicate that episodic priming and the component binding in the episode had beneficial as well as detrimental effects on performance – even within the same condition of the component interaction.

Yet, controlled processing in terms of active cue-based preparation was shown to modulate the component interaction pattern. Specifically, sufficient time for cue-based component preparation led to a more pronounced component interaction with a disordinal pattern. An overview of the specific empirical effects of each manipulation is provided in Table 2.

Table 2.

*Overview of the different manipulations in Studies B and C, and whether they modulated the components and their interaction.*

| Manipulation | Study | Judgment Component | Attention Component | Component Interaction |
|---|---|---|---|---|
| Attention Criterion<br>Ear vs. Speaker-Sex; blocked | B | | | |
| Cue Modality<br>Visual vs. Auditory; blocked | C | | RT & PE | |
| Cue Type<br>Exogenous vs. Endogenous; blocked | C | | RT & PE | |
| Explicit Knowledge<br>Yes vs. No: between Experiments | C | | | |
| Preparation Time<br>100 ms vs. 1000 ms; trial-by-trial | C | RT & PE | | RT & PE |
| Component Processing Order<br>Attention Cueing vs. Judgment Cueing; blocked | B | RT & PE | RT | RT & PE |

*Note*. The manipulation order chronologically followed the respective mention order in this thesis. The results are presented in a simplified way. Trends and unsystematic findings are not reported. Please see the respective studies for details. Note that the variable names may deviate in the respective study. RT: modulation in the reaction times. PE: modulation in the error rates.

Since we wanted to further explore potential hierarchical switch facilitation in complete switches of disordinal component interaction patterns, we conducted Study D. Here, we examined the judgment component and the response component within a simple judgment switching paradigm, because previous studies showed that a disordinal interaction pattern is a robust finding here. The similarities and differences to the component interactions of Studies B and C will be discussed.

### 2.4 The interaction of the judgment component with the response component

In our previous studies, we did not analyze the response component, although this would have been possible, as the bivalent response keys would have allowed for all factorial combination of judgment repetitions and switches and response (key) repetitions and switches. Like I pointed out in the introduction, a line of research emerged that is concerned with the disordinal interaction pattern of the judgment component and the response component, which is often called “response repetition effects” (e.g., Altmann, 2011; Brown, Reynolds, & Braver, 2007; Druey, 2014a, 2014b; Druey & Hübner, 2008; Hübner & Druey, 2006, 2008; Kleinsorge, 1999; Koch, Frings, & Schuch, 2018; Koch, Schuch, Vu, & Proctor, 2011; Rogers & Monsell, 1995; Schuch & Koch, 2004, 2010). This research was only rarely explicitly linked to other multicomponent switching studies (e.g., in multicomponent switching studies of Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001, 2002), which indicates that researchers were not convinced that the response component should be understood as a component in multicomponent switching.

Previous studies demonstrated that the response repetition effects arise on the response selection level and not on the response key level. For example, Campbell and Proctor (1993) found that the interaction can be obtained even across hands and fingers, if the coding of the responses is consistent across effectors (e.g., coded as “left” and “right” response, see Pashler & Baylis, 1991). In line with that, Hübner and Druey (2006), as well as Schuch and Koch (2010), could demonstrate that not even response execution (i.e., the key press) is a necessary requirement for the component interaction. These findings imply that the judgment-specific response codes create dependencies between judgment component and response component. The dependencies can be understood as instructed permanent component bindings. Namely, a cued judgment switch always coerced a response code switch, even in a partial response repetition (e.g., in a switch to a magnitude judgment, the left response’s code “even” needs to be switched to “smaller than five”). Still, I argue that such dependencies do not justify to treat the response component differently than the other components. For example, Kleinsorge and Heuer (1999; see also Kleinsorge et al., 2001, 2002) examined a judgment component and a response mapping component, which depended on the present judgment. Therefore, a judgment switch always coerced a mapping switch. Notably, the latter two components always led to a disordinal interaction pattern, like constantly found in studies on response repetition effects.

With the dependencies in mind, I will summarize the results of our Study D and compare them to those of Studies B and C. Like in the other empirical contributions of this thesis, we used only auditory stimuli to see whether the component interaction generalized to an auditory setup. A trial of Study D (see Figure 9) was composed of a cue, which indicated the judgment prior to a diotically presented bivalent number stimulus (i.e., presented to both ears). The judgments were a magnitude judgment (smaller vs. larger than five) and a parity judgment (odd vs. even).

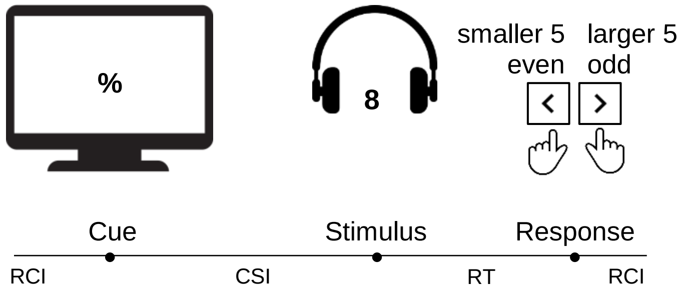

*Figure 9.* Exemplary trial of Study D. The cue (%) indicated a magnitude judgment. The present stimulus (8) therefore required a right key press response (larger than five).

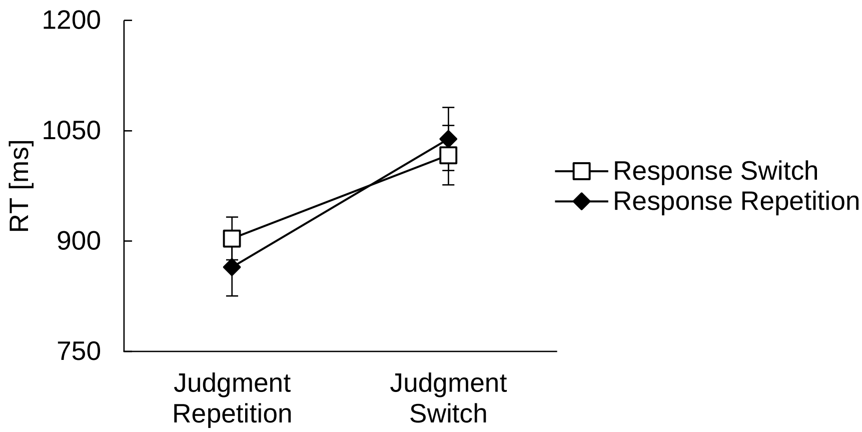

*Figure 10.* Disordinal interaction pattern of judgment component and response component in the RT of Study D's Experiment 1. Please note that the y-intercept in this figure was halved compared to the other figures to provide a more detailed impression of the disordinal interaction pattern. The error bars reflect 95% Cousineau-Morey confidence intervals (Morey, 2008).

Replicating earlier findings of studies with visual stimuli (e.g., Druey 2014b; Druey & Hübner, 2006; Schuch & Koch, 2004), a disordinal component interaction pattern was obtained. Thus, like the other component interactions, the interaction of judgment component and response component seemed to arise irrespective of the modality-specific processing demands of the stimuli. In detail, the RT interaction pattern was very similar to that obtained in the previous multicomponent switching experiments with disordinal patterns (see Figure 10). Complete repetitions led to the largest performance benefits with respect to complete switches. Partial judgment repetitions also elicited considerable performance benefits, and partial response repetitions elicited performance costs with respect to complete switches.

The error rates confirmed the disordinal pattern of the RT, although their pattern was much more pronounced. Response repetition costs with respect to response switches were even present in judgment repetitions – though smaller than in judgment switches. The pronounced interaction pattern in the error rates is a rather frequent finding in studies on such response repetition effect (e.g., Kleinsorge & Heuer, 1999; Koch, Frings, & Schuch, 2018; Rogers & Monsell, 1995), and it could indicate a dissociation from other two-component interactions. In other two-component switching setups, the interaction pattern in the error rates is often found to be similar or less pronounced than in the RT (see e.g., Study B; Study C; Philipp & Koch, 2010; Vandierendonck et al., 2008).

The priming and inhibition account was specifically developed to explain the often found overall response repetition costs in the error rates and the robust disordinal interaction pattern of a judgment component and a response component (Rogers & Monsell, 1995; see also, Druey, 2014a, 2014b; Druey & Hübner, 2006; Hübner & Druey, 2006, 2008). It is assumed that a response is always inhibited after its execution to prevent accidental response perseveration in the next trial. The inhibition needs to be overcome to select the same response in the next trial, which is time-consuming and may even fail. Such failures could explain the generally higher error rates in response repetitions than in response switches. Only in complete repetitions, the response inhibition can easily be overcome by stimulus category priming (Rogers & Monsell, 1995), or by episodic priming (see hybrid account of Koch, Frings, & Schuch, 2018).

Like partial response repetitions in the response repetition effects, small partial repetition costs with respect to complete switches were sometimes found in Studies B and C. The latter could not be produced by response specific inhibition, since response repetitions and switches appeared equally often in partial judgment repetitions and complete switches, which should have balanced out response specific inhibition. A rather general cause of the partial repetition costs therefore seems to be more likely – although a contribution of response-specific inhibition to the response component can obviously not be ruled out.

The data would be compatible with the idea that the previous trial's episode is inhibited after a switch of the cued component (i.e., the attention criterion in Studies B and C, or the judgment in Study D). This episode-inhibition would implicitly facilitate the selection of the alternative judgment, or response, by hindering the selection of the repeated judgment, or response. To further explore the role of inhibition in the response repetition effect interaction, we added two manipulations to Study D: a spatial response distance manipulation and a response-stimulus interval (RSI) manipulation. The respective findings and implications will be discussed in the following.

### 2.4.1 Response inhibition

The spatial response distance (i.e. the spatial response key separation on the keyboard) was manipulated, because it led to a modulation of the response component in a study of Koch, Schuch, et al. (2011) with visual stimuli. The latter study showed that in blocks with spatially separated response keys, the performance in response repetitions was more impaired with respect to response switches than in blocks with adjacent response keys. The authors argued that the reason was a better response discriminability with separated keys, which increased the risk for response perseveration. This risk was said to require stronger response inhibition, which, in turn, resulted in longer RT and higher error rates of response repetitions. Hence, instead of reactive response inhibition as a result of decreased activation levels (e.g., Logan, 1994), strategically adapted response inhibition implies the contribution of controlled processing (i.e. "inhibition" as part of executive functions, see Miyake et al., 2000).

We did not replicate the response component modulation by spatial response distance in both experiments of Study D. The null-effect could indicate that spatial response distance was less salient with auditory stimuli than with visual stimuli due to modality-specific spatial processing (see e.g., Aschersleben & Bertelson, 2003; King & Nelken, 2009), or because of an input-output incompatibility of auditory stimuli and manual responses (see Stephan & Koch, 2011). Alternatively, the null-effect may provide evidence against a form of response inhibition that can be adapted to the risk of response perseveration.

The impact of the RSI manipulation on the response component and the response repetition effects seemed to be rather unsystematic and could not be replicated in a recent, not yet published experiment in our lab. In detail, we expected a dissipation of response inhibition, which was suggested by Rogers and Monsell (1995), since also the task set is supposed to decay during the RSI (e.g., Allport et al., 1994; Altmann, 2005; Meiran, 1996, 2000a; for a critical review, see Horoufchin, Philipp, & Koch, 2011). Reduced response repetition costs were obtained in blocks with long RSI, but unexpectedly a more pronounced component interaction pattern. The reduced response repetition costs therefore could be again the general characteristic of a more pronounced component interaction pattern, like I proposed earlier (2.3.2). The overall longer RT in blocks with long RSI might indicate that participants applied different processing strategies than in the blocks with short RSI – adapting their processing pace, for example. In the following, I will therefore refrain from a further discussion of RSI manipulation.

### 2.4.2 Interim summary and interim conclusion

Altogether, the findings of Study D revealed similarities to those of Studies B and C, like the generalizability of the component interaction to a setup with auditory stimuli. In line with that, the component interaction pattern was also not modulated by spatial response distance, confirming that modality-specific processing demands did not critically affect the component interaction pattern (see an overview of the effects of Study D in Table 3, below).

Table 3.

*Overview of the manipulations in Study D and whether they modulated the components and their interaction.*

| Manipulation | Judgment Component | Response Component | Component Interaction |
|---|---|---|---|
| Spatial Response Distance<br>Adjacent vs. Separate Keys; blocked | | | |
| Response-Stimulus Interval<br>400 ms vs. 1600 ms; blocked | RT | PE | PE |

*Note.* The results are presented in a very simplified way. Trends and unsystematic findings are not reported in this table. Please see the respective studies for details. RT: modulation in the reaction times. PE: modulation in the error rates.

The component interaction of Study D differed from those of Studies B and C in the way that the interaction pattern was constantly disordinal and that particularly pronounced response repetition costs were present in the error rates. Rogers and Monsell (1995) proposed that inhibition of the just executed response causes the partial response repetition costs with respect to complete switches. Since we found no evidence for an adaptation of response inhibition due to the spatial response distance manipulation, the potential response inhibition would need to have a constant strength and be applied automatically. In line with our findings, the existence of inhibition as a part of the executive functions that can be adapted to current processing demands has been under debate lately. So-called inhibition effects in task switching appeared to be at least partly explainable by episodic priming effects (see e.g. Grange, Kowalczyk, & O'Loughlin, 2017). This would also speak against voluntary episode inhibition after a cued switch is detected. Strictly speaking, however, a null-effect of the spatial response distance manipulation should be interpreted very cautiously.

As I mentioned earlier, the presence of dependencies between components might be connected to the finding of the disordinal component interaction pattern. Hence, a judgment switch could have led to a retrieval of the response that is currently not bound to the previous trial's episode – thus, like the effect of cue-based component switch preparation (see 2.3.2). The dependencies may have strengthened the episodic binding and thereby boosted the mismatch-episode retrieval in cued-switch trials.

## 2.5 Remaining issues

Before outlining my conclusion, I want to mention at least two remaining issues that require to be addressed in future research. First, some experiments are needed to connect the four studies of the present thesis and its findings more thoroughly. The response component needs to be examined with respect to the attention component in a setup, like in Study A. This experiment would help to understand the role of component dependencies, since an attention switch in Study A did not coerce a response code switch. Moreover, the response component should also be considered within the setups of Studies B and C. Particularly, the three-component interactions should be examined, like in Kleinsorge and Heuer (1999), Kleinsorge et al. (1999, 2001, 2002), and Koch, Frings, & Schuch (2018). These experiments could help to understand how the response component is affected by attention switches, judgment switches, and combinations of both. This may provide further insights about the presence and potential influence of response inhibition, or general episode inhibition.

Second, I argued that our explicit knowledge manipulation in Study C (2.3.1) may have been too weak to modulate the component interaction pattern – especially since other supposedly controlled processing, like cue-based preparation, modulated the component interaction pattern. It would be of interest whether proportional manipulations of component combinations (e.g., a male speaker sex more often requires a number judgment than a letter judgment) can modulate the interaction pattern. This manipulation could provide insights about the role of associative learning in multicomponent switching and whether this affects the component interaction pattern (Abrahamse, Braem, Notebaert, & Verguts, 2016). Such a manipulation would establish dependencies between components of the task set. It would be especially interesting whether such artificial probability-based dependencies can lead to disordinal component interaction patterns of components that usually lead to ordinal component interaction patterns.

## 3 Summary and conclusion

In the present thesis, I explored the integrated processing of two independently switching components of an auditory task set. The integrated processing is indicated by a robust interaction of the components' switches and repetitions. In the four studies included in this thesis, specifically the interaction of an auditory attention component with a judgment component was examined, and the interaction of a judgment component with a response component, which is often referred to as response repetition effects. My aim was to enclose the underlying mechanism in component interactions by integrating theories and practices of multicomponent switching and of the response repetition effect literature.

It appeared that, although the component interactions were previously mainly examined in paradigms with visual stimuli, the auditory stimuli and additional manipulations of modality-specific processing demands did not affect the component interaction patterns. A component interaction was even present when the attention criteria of the attention component were triggered by exogenous cues and not by voluntary switches.

The following inferences could generally be drawn about the underlying mechanism of the component interaction: Consistently, large repetition benefits obtained in complete repetitions and often also in partial repetitions of the cued component speak in favor of a strong contribution of episodic priming to the integrated processing. Moreover, the performance in complete switches being similar to that in partial repetitions indicates episodic component binding. A cued component switch may retrieve the other component that is currently also not bound to the previous trial's episode. This may improve performance in complete switches and at the same time deteriorate performance in partial repetitions of the uncued component, since in the latter the incorrect component is retrieved (e.g., with cued judgment repetitions that retrieved the incorrect but previously bound target-speaker's sex).

Compatible with findings in the task switching literature, participants seemed to use a prolonged CSI to prepare for a cued component switch. This preparation resulted in a more pronounced component interaction pattern. For example, the usually ordinal interaction of an auditory attention component and a judgment component became disordinal. I argue that cue-based preparation allows a more thorough retrieval of the components not bound to the previous trial's episode and I suggest a similar effect of dependencies between components.

In the literature on response repetition effects, disordinal component interaction patterns are a robust finding. It has been proposed that response inhibition impairs the repeated selection of a response, which, in turn, causes the partial response repetition costs in judgment switches and thereby the disordinal component interaction pattern. Reviewing the multicomponent switching literature revealed that dependencies between components seemed to consistently produce disordinal component interaction patterns. Such dependencies were especially evident between the judgment component and the response component. Although our study on response repetition effects could not entirely rule out the general presence of response inhibition, the many similarities to the interactions of other switching components rather point to a common mechanism.

Altogether, integrated processing of different components' switches and repetitions seems to be strongly driven by automatic processes like episodic priming and binding, but cue-based switch-specific component preparation can contribute. The present thesis suggests that there is a general mechanism underlying different component interactions and emphasizes an integrated view on multicomponent switching and response repetition effects, because it may help to advance theories of both fields of research.

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## Scientific contributions

**Study A**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018a). Intentional preparation of auditory attention-switches: Explicit cueing and sequential switch-predictability. *Quarterly Journal of Experimental Psychology*, *71*, 1382-1395.

**Corrigendum A.c**

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**Study B**

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**Study C**

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**Study D**

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**Study A**

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Intentional Preparation of Auditory Attention-Switches:

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ABSTRACT

In an auditory attention-switching paradigm, participants heard two simultaneously spoken number-words, each presented to one ear, and decided if the target number was smaller or larger than five by pressing a left or right key. An instructional cue in each trial indicated which feature had to be used to identify the target-number (e.g. female voice). Auditory attention-switch costs were found when this feature changed compared to when it repeated in two consecutive trials. Earlier studies employing this paradigm showed mixed results when they examined whether such cued auditory attention-switches can be prepared actively during the cue-stimulus-interval. The present study systematically assessed which preconditions are necessary for the advance preparation of auditory attention-switches. Three experiments were conducted that controlled for cue-repetition-benefits, modality-switches between cue and stimuli, as well as for predictability of the switch-sequence. Only in the third experiment, in which predictability for an attention-switch was maximal due to a pre-instructed switch-sequence and predictable stimulus–onsets, active switch-specific preparation was found. These results suggest that the cognitive system can prepare auditory attention-switches, and this preparation seems to be triggered primarily by the memorized switching-sequence and valid expectations about the time of target-onset.

Keywords: auditory attention, dichotic listening, attention-switching, selective attention, task-switching

In each second of our life we are confronted with a variety of information coming from the environment, but also from internal processes. However, we are able to act quite efficiently and goal-directed most of the time. *Selective attention* is a key process that helps us to separate relevant from irrelevant information and to maintain a stable focus.

Cherry (1953) was amongst the first who examined the efficiency of auditory selective attention with so-called dichotic listening tasks. Participants were presented with two dichotic auditory messages via headphones. The participants were told to focus exclusively on one ear and repeat the information while ignoring the information presented to the other ear – a task named "shadowing". Afterwards, the participants were asked what information they remembered from the unattended message. Only very salient information was remembered, such as beep sounds interrupting the verbal message, or a change of the speaker's sex. This led the author to the idea of an attention-filter, which separates relevant from irrelevant information early in the process – namely based on basic physical characteristics, such as color or form in vision, and pitch or location in audition. This account has been revised in 1959, when Moray presented the participant's own name to the unattended ear, which was heard in about 20 out of 39 cases, in contrast to other instructions or wordlists, which were only heard rarely (see Table III in Morey, 1959). Hence, information from the irrelevant message was not filtered out completely, but was processed at least partly semantically (see also Wood & Cowan, 1995).

Selective attention is quite efficient at maintaining a focus and at filtering relevant information. However, interacting with our environment does also require flexible switches between different sources of information – when for example listening to a speaker at a conference while also talking to the person sitting next to you (see also reviews of Bronkhorst, 2000, 2015, and Shinn-Cunningham, 2008). Broadbent (1954) was the first to assess situations that required attention-switches between simultaneously presented auditory information. Participants heard three pairs of simultaneous number-words – one number-word to each ear at a time. They were asked to remember all the numbers, and to write them down afterwards. The time interval between the three pairs was varied (500, 1000, 1500 and 2000 ms), and this interval influenced the reproduction of the memorised sequence. The results showed that participants wrote down the numbers separated by ear when there was only a short time interval between the number-pairs. Yet, when the time interval was very long (1000 – 2000 ms) they began to report the numbers pairwise in their temporal order. Broadbent concluded that switches of auditory selective attention between ears are time consuming and need at least 1000 ms to be completed.

However, in Broadbent's (1954) study, working memory capacity could have been confounded with memorizing strategy. Besides, the filter-function of selective attention was not required since all numbers had to be remembered. Plus, switching between memory representations instead of actual stimuli is more an offline measure of selective attention.

In order to close this gap, an auditory attention-focus-switching paradigm was developed by Koch, Lawo, Fels, and Vorländer (2011) which measures flexibility of auditory selective attention through the immediate online measure of reaction times (RT) and error rates (percentage of errors, PE). The authors combined the idea of a dichotic listening task with the task-switching methodology, as described by Kiesel et al., (2010). Similar to Broadbent (1954), participants were presented with two simultaneous number-words spoken by a male and a female voice. The mapping of speaker-sex to ear varied randomly from trial to trial. Using a variant of the task-cueing paradigm (Meiran, 1996), an imperative visual cue at the beginning of each trial indicated whether the following target stimulus would be presented by the male or female voice. Then, a simple magnitude judgment-task had to be performed on the target-number – namely deciding if the target-number was smaller or larger than five. Participants responded by pressing a left (smaller) or right (larger) key accordingly. RT and PE of trials in which the target was presented by the same speaker-sex as in the previous trials were compared to such trials in which the target was presented by a different speaker-sex. The difference in performance between those categories of trials is called attention-switch costs in analogy to task-switch cost (Kiesel et al., 2010), and reflects an online measurement of auditory attention-flexibility via RT and PE. In the study by Koch et al. (2011), and in subsequent studies using variants of this paradigm, the auditory attention switch costs represent a robust effect (Koch & Lawo, 2014; Koch et al., 2011; Lawo, Fels, Oberem, & Koch, 2014; Lawo & Koch, 2014a, 2014b, 2015) and confirm the conclusion of Broadbent (1954) about auditory attention switches being effortful and time consuming.

Posner (1980) proposed three processes that would take place during intentional attention-switches. Although the idea of this triad was based on findings from visual attention-switching, it can be used for auditory attention as it is not necessarily modality-specific: The model assumes that first of all, one has to *disengage* the attention focus from the current target, then the focus can be *switched* towards the new target, to which it is then *engaged.*

To get empirical evidence for processes like switching and engaging taking place during an attention-switch, a well-established method in task-switching research is to look at the preparation effects. The preparation time is usually operationalised by the time between a cue and the target stimulus, the cue-stimulus interval (CSI), which can either be relatively short or long, and a longer CSI typically results in shorter overall RT. Hence, it seems like at least some components of a task-switch can be prepared by the cognitive system based on information provided by the cue. Most commonly, it is assumed that task-switch costs are at least partially caused by active task-set reconfiguration, and reconfiguration contains retrieval of the required task-rules from working memory and (re)programming of the cognitive system in order to solve the new task (Kiesel et al., 2010, for a review on task-switching). Thus, reduced switch costs after a long CSI are said to indicate that, for example, the retrieval of the required task-rule already happened before stimulus onset.

However, Logan and Bundesen (2003), Mayr and Kliegl (2003), as well as Logan and Schneider (2006) argued that preparation time is used mainly for cue encoding, and that the switch-specific preparatory reduction of RT could be a product of cue-encoding processes instead of task-set reconfiguration. These three studies used a 2:1 cue-target mapping, compared to the typical 1:1 mappings, because in the 1:1-cue-task mapping cue-repetitions and task-repetitions are confounded. In a 2:1 mapping in contrast, the “pure“ task-switch costs can be measured by subtracting the RT of trials with a cue-switch and a task-repetition from that trials in which both, cue and task-switch. Confirming their assumption, the preparation effect did not reduce the “pure“ task-switch costs in their experiments, but only the cue-switch costs (see Jost, De Baene, Koch, & Brass, 2013, for a review).

Nevertheless, there is some agreement that the preparation of task-switches should be possible in general, though maybe only partly (see e.g. Mayr & Kliegl, 2000; Meiran, 2000). Participants might just not be encouraged to do so by the experimental setup. In this respect, Monsell and Mizon (2006) showed a preparatory reduction of “pure“ task-switch costs in a 2:1 cue-to-task mapping, when increasing the proportion of task-repetition trials to task-switch trials. They argue that through increased task-repetition probability, more processing capacity is available that can be used to actively prepare for an upcoming task-switch. In accordance with that, Mayr (2006) showed that the probability of a task-switch influences the size of the “pure” task-switch costs in a 2:1 cue-task mapping. Mayr furthermore analysed the size of these “pure“ task-switch costs, when manipulating the probability for different specific cue transitions between consecutive trials. For example, transitions between cues indicating a switch from task A to task B (cues: A and a; B and b) were presented frequently in the order A – b, but rarely in the order a - b. However, the “pure” task-switch costs seemed to be independent from such manipulations.

Previous studies on auditory attention-switching showed mixed findings with regard to a switch-specific reduction of RT after a long preparation interval. In the study of Koch et al. (2011), the interaction was found when participants switched attention between the speaker-sexes guided by cues that were blue and orange asterisks. However, in their Experiment 3 the interaction could not be reproduced with a 2:1 cue-sex-mapping. The absence of the interaction of CSI and transition indicates that the “pure” attention-switch costs were not reduced through increased preparation time. This led the authors to conclude that with the present experimental setup the CSI was rather used for visual cue encoding and for cue-priming processes that are found in switch- and repetition trials alike. The active switch-specific reconfiguration of the attention set, and the top-down attention-biasing might have happened after stimulus onset.

With the same 2:1 cue-sex mapping, Lawo and Koch (2015) compared abstract and direct verbal responses (“left” / “right” and “smaller” / “larger”), as well as manual responses within the paradigm, but similarly no preparatory reduction of switch costs was found - apart from a general preparation effect. The same applies to a study of Lawo et al. (2014), in which the speaker-sex feature dimension was compared to blocks in which participants had to switch between ears, irrespective of the speaker-sex of the voice presenting the target. Here, the interaction of CSI and transition was not significant, although a 1:1 cue-target-feature mapping was used.

Nevertheless, active preparation of auditory attention-switches may be possible, and the effect might simply be disrupted by contextual influences that hinder active preparation in the paradigm of Koch et al. (2011). Therefore, we saw the need to systematically analyse the contextual factors and preconditions that might be critical for the effect to arise, which we did in three experiments. We replicated earlier findings while controlling for cue-repetition benefits (Experiment 1), we examined within- and across-modality priming of the target modality by the cue-modality (Experiment 2), and we looked at the predictability of upcoming auditory attention-switches (Experiment 3).

To anticipate, Experiment 1 was a replication of Lawo et al.'s (2014) Experiment 3 with sex- and ear-feature blocks, in which no preparatory switch cost reductions were found. Our experiment controlled for cue-repetition-benefits with a 2:1 cue-to-target-feature mapping in order to obtain “pure” auditory attention switch costs. The replication was successful despite the small modification, demonstrating robust effects. Hence, cue-modality was manipulated in

Experiment 2 by comparing the previously used visual cues to auditory ones. Yet, the within-modality cue priming (auditory cue modality primes auditory stimulus modality) did not change the result pattern in terms of an active switch-preparation. Finally, Experiment 3 provided maximal predictability of the switch-sequence by removing the external cues from the design and pre-instructing the switch-sequence at the beginning of each short experimental block, producing predictable attention-switches without any explicit cueing. This resulted in reliably reduced attention-switch costs in trials with long response-stimulus interval (RSI).

## Experiment 1

In Experiment 1, we aimed to replicate the main findings of Lawo et al.'s (2014) Experiment 3. They did not find a preparatory switch-cost-reduction, using a 1:1 cue-to-target-feature mapping. In our experiment, we introduced a second set of cues (2:1-mapping) to disentangle cue-repetition-benefits from attention-switch costs. With this modification, we aimed to obtain "pure" auditory attention-switch costs (Koch & Lawo, 2014; Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell & Mizon, 2006).

Besides, the study of Lawo et al. (2014) controlled for target feature dimension by comparing non-spatial speaker-sex cueing to spatial ear-cueing. This factor interacted with preparation time (CSI) because the preparation effect was larger for ear-cue blocks compared to preparation for the sex-cue blocks. The present experiment examined whether this interaction represents a robust effect.

### Method

**Participants.** The participants were 20 German-speaking students (15 women, 5 men) from RWTH Aachen University aged between 18 and 33 years ($M$ = 21, $SD$ = 4). They received partial course credit for their participation. Most participants were right-handed, except one participant who was left-handed. No hearing problems were detected in any participant, neither in the self-report, nor in an audiogram, which was conducted on a Maico MA33 audiometer.

**Apparatus, stimuli and task.** The experiment was developed in PsychoPy 2.0 (Peirce, 2008), run under Linux. The auditory stimuli were the spoken number-words from 1 to 9, except for 5, with an adjusted duration of 400 ms and an adjustment for subjective loudness (DIN 45613). They were recorded at the Institute of Technical Acoustics of the RWTH Aachen in an anechoic chamber. In the experiment, the stimuli were presented via headphones (Philips SBC HL140) in dichotic pairs, of which one stimulus was spoken by a male speaker and the other stimulus was spoken by a female speaker. In contrast to Lawo et al. (2014), we only used stimulus material from one male and one female speaker with regard to speaker-sex blocks, as the number of cued speaker-sex features should be the same as the number of cued the ear-selection features (one "left" and one "right").

A visual cue at the beginning of each trial indicated which stimulus was the target-number in the present trial. The cue was presented in the centre of a 22-inch computer monitor (LG 22MB65PM) and indicated in the sex-based selection blocks, whether the male or the female speaker presented the target within the following target-distracter pair. For the location-based selection blocks, the cue indicated whether the target would be presented to the left or right ear, irrespectively of the speaker-sex. Two different cues were used for each sex and each direction, which alternated between trials. By this, repetitions of the very same cue in subsequent trials were avoided, while the speaker-sex or -side could repeat or switch independently. A female speaker was cued by either the German word "Frau" (German for "woman") or the symbol "♀", whereas a male speaker was cued by the word "Mann" (German for "man") or the symbol "♂". For the ear cue, the German word "links" ("left") or the symbol of a leftwards pointing arrow indicated that the target word would be presented on the left ear, and the word "rechts" (German for "right") or a rightward pointing arrow cued the right ear. The word- and pictogram-cues were all easy to understand in order to reduce working-memory load for the participants (Kiesel et al., 2010). The cues were presented in black color on a white screen and had an on-screen average height of 8.2 cm and an average width of 4.0 cm. The participants were seated at about 70 cm viewing distance from the monitor.

The participants were instructed to press the left arrow key on a QWERZ keyboard with their left index finger if the relevant stimulus number was smaller than 5. In case of a target number larger than 5, the participants were instructed to press the right arrow key with their right index finger. With this, the mental number-line was taken in account, which maps smaller numbers to the left and larger numbers to the right (Dehaene, Bossini, & Giraux, 1993).

**Procedure.** The experiment started with a questionnaire asking for biographic data like age and sex. It was followed by the hearing sensitivity test, and by the experimental instructions on the computer screen. The experiment consisted of four blocks with 128 trials, resulting in 512 trials. In two of the four blocks, participants had to perform sex-feature selection, whereas in the other half of the blocks they had to attend to the ear-features. Both experiment-halves were preceded by a short practice block that consisted of 16 trials each. The experimental session took approximately 50 minutes.

In each trial, a cue appeared and after a CSI of either 100 ms or 900 ms the stimuli were presented via headphones. The CSI varied randomly on a trial-by-trial basis. The visual cue stayed on the screen until a response was given. The response was followed by a response-cue interval (RCI) of either 1000 ms or 200 ms, which varied inversely to the CSI to keep the overall response-stimulus-interval (RSI) constant. In case of an incorrect response, the word "Fehler" (German for "error") was printed in red on the screen for 500 ms immediately after the response.

Each cue appeared equally often, and there were the same amount of feature switches and feature repetitions. The order of the sex- and ear-cue halves of the experiment was counterbalanced across participants.

**Design.** Independent variables were CSI (short vs. long preparation time), transition (feature-repetition vs. feature-switch), and feature dimension (ear- vs. speaker-sex criterion). The dependent variables were RT and PE.

**Results**

Practice trials and the first trial of each block were not included in the analyses, as well as RT outliers below 100 ms and above 3 standard deviations from the participant's mean, respectively (2% of the trials). For the analyses of the RT, errors (6%) plus each trial directly following an error were excluded, while for the analysis of the error rates only the trials directly following an error were excluded in addition to the RT outliers. RT and error rates were analysed in separate analyses of variance (ANOVA).

The ANOVA of the RT revealed a significant main effect of CSI, $F(1, 19) = 148.25$, $p < .001$, $\eta_p^2 = .89$, indicating 209 ms shorter RT in trials with long CSI compared to ones with short CSI. The main effect of transition was significant, too, $F(1, 19) = 48.67$, $p < .001$, $\eta_p^2 = .72$, showing auditory attention-switch costs of 94 ms. The main effect of feature dimension was not significant, $F(1, 19) = 1.45$, $p = .24$, $\eta_p^2 = .071$, but this variable interacted with CSI, $F(1, 19) = 66.90$, $p < .001$, $\eta_p^2 = .78$. Bonferroni-corrected post-hoc tests specified that there were significant preparation advantages in both feature dimensions with long compared to short CSI ($p = .018$, $p = .020$), yet the RT difference between short and long CSI-trials for ear-cue blocks was larger than for sex-cue blocks ($\Delta M_{Ear} =$ 272 ms, $\Delta M_{Sex} = 147$ ms, $p < .001$), which is similar to findings reported by Lawo et al. (2014). The other two-way interactions and the three-way interaction were not significant (*Fs* < 1), see also Figure 1.

The same ANOVA with PE as dependent variable showed only a significant main effect of CSI, $F(1, 19) = 7.68$, $p = .012$, $\eta_p^2 = .29$, as 2% more errors were found with short compared to long CSI. Transition showed numerical switch costs of 1% errors, yet it was not significant, $F(1, 19) = 2.66$, $p = .119$, $\eta_p^2 = .12$, neither was feature dimension ($F < 1.5$) nor any other interaction (*Fs* < 1).

**Discussion**

We replicated the main findings of Lawo et al.'s (2014) Experiment 3, although we controlled for a potential confound by avoiding cue-repetitions using a 2:1 cue-to-feature mapping[3]. Besides that, the CSI was varied between trials instead of block-wise, and the number of speakers was reduced from three to one per sex.

Significant "pure" auditory attention-switch costs were obtained in RT and numerically in error rates, too. This once more proves the time that is needed to switch attention compared to trials in which the auditory attention-focus remained constant. Furthermore, a general preparation effect was found: RT was reduced with a long CSI compared to a short one, and this general preparation effect interacted with feature dimension: blocks with ear-based selection requirements showed a larger preparation benefit than blocks with sex-based selection requirements.

The finding of this interaction supports the idea of Lawo et al. (2014) that disengaging attention from a previously attended spatial feature, (i.e. side of relevant ear), takes more time compared to disengaging it from a speaker-sex. This is in accordance with results of two studies involving auditory sequence memorizing, in which participants' performance improved when the target sequence was presented constantly to one ear. It furthermore improved by a constant speaker instead of varying speakers (Best, Ozmeral, Kopco, & Shinn-Cunningham, 2008; Best, Shinn-Cunningham, Ozmeral, & Kopco, 2010).

Most importantly, with regard to the aim of this study, no switch-specific preparatory reduction of RT was found in Experiment 1, although we measured "pure" auditory attention-switch costs. Nevertheless, we still think that active preparation of auditory attention-switchs as obtained in task-switching studies is possible. The auditory attention-switching paradigm might just discourage or disguise the preparation. The cue-encoding effort might be relatively high due

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[3] Since the category of the cue (word vs. symbol) could have influenced the preparation of the auditory attention shifts, this was examined in an additional repeated-measurements ANOVA that contained cue-category as an additional independent variable. However, cue-category (symbol vs. word) did not interact with the critical variables of CSI, nor with attention-transition (*F*s < 1) in RT. This trend was confirmed by the analysis of the error rates.

to visual cues, which required a modality switch of the attention focus within every single trial between visual cue and auditory target. Therefore, like Monsell and Mizon (2006) would suggest to reduce processing demands, we added blocks with auditory cues in Experiment 2 in order to foster switch-specific preparation through priming the stimulus modality by the cue modality.

## Experiment 2

In Experiment 2, the performance in blocks with auditory cues was compared to performance in blocks with visual cues. Hereby, we examined if modality-switches of the attention focus between cue and target in the visually cued blocks hindered active preparation of auditory attention-switches. We continued using a 2:1 cue-to-target-feature mapping in order to measure "pure" auditory attention-switch costs.

With regard to the cue modality, different outcomes were possible: in auditory cued blocks, within-modality cue-priming could decrease RT compared to the visually cued blocks (Ferstl, Hanewinkel, & Krag, 1994; Lukas, Philipp, & Koch, 2010; Spence & Driver, 1997). However, we thought it would be equally likely that visually cued blocks produce shorter RT, because Lukas et al. (2010) found that RT in a crossmodal attention-switching paradigm were overall shorter when cue and target were presented in different modalities compared to in the same modality, due to possible modality-specific capacity limitations.

Apart from this latter effect, we expected to replicate the main pattern of Experiment 1 for the visually cued part. For the auditory cued blocks, we expected similar outcomes: auditory attention-switch costs should be present, as well as a significant general preparation effect. On the other hand, this preparation effect could be increased through the absence of crossmodal attention-switches between cue and target. The absence of the crossmodal requirements could encourage participants to actively prepare for upcoming auditory attention-switches between target features and would show up as a three-way interaction of cue-modality, CSI and transition.

### Method

**Participants.** The 24 right-handed participants (16 women, 8 men) were German-speaking students from the RWTH Aachen University between 19 and 36 years of age (*M* = 24, *SD* = 4). The increase in the number of participants was a requirement of the counterbalancing conditions in the experimental setup. No hearing problems were detected for any of the participants.

**Apparatus, stimuli and task.** Apparatus and stimuli were exactly the same as in Experiment 1 for the part using visual cues. The newly introduced auditory cues consisted of sounds and spoken letters that were presented diotically. A low pitch tone at 200 Hz and a high pitch tone at 800 Hz were used for cueing a male and female speaker. The second pair of speaker-sex cues were the spoken letters “M”, and “F”, and they were spoken by new female and male speakers that were different from the stimuli-speakers. The sex of the cue-speaker was thereby counterbalanced between participants.

Two 450 Hz tones were used as ear-selection cues: one at a low volume indicated the target was on the left side and the other at high volume (30 dB difference) indicated the target was on the right side. The second cue-pair consisted of the spoken letters “L” and “R” for left and right targets, respectively, that were spoken by the same speaker as the sex-cues.

A slight modification regarding the duration of CSI and RCI had to be made, to ensure the comparability of trials with auditory and visual cues. As the auditory cues’ duration was 400 ms, the CSI manipulation had to be adjusted to a short interval of 400 ms, and a long CSI of 800 ms in both auditory and visually cued blocks. This decreased the difference between short and long CSI, but apart from a reduced general CSI effect the manipulation should not have any critical impact on the result pattern.

**Procedure.** The procedure, the number of trials and therefore also the duration of the experiment were the same as in Experiment 1. It was divided in quarters due to the four cue-modality-feature dimension conditions. Each quarter of the experiment was introduced by short instructions and 16 training trials. The order of the quarters was counterbalanced between participants.

**Design.** The independent variable of cue-modality (visual vs. auditory) was added to the variables introduced in Experiment 1, which were CSI (short vs. long), transition (feature-repetition vs. -switch), and feature dimension (ear vs. sex). RT and PE remained the dependent variables.

**Results**

Outliers (2%), erroneous trials (6%), and trials directly following an error were excluded from the analysis of the RT. The ANOVA for repeated measurements in the RT data revealed a main effect of cue modality, $F(1, 23) = 24.49$, $p < .001$, $\eta_p^2 = .52$, with responses to auditory cued trials being 181 ms slower than visually cued trials. A main effect of CSI was found, indicating the expected shorter RT ($\Delta M = 136$ ms) with the long CSI, $F(1, 23) = 86.51$, $p < .001$, $\eta_p^2 = .79$. The main effect of transition was found as well, $F(1, 23) = 17.38$, $p < .001$, $\eta_p^2 = .43$, with attention-switch costs of 42 ms.

CSI interacted with cue-modality, $F(1, 23) = 50.53$, $p < .001$, $\eta_p^2 = .69$, since the CSI effect was 201 ms in the auditory cued trials, and only 71 ms in the visually cued trials. CSI furthermore interacted with feature dimension, $F(1, 23) = 7.92$, $p = .010$, $\eta_p^2 = .26$, because the general preparation effect was 30 ms larger with ear-cues than with speaker-sex cues, similar to the results of Expeirment 1. Nevertheless, the Bonferroni-corrected post-hoc comparisons showed that both were significant ($p < .001$).

Transition interacted with cue modality, $F(1, 23) = 15.82$, $p = .001$, $\eta_p^2 = .41$. Post-hoc comparisons showed that auditory attention-switches were costly only in the visually cued trials ($\Delta M = 70$ ms, $p < .001$), but not in the overall slower auditory cued trials ($\Delta M = 14$ ms, $p = .74$). The three-way interaction of cue-modality, CSI and transition showed a nonsignificant trend, $F(1, 23) = 3.64$, $p = .069$, $\eta_p^2 = .52$, as switch costs numerically decreased from short to long CSI in the visually cued blocks ($M_{short} = 83$ ms $M_{long} = 56$ ms, $p = .0.92$), whereas switch costs surprisingly even increased in the auditory blocks ($M_{short} = 5$ ms, $M_{long} = 24$ ms, $p = .328$; see Figure 2). No other effect reached the level of significance (*Fs* < 2).

The analysis of the percentage of errors revealed similar effects: auditory cued trials were 0.9% more erroneous than visually cued trials, which produced a main effect of cue modality, $F(1, 23) = 4.53$, $p = .044$, $\eta_p^2 = .16$. A main effect of CSI of 1% was found, $F(1, 23) = 10.06$, $p = .004$, $\eta_p^2 = .30$, and a main effect of transition revealed attention-switch costs of 1%, $F(1, 23) = 8.69$, $p = .007$, $\eta_p^2 = .27$.

Similarly to the RT data, cue modality and CSI interacted, $F(1, 23) = 9.19$, $p = .006$, $\eta_p^2 = .29$, as auditory cued trials with long CSI were 2% less erroneous than auditory cued trials with short CSI ($p < .001$), while visually cued trials showed no difference between short and long CSIs ($p = .971$). A nonsignificant trend was found for the interaction of feature dimension and transition, $F(1, 23) = 3.13$, $p = .090$, $\eta_p^2 = .12$, as larger switch costs were found for switching attention between ears (2%) than for switching attention between speaker-sexes (1%). All other effects were clearly nonsignificant (*Fs* < 1), including the interaction of CSI and transition.

**Discussion**

As expected, the results of the visually cued blocks followed the pattern of Experiment 1, with auditory attention-switch costs, a general preparation effect and a preparation advantage of ear-based over sex-based selection.

The auditory cued blocks were overall more error prone and produced higher RT than visually cued blocks. This could be simply due to perceptual differences of vision and audition in terms of for example spatial and processing (see e.g. Lukas et al., 2010). More importantly, cue-modality interacted with switch costs in the analysis of the RT, as auditory attention-switch costs were a variable effect and only significant in the visually cued blocks. In error rates, though, the switch costs were present in the auditory cued blocks as well.

It is hard to say whether the absence of auditory attention-switch costs in RT data in the auditory cued blocks is the reason why no preparatory reduction of switch costs was obtained, or whether a third unknown variable influenced both switch costs and its interaction with preparation interval. A control experiment in our lab with the same paradigm but using a fixed CSI of 400 ms replicated exactly this pattern of absent auditory attention-RT switch costs in blocks with auditory cues[4].

We can only speculate about the reasons: In our experiment the cues in the two modalities differed in terms of cue "transparency" (see Grange & Houghton, 2010). Namely, the visual cues were more transparent because the meaning of the word (e.g. "female") or symbol (e.g. symbol for female) was obviously related to the target, whereas auditory letter and tone cues (e.g. "F" and a high pitch tone for female) were less transparent. However, switch costs should typically be increased with the less transparent auditory cues compared to the more transparent visual cues (Arbuthnott & Woodward, 2002; Grange & Houghton, 2010), but we found the opposite in our results.

The reason for the absence of switch costs in the auditory cued blocks could also be a ceiling effect. The short CSI of 400 ms might have already allowed full preparation of the upcoming attention-switch, which was 300 ms longer than the short CSI of Experiment 1. However, in Experiment 1 even with a long CSI of 900 ms residual attention-switch costs were still found, and although auditory cues might help to flexibly switch auditory attention, it seems unlikely that preparation can be perfect within 400 ms, also given that the content of the auditory letter cues cannot be fully understood before cue-presentation is finished.

Although no switch costs were found in RT, they were present in the error rates, which suggests that participants rather used a kind of accuracy bias as a strategy to deal with the auditory information load, and simply invested generally more time to select the correct response.

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[4] Data of the RT of 23 participants revealed a main effect of cue modality ($F(1, 22) = 39.97$, $p < .001$, $\eta_p^2 = .65$), with 229 ms shorter RT for visual cued blocks. Attention-shift costs of 33 ms were present ($F(1, 22) = 12.30$, $p = .002$, $\eta_p^2 = .36$), and both variables also interacted ($F(1, 22) = 16.26$, $p = .001$, $\eta_p^2 = .43$): shift-costs were significant in visually cued blocks (70 ms, $p < .001$) but not in auditory cued blocks (-4 ms, $p = .738$). All other effects were nonsignificant (*Fs* < 1.3). In the error rates, cue modality and transition elicited main effects ($F(1, 22) = 15.68$, $p < .001$, $\eta_p^2 = .42$; $F(1, 22) = 5.34$, $p = .031$, $\eta_p^2 = .195$; other Fs < 1.9), showing error-switch costs also for the auditory cue condition, like in the present experiment.

Typically no switch-specific preparation effect is found in task-switching studies or in attention-switching studies in error rates, as it rather seems to be an effect influencing RT (see Kiesel et al., 2010, for a review). Thus, to assess preparation effects in auditory attention-switching, auditory cued blocks do not seem to be a better choice than visual cues. That is, although we controlled for many possible confounds like feature dimension, cue-repetitions, within-modality priming, and mapping-effects we still did not find switch-specific preparation effects with the present paradigm.

The results indicate that cue-encoding processes that produce a variety of effects that could potentially interfere with switch-specific preparation. We therefore needed a manipulation that helped us to exclude any cue from the paradigm. Accordingly, we adopted a method frequently used in task-switching research: the alternating-runs paradigm (e.g. Koch, 2003; Kray & Lindenberger, 2000; Rogers & Monsell, 1995). In this paradigm, the switch-sequence is instructed in the beginning of each experimental block, and has to be remembered by the participant.

## Experiment 3

In Experiment 3, we used an alternating-runs paradigm (Rogers & Monsell, 1995; Spector & Biederman, 1976) instead of the previously used cued auditory attention-switching paradigm. This means that cues were completely removed from the experiment, and the sequence of feature dimension repetitions and switches was instructed at the beginning of each short experimental block. The sequence-pattern was AABBAABB, with A and B as the two selection-features. This pattern is often used in studies employing an alternating-runs paradigm (see Kiesel et al., 2010). Although this imposes a working-memory load on the participant's cognitive system, the alternating-runs paradigm has some advantages when examining preparation effects: no cues are required and the entirely predictable switch-sequence could provide a stronger incentive for participants to prepare task-switches. In task-switching research, preparatory reduction of switch costs is a common finding with the alternating-runs paradigm, which gives us a reason to expect such a preparatory reduction of attention-switch costs as well.

Due to the absent cues, the response-stimulus interval (RSI) was manipulated to provide short and long time between the trials that could be used for active attention-switch preparation. Importantly, the RSI was not varied on a trial-by-trial basis, but block-wise. This was done to increase the predictability of stimulus-onset for upcoming attention-switches and repetitions.

Furthermore, the modification was done because in task-switching Rogers and Monsell (1995) found active switch-specific preparation effects mainly with block-wise variation of the RSI. They argued that unpredictable stimulus onsets disturbed the preparation process. Thus, in our third experiment, we wanted to provide the best possible preconditions for participants to prepare for upcoming auditory attention-switches – including a predictable feature switch-sequence and predictable onsets of the stimuli.

From a theoretical point of view the alternating-runs paradigm should require the three switching-components of Posner's (1980) definition of an attention-switch: disengagement, switching, and engagement. Since the auditory attention-switch sequence is instructed only in the beginning of the experimental block, the participants must initiate attention-switches and repetitions themselves by keeping track of the instructed sequence they have memorised. In a cued switching paradigm, in contrast, the cue might disrupt the disengagement process. Thus, there should not be a cue-triggered attention-“reset” at the beginning of each trial, and it should be possible to actively start preparing for an attention-switch after the response to the previous target. Accordingly, participants should be able to finish at least parts of the disengage-process and maybe also of the switch-process during RSI – at least regarding those components of an attention-switch that do not require the presence of the stimulus.

We therefore expected a significant interaction of RSI and transition, reflecting active preparation for auditory attention-switches. In addition to that we anticipated to replicate the main result pattern from the first two experiments of the present study. There should be significant attention-switch costs, as well as a general preparation advantage of trials with long RSI over trials with short RSIs. Furthermore, we re-assessed whether the preparation advantage of ear-based selection over sex-based selection would be present.

**Method**

**Participants**. The participants were 24 German-speaking students (17 women, 7 men) from RWTH Aachen University between 18 and 33 years of age ($M$ = 22, $SD$ = 4). All participants were right-handed, except for one left-handed person. Neither in the self-report nor in the hearing test problems were detected for any of the participants.

**Apparatus, stimuli and task.** The stimuli and parts of the experimental setup were the same as in Experiment 1. In contrast to the previous experiments there were no external cues, but the trial-sequence and its start-feature (left / right ear or male / female speaker-sex) for selecting the target were instructed at the beginning of each short experimental block.

**Procedure.** The procedure was as similar as possible to the previous experiments, with questionnaire and hearing test at the beginning of the experiment. Within the experiment, the block-size was reduced to 16 trials to avoid aftereffects of errors. By aftereffects, we mean increased error rates due to participants tangling up their current position within the trial-sequence and continuing with a displaced pattern. To keep the number of trials comparable to Experiment 1 and 2, the number of blocks was increased to 32, which resulted in 512 experimental trials in total. At the beginning of each half of the experiment, one practice block consisting of 16 trials was added to introduce each feature dimension (ear- and sex-based target-selection). The feature dimension that was used first varied between participants, and changed in the second half of the experiment. The RSI was alternated between consecutive blocks, and the starting feature (left or right ear; male or female voice) varied randomly between blocks.

**Design.** The independent variables were RSI (100 ms vs. 1000 ms), transition (attention repetition vs. attention-switch), and feature dimension (sex- vs. ear-based selection). RT and PE were the dependent variables.

**Results**

The data filtering procedure was the same as in the previous experiments. RT outliers (9%) and errors (10%) plus trials following an error were excluded for the analysis of the RT.

The ANOVA of the RT revealed a main effect of RSI, $F(1, 23) = 8.11$, $p = .009$, $\eta_p^2 = .261$, indicating a mean advantage of 47 ms for long compared to short RSIs. As expected, the main effect of transition was significant as well, $F(1, 23) = 94.17$, $p < .001$, $\eta_p^2 = .80$, showing switch costs of 184 ms. The main effect of feature dimension, $F(1, 23) = 15.28$, $p = .001$, $\eta_p^2 = .40$, revealed 113 ms shorter RT for speaker-sex selection compared to ear selection.

Importantly, the interaction of RSI and transition was significant, $F(1, 23) = 10.91$, $p = .003$, $\eta_p^2 = .32$, which showed a significant reduction of switch costs from short to long RSI trials, which was confirmed by Bonferroni-corrected post-hoc tests: A significant RSI-effect was found for switch trials ($\Delta M = 81$ms, $p = .002$), but not for repetition trials ($\Delta M = 13$ ms, $p = .388$), which caused a reduction of switch costs in the trials with long RSI. However, even in the trials with long RSI, significant attention-switch costs were still present ($\Delta M_{shortRSI}$ = 218 ms, $\Delta M_{longRSI}$ = 150ms, *ps* < .001). No other effect reached the level of significance (*Fs* < 2.0).

The same ANOVA with percentage of errors as dependent variable showed only a significant main effect of transition, $F(1, 23) = 63.88$, $p < .001$, $\eta_p^2 = .74$), as 4% more errors were found in attention-switch trials compared to attention-repetition trials. All other main effects and interactions were clearly nonsignificant (*Fs* < 1).

**Discussion**

In Experiment 3, a preparatory reduction of the RT switch costs with long compared to short RSI trials was found. Hence, with an entirely predictable switch-sequence as well as a paradigm void of cue-encoding requirements, we reliably produced a preparatory reduction of auditory attention-switch costs. The current finding resembles results from task-switching research, as the alternating-runs paradigm showed the switch-specific preparation effect quite consistently, too (e.g. Altmann, 2002; Koch, 2003; Rogers & Monsell, 1995).

However, it might be criticised that the preparatory reduction of switch-costs with long RSI compared to a short RSI in Experiment 3 could also reflect passive “decay” processes from the previous attention-focus instead of active disengagement and preparation for the upcoming target-feature (Houroufchin, Philipp, & Koch., 2011; Meiran, 1996). Yet, Koch and Lawo (2014) manipulated the response-cue interval (RCI) in the cued auditory attention-switching paradigm, which is the time available for passive decay of the previous task-set since there is no information about the upcoming trial available during this trial. At the same time, they kept the cue-stimulus interval constant – namely the time during which active preparation is expected to happen. The results of the two experiments of the above-mentioned study showed that RCI did not elicit a main effect and neither did it interact with any other variable in the paradigm. Thus, we subsume that it is not passive decay of the previous attention-set that is responsible for the reduction of auditory attention-switch costs in our experiment.

Besides this main outcome, we replicated some findings from the previous experiments: Attention-switch costs were present and a general preparation advantage of long preparation intervals over short intervals was found. This is noticeable in the present context, because the switch costs were observed despite the increased working-memory load through the instructed switch-sequence. Furthermore, we found an RT advantage of ear-selection over speaker-sex selection, but not the stronger preparation effects for ear- over speaker-sex selection of earlier experiments (Lawo et al., 2014).

## General Discussion

The present study examined what preconditions are necessary for participants to actively prepare for upcoming auditory attention-switches. Therefore, a switching paradigm was employed (Koch et al., 2011), in which participants heard two simultaneously spoken number-words. A cue at the beginning of each trial indicated whether the target-number was presented by the female or a male speaker, or whether the target-number was presented to the left or to the right ear of the participant. The task was to decide whether the cued target number was smaller or larger than five and to respond by left or right key-press accordingly. Significant auditory attention-switch costs were obtained when comparing target-feature repetitions (e.g. same speaker-sex in the previous and in the current trial) to target-feature switches (differing speaker-sex in previous and current trial).

Active preparation for auditory attention-switches was not consistently found in earlier studies. Cue-modality and switch-sequence predictability were identified as potentially critical variables in this regard. With a systematic variation of these two variables over three consecutive experiments, the present study suggests that the variable of switch-sequence predictability contributed to active preparation of auditory attention-switches.

### Synopsis of the Results

All three experiments replicated earlier findings of auditory attention-switch costs with spatial and non-spatial feature dimensions (Lawo et al., 2014). Furthermore, an RT advantage of increased preparation time between cue and stimulus (Exp. 1 & 2) or between response and stimulus (Exp. 3) was found. Moreover, in the visually cued blocks in Experiment 1 and 2, the preparation effect was larger when switching attention between spatial features of the ear of the target stimulus compared to the non-spatial feature of speaker-sex. In Experiment 3, in which the switch-sequence was instructed in the beginning of each experimental block, selection of the relevant ear was faster than selection of the speaker sex for both, short and long preparation intervals.

A preparatory reduction of auditory attention-switch costs was only found in Experiment 3. Auditory attention-switches therefore seem to have benefited from the entirely predictable switch-sequence, but also from the absence of additional cue-encoding processes that were required in Experiments 1 and 2. Possible explanations and problems in this regard are discussed in the following.

**Switch costs**

Before focusing on active attention-set reconfiguration and preparation processes, it is important to note that we obtained significant auditory attention-switch costs in all three experiments. The only deviation in this regard is the finding in the auditory cued blocks of Experiment 2. There, no switch costs were detected in RT, but the costs were present in the error rates. Hence, we tend to infer from this finding that auditory attention-switch costs were always present, yet the auditory cued-blocks encouraged different speed-accuracy weighting strategies.

With regard to earlier studies on the auditory attention-switching paradigm, we can state that switch costs were consistently found, even with long preparation intervals of up to 1000 ms (for example Lawo et al., 2014; Lawo & Koch, 2014b). Thus, auditory attention-switching does seem to be costly in terms of RT, as Broadbent already proposed in 1954, or they might cause more errors, or even both. Furthermore, auditory attention-switches partly rely on processes that cannot be prepared or finalised before target onset (see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010).

**Preparation effects on auditory attention-switches**

As the goal of the present study was to systematically assess which preconditions are required to actively prepare for auditory attention-switches, we examined two possible mediators: the impact of different cue modalities, and the influence of the predictability of the switch-sequence.

**The impact of cues.** In the task-switching literature, reduced switch costs after a long preparation interval represent a rather frequent result (see Kiesel et al., 2010). However, a large part of the preparation interval is probably used for cue-encoding rather than for the preparation of actual task-switches (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). One attempt to disentangle cue- and task-switches is the use of a 2:1 cue-task mapping. When comparing task-repetitions and switches in cue-switch trials, the preparatory reduction of switch costs with a long preparation interval may be reduced compared to a 1:1 cue-task mapping.

Attention-switches can be understood as a subdomain of task-switches, because a task-switch often requires an attention-switch to a different stimulus feature as well. In our study, we used the 2:1 cue-target-feature mapping, and similarly to some task-switching results (Logan & Bundesen, 2003; Mayr & Kliegl, 2003), no preparatory reduction of switch costs was found. At the same time cue-encoding processes produced considerable influences: with auditory cues, the typically very robust finding of attention-switch costs in RT data completely vanished.

Especially in the 2:1 cue-target-feature mapping, cue-encoding requirements and working-memory load are strongly increased in comparison to the 1:1 mapping. In this regard, the contentious question can be asked if people actively switch their attention when two different cues can trigger a target feature. If a cue and the required encoding processes at the beginning of each trial "reset" the attention-set, attention-switch costs could as well reflect the difference between full and partial resets in switch and repetition trials, respectively. In the light of Posner (1980), such a reset would make at least the active *disengagement* from the previous trial unnecessary and could also change the quality of the attention-*switch.* This would make a cued trial qualitatively different from internally motivated intentional attention-switching, like it should be present for example in a voluntary attention-switching paradigm (e.g. Arrington & Logan, 2004).

Anyhow, instead of using the 2:1 attention-feature cueing paradigm once more, we avoided cues in Experiment 3, and since voluntary switching paradigms might be problematic - when thinking of the requirement for participants to switch unpredictably, and their use of individually different strategies like perseverating on one task or trying to see trials as closed entities (Mayr & Bell, 2006) – we choose the alternating-runs paradigm. Like mentioned earlier, this paradigm (Rogers & Monsell, 1995) should theoretically require the three switching-components of Posner's (1980) definition: the participants must initiate attention-switches and repetitions themselves by keeping track of the instructed sequence they have memorised. Thus, attention is not "resetted" by a cue at the beginning of each trial, and active preparation for an attention-switch after the response to the previous target should take place. By this, participants should be able to finish at least parts of Posner's disengage-, and maybe also of the switch-process during the time-interval between the previous trial and the upcoming trial's target onset. Consistent with this latter consideration, results from task-switching research employing the alternating-runs paradigm typically show a preparatory reduction of switch costs (Rogers & Monsell, 1995), and as our results from Experiment 3 demonstrate it is found with auditory attention-switches, too.

One might argue that the memorised switch-sequence could produce internal cues in the alternating-runs paradigm. Such internal cues, i.e. internally speaking "left – left – right – right …", could produce intentional cue-repetition benefits like in a cueing-paradigm with a 1:1 cue-target-feature mapping. This argument depends on the definition of an attention- or task-set: Are internal cue representations just reflecting the external cues, introduced by the instructions in an alternating-runs paradigm, and these representations are stored in a separate memory-set? Alternatively, the internal cues could be a part of the attention-set that is retrieved when repeating and switching between target-features, since during reading and understanding the instructions, the sequence gets translated into a memory representation. To retrieve the sequence, cue-like triggers are needed. However, the triggers then should be an inseparable part of the attention-sets, between which participants switch intentionally. Unfortunately, this question cannot be answered on the basis of the present data.

We think that only some components of an attention-switch can be prepared before stimulus-onset. This could imply that the absence of preparation effects in the cueing paradigm with a 2:1-cue-feature mapping is not a sole result of the absence of cue-repetitions. Possibly, some switch-processes that can take place before stimulus onset in attention-switching are not or in a lesser extent required in a cueing paradigm than in an alternating-runs paradigm – this could be the active disengagement for example.

One more point is worth consideration regarding the assumed cue-repetition benefits in a 1:1 cue-target feature mapping. From comparing 2:1 to 1:1 cue-target mappings it is not possible to doubtlessly deduce the presence of large cue-repetition benefits, because it is not possible to examine trials in which the attention-target switched but the cue-repeated (Forstmann, Brass, & Koch, 2007). Therefore, it is unclear whether cue-repetitions produce the switch-specific preparation advantage, but it could as well be assumed that task-repetitions produce a strong repetition benefit in a 1:1 mapping and the cue-repetition benefit is rather small.

**The predictability of upcoming attention-switches.** Besides from cue- and feature-repetitions, participants should also be motivated to prepare for upcoming trials if the attention-switches are highly predictable. Active preparation is always goal-directed. For auditory attention-switching this implies that the upcoming target-feature must be known to initiate something like Posner's (1980) disengage – switch – engage triad. The alternating-runs paradigm provided more information about upcoming switches and repetitions than the cueing-paradigms in Experiments 1 and 2, because the switch-sequence was pre-instructed the sequence-pattern was easy to remember – two factors that helped to make each upcoming trial highly predictable. The participants probably used the RSI to prepare for an upcoming switch or a repetition, but they could as well have started anticipating attention-switch requirements earlier. This was furthermore supported by predictable stimulus onsets through block-wise RSI manipulation to avoid disrupting the preparation process during the response-stimulus interval, as Rogers and Monsell (1995) suggest – although there seem to be exceptions in the literature (e.g., DeJong, 2000).

The important role of predictability for task-switching was amongst others shown by Monsell and Mizon (2006). With a task-cueing paradigm and a 2:1 cue-target mapping, switch-specific preparation effects can be obtained when the probability for a task-switch is reduced to 25% and by that the predictability for repetition trials is increased automatically. However, one always has to be cautious when interpreting difference scores in terms of task- or attention switch costs, as a reduction of these might either be produced by a RT reduction in switch-trials or by strong priming in repetition trials, which does not benefit from increased preparation time. When the probability for a task-switch is only 25%, participants have a high benefit of anticipating task-repetitions for upcoming trials and therefore RT in repetition trials gets shorter and does not benefit greatly from increased preparation time. Instead, a rare task-switch “disturbs” participants relatively more and therefore benefits from longer time available for preparation. When, in contrast, the switch-probability is as high as 75%, switch-specific preparation might take place, but is not revealed by the data because the rare task-repetition trials then might be slower due to their low predictability and produce longer RT than in trials with a short preparation interval. The alternating-runs paradigm instead is void of this switch-probability confound, and nevertheless provides an entirely predictable switch-sequence. Hence, a switch-specific reduction of RT in the alternating-runs paradigm, as found for auditory attention-switching in our third experiment may show true switch-specific preparation.

Besides, the RT advantage of switching auditory attention between ears over switching attention between the two speaker-sexes in Experiment 3 may be produced by this increased switch-predictability, too: Although short and long CSIs in Experiment 1 and 2 were of similar durations as short and long RSIs in Experiment 3, the results differed. In the cued Experiments 1 and 2, attention-selection in ear feature-blocks was only better in trials with a long CSI available for preparation. Lawo et al. (2014) argued that disengaging auditory attention from ear-features could be more difficult than disengaging attention from speaker-sex. Therefore, ear-based selection gained more from increased preparation time than speaker-sex-based selection. The full switch-predictability in Experiment 3 might have fostered this advantage for ear-based selection:

the effect generalised to trials with short CSIs and therefore resulted in a general advantage for ear- selection over speaker-sex selection.

**Conclusion**

The present study systematically examined the influence of cue-priming and switch-predictability regarding the preparatory reduction of auditory attention-switch costs. Our results indicate that the cued auditory attention-switching paradigm does not show the switch costs reduction, because cue-encoding and cue-priming processes might interrupt active preparation for attention-switches. In the alternating-runs paradigm, however, participants showed reduced auditory attention switch costs with increased preparation time, most probably due to the entirely predictable attention-switch requirements. Altogether, we conclude from this finding that auditory attention-switches seem to be costly, and therefore the cognitive system invests in actively preparing for such switches only under optimised conditions in terms of predictability of the upcoming stimuli.


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## Appendix

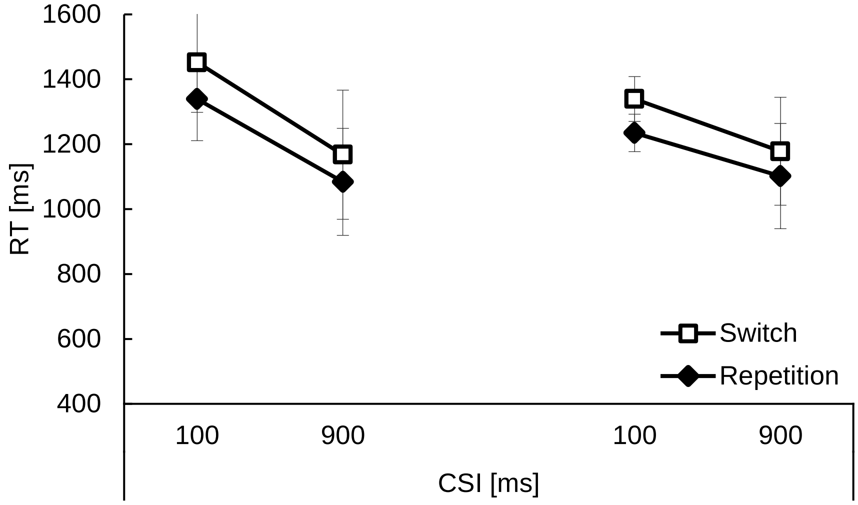


*Figure 1*. RT data of Experiment 1 as a function of feature dimension (ear vs. sex), transition (feature-switch vs. -repetition), and CSI (100 ms vs. 900 ms). Error bars reflect Cousineau-Morey confidence intervals (Morey, 2008).

Table 1

*PE data of Experiment 1*

| | Feature Dimension | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Ear-Sequence | | | | Sex-Sequence | | | |
| | CSI [ms] | | | | | | | |
| Transition | 100 | | 900 | | 100 | | 900 | |
| Switch | 13.1 | (±2.3) | 11.5 | (±4.5) | 12.0 | (±3.9) | 8.5 | (±3.3) |
| Repetition | 12.2 | (±3.6) | 9.7 | (±2.2) | 9.1 | (±3.2) | 10 | (±2.6) |

*Note*. PE [%] as a function of feature dimension (ear vs. sex), transition (feature-switch vs. feature-repetition), and CSI (100 ms vs. 900 ms). Cousineau-Morey confidence intervals are provided in parentheses (Morey, 2008).

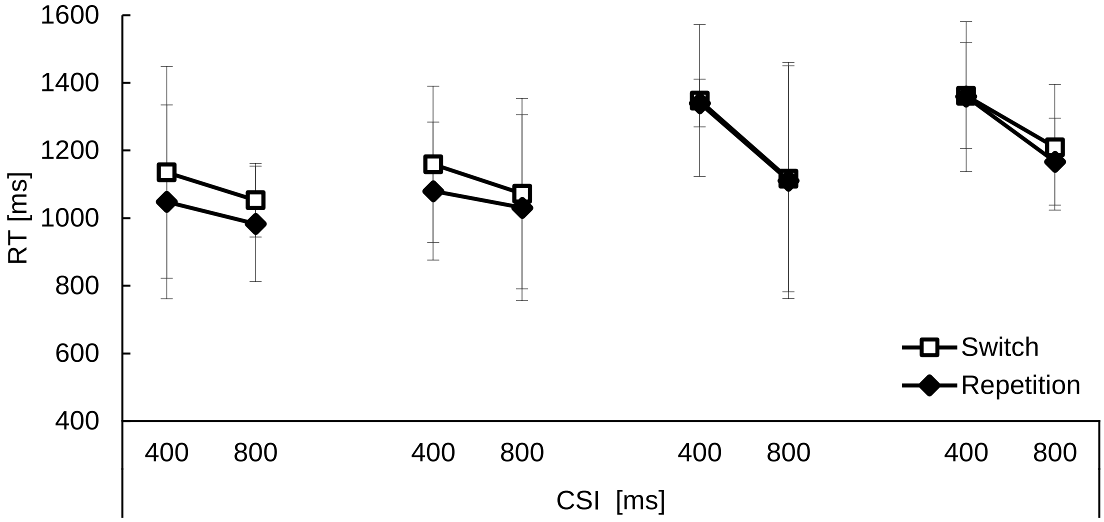


*Figure 2.* RT data of Experiment 2, as a function of cue-modality (visual cues vs. auditory cues), feature dimension (ear vs. sex), transition (feature-switch vs. –repetition), and CSI (400 ms vs. 800 ms). Error bars reflect Cousineau-Morey confidence intervals (Morey, 2008).

Table 2

*PE data of Experiment 2*

| | | Feature Dimension | | | |
|---|---|---|---|---|---|
| | | Ear-Sequence | | Sex-Sequence | |
| | | CSI [ms] | | | |
| Cue Modality | Transition | 400 | 800 | 400 | 800 |
| Visual | Switch | 7.0 (±2.2) | 7.5 (±1.3) | 5.5 (±1.6) | 5.8 (±1.3) |
| | Repetition | 5.6 (±1.5) | 4.4 (±1.5) | 5.0 (±1.0) | 5.3 (±1.4) |
| Auditory | Switch | 8.8 (±2.3) | 6.2 (±1.7) | 7.7 (±1.4) | 6.5 (±1.5) |
| | Repetition | 7.2 (±1.4) | 4.9 (±1.2) | 7.5 (±1.4) | 4.6 (±1.4) |

*Note*. PE [%] as a function of cue modality (visual vs. auditory), feature dimension (ear vs. sex), transition (feature-switch vs. feature-repetition), and CSI (400 ms vs. 800 ms). Cousineau-Morey confidence intervals are provided in parentheses (Morey, 2008).

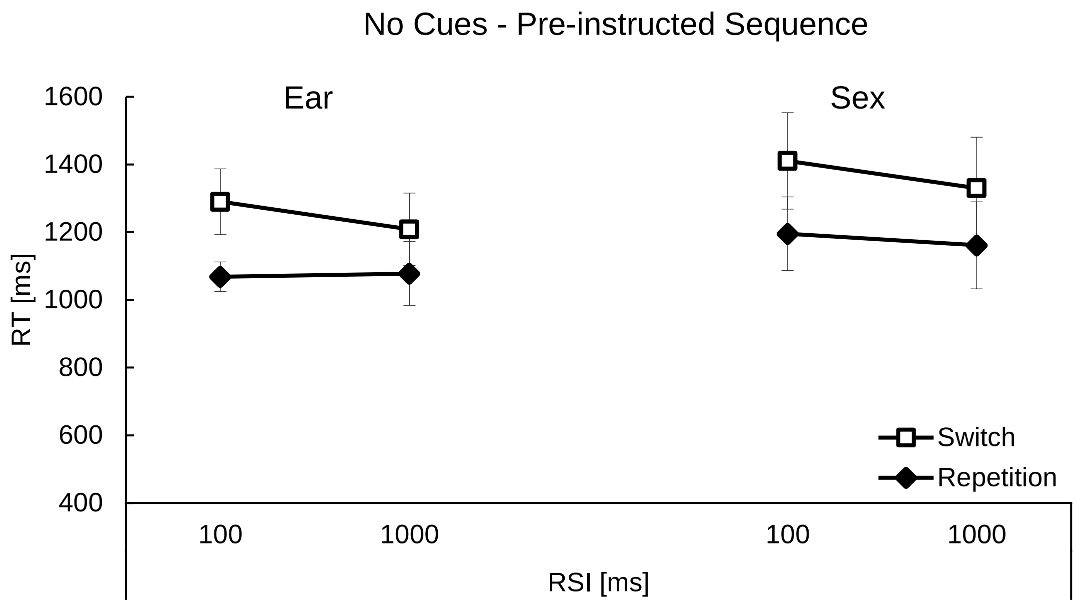


*Figure 3.* RT data of Experiment 3 as a function of feature dimension (ear vs. sex), transition (feature-switch vs. repetition), and RSI (100 ms vs. 1000 ms). Error bars reflect Cousineau-Morey confidence intervals (Morey, 2008).

Table 3

*PE data of Experiment 3*

| | Feature Dimension | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Ear-Sequence | | | | Sex-Sequence | | | |
| | RSI [ms] | | | | | | | |
| Transition | 100 | | 1000 | | 100 | | 1000 | |
| Switch | 12.4 | (±2.4) | 13.0 | (±2.2) | 13.0 | (±2.6) | 12.0 | (±3.0) |
| Repetition | 8.9 | (±2.8) | 8.9 | (±2.1) | 8.1 | (±2.1) | 8.2 | (±2.9) |

*Note*. PE [%] as a function of feature dimension (ear vs. sex), transition (feature-switch vs. feature-repetition), and RSI (100 ms vs. 1000 ms). Cousineau-Morey confidence intervals are provided in parentheses (Morey, 2008).

**Corrigendum A.c**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018).

*Corrigendum: Intentional preparation of auditory attention-switches: Explicit cueing and sequential switch-predictability.*

Manuscript submitted for publication.

# Corrigendum to: “Intentional Preparation of Auditory Attention-Shifts: Explicit Cueing and Sequential Shift-Predictability”

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In our article, we presented evidence from three experiments suggesting that preparatory reductions of the performance costs of auditory attention switching occur only to a very limited degree. In Experiment 1 and 2, we manipulated preparation by varying the interval between the cue indicating the attentional selection criterion and the target (cue-stimulus interval, CSI) and reported no preparatory reduction of attention switch costs, confirming previous findings from our lab. We found a clear switch-specific preparation effect only if attention switches are fully predictable based on a fixed sequence of attention switches (Experiment 3). Unfortunately, the original version of our article contained an error in Experiment 1 and Experiment 2. Namely CSI and response-cue interval (RCI) were inversely varied (as intended), but due to a programming error this referred to CSI and RCI across trials rather than within one trial. Thus, a short CSI always led to a subsequent long RCI (or a long CSI to a short RCI). This led to three-different possible response-stimulus interval (RSI) lengths (i.e., RCI+CSI: short + short [short], short + long [medium], long + short [medium], long + long [long]). That is, due to this programming error, the influence of the CSI manipulation was in fact not separable from RSI effects. Hence, we conducted a re-analysis of the data using only those 50% of the trials with medium RSI, in which the effect of CSI manipulation could be assessed independently from that of RSI (i.e., short/long RCI+ CSI vs. long/short RCI + CSI). To anticipate, the results of the re-analyses confirm the interpretation reported in the article. Even though we found a hint at a preparatory reduction in the RT (but not in the error rates) of Experiment 1 in one of the feature dimension conditions (i.e., with ear cues), this effect was actually even numerically reversed the other condition (sex cues), and the preparatory reduction of switch costs with ear cues could not be replicated in Experiment 2.

Specifically, for the re-analyses we found the following results. In the RT data of Experiment 1, the three previously obtained effects of transition (attention switch vs. repeat), $F(1, 19) = 21.82$, $p < .001$, $\eta_p^2 = .54$, CSI (short vs. long), $F(1, 19) = 65.66$, $p < .001$, $\eta_p^2 = .78$, and the interaction of feature dimension (ear cues vs. sex cues) and CSI, $F(1, 19) = 24.30$, $p < .001$, $\eta_p^2 = .89$, were confirmed. It is new that the three-way interaction of transition, CSI, and feature dimension was significant, $F(1, 19) = 6.39$, $p = .020$, $\eta_p^2 = .25$. In the ear-cue blocks, there was a numerical preparatory reduction of switch costs of 34 ms, $F(1, 19) = 1.23$, $p = .280$, $\eta_p^2 = .06$, whereas this effect was even reversed in the sex-cue blocks (i.e., a preparatory *increase* of switch costs, 52 ms), $F < 1$. All other RT effects were non-significant, *F*s <1. The analysis of the error rates revealed an interaction of feature dimension and CSI, $F(1, 19) = 8.40$, $p = .009$, $\eta_p^2 = .31$. All other effects were non-significant, $F$s $< 3.3$, $p$s $> .085$.

In Experiment 2, transition, $F(1, 23) = 15.55$, $p = .001$, $\eta_p^2 = .40$, CSI, $F(1, 23) = 59.62$, $p < .001$, $\eta_p^2 = .72$, and cue modality (visual vs. auditory), $F(1, 23) = 19.56$, $p < .001$, $\eta_p^2 = .46$, elicited significant main effects. Cue modality and CSI interacted, $F(1, 23) = 16.91$, $p < .001$, $\eta_p^2 = .42$, as well as cue modality and transition, $F(1, 23) = 4.37$, $p = .048$, $\eta_p^2 = .16$, and marginally also cue modality and feature dimension, $F(1, 23) = 3.72$, $p = .066$, $\eta_p^2 = .14$. All other effects were non-significant, $F$s $< 2.2$, $p$s $> .15$. Most notably, the interaction of transition and CSI, and the three-way interaction with CSI, which was previously significant, were now clearly non-significant, $F$s $< 1$.

In the analysis of the PE, the main effects of transition, $F(1, 23) = 59.62$, $p < .001$, $\eta_p^2 = .72$, and cue modality, $F(1, 23) = 5.37$, $p$ .030, $\eta_p^2 = .19$, were obtained, as well as a trend for an interaction of feature dimension and transition, $F(1, 23) = 3.82$, $p = .063$, $\eta_p^2 = .14$. All other effects were non-significant, $F$s $< 2.9$, $p$s $> .10$, including those containing both, transition and CSI, $F$s $< 1$, as well as the four-way interaction, $F < 1.9$; $p > .17$.

In summary, the re-analyses of the subset of trials that allowed an unconfounded assessment of CSI manipulations (i.e., of cue-based preparation effects) largely confirms our previous conclusions of only limited preparatory reductions of switch costs. We would like to emphasize that the variation of CSI was completely independent of that of the other independent variables, so that our correction refers only to the effects of CSI in Experiment 1 and 2 (the data of Experiment 3 are not affected because of a block-wise manipulation of the CSI). We apologize for the programming error leading to incorrect analyses of CSI effects of Experiment 1 and 2 in our original article. The general conclusion of our article can still be maintained.

**Study B**

Seibold, J. C., Nolden, S., Oberem, J., Fels, J., & Koch, I. (2018b).

Auditory attention switching and judgment switching – exploring multicomponent task representations.

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Auditory Attention Switching and Judgement Switching – Exploring multi-component Task Representations


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ABSTRACT

An auditory attention switching paradigm was combined with a judgement switching paradigm in order to examine the interaction of a varying auditory attention component and a varying judgement component. Participants heard two dichotically presented stimuli - one spoken by a female speaker and one spoken by a male speaker. In each trial, the stimuli were a spoken letter and a spoken number. A visual explicit cue at the beginning of each trial indicated the auditory attention criterion (speaker sex / ear) to identify the target stimulus (Experiment 1) or the judgement that had to be executed (Experiment 2). Hence, the attentional selection criterion switched independently between speaker sexes (or between ears), while the judgement alternated between letter categorization to number categorization. The data indicate that auditory attention criterion and judgement were not processed independently, regardless of whether the attention criterion or the judgement was cued. The partial repetition benefits of the explicitly cued component suggested a hierarchical organization of the auditory attention component and the judgement component within the task set. We suggest that the hierarchy arises due to the explicit cueing of one component rather than due to a "natural" hierarchy of auditory attention component and judgement component.

Studies showed that switching between different judgements is costly in terms of reaction times and error rates. Such judgement switch costs are usually measured as the performance difference between judgement repetition trials and judgement switch trials and are supposed to represent at least partly the additional time required for judgement reconfiguration in a switch trial (i.e., the costs; Jersild, 1927; for reviews see Kiesel et al., 2010; Koch, Poljac, Müller, & Kiesel, 2018; Vandierendonck, Liefooghe, & Verbruggen, 2010). Yet, in the present study, we want to look at the difference between switch and repetition performance from an episodic retrieval perspective. Namely, we want to emphasize that the relative benefits presumably arising from episodic retrieval in judgement repetitions may as well contribute to the performance differences score. Therefore, we use performance in judgement switches as a baseline (see similar ways of reporting task-switching data also in Dreisbach, Haider, & Kluwe, 2002; Koch, 2001, 2005; Oberauer et al., 2013; Ruthruff, Remington, & Johnston, 2001; Schmidt & Liefooghe, 2016; Wylie, & Allport, 2000).

In many studies, more than just one component of the “task set” alternates between trials. As an example, Vandierendonck, Christiaens and Liefooghe (2008) used a cued switching paradigm in which an additional cue indicated whether participants had to perform a judgement (parity judgement or magnitude judgement) on the global or local dimension of visual global-local number stimuli (e.g. the global number 4, which was locally composed of small digits that either corresponded or did not correspond to the number at the global dimension). Thus, in every trial a repetition (or switch) of the judgement, but also a repetition (or switch) of the stimulus dimension could occur. The resulting interaction of those two varying components suggests that they were not processed independently (see similar findings with different components in e.g., Allport, Styles, & Hsieh, 1994; Hahn, Anderson, & Kramer, 2003; Hübner, Futterer, & Steinhauser, 2001; Kleinsorge & Heuer, 1999; Kleinsorge, 2004; Kleinsorge, Heuer, & Schmidtke, 2001; Kleinsorge, Heuer & Schmidtke, 2002; Murray, De Santis, Thut, & Wylie, 2009; Philipp & Koch, 2010; Sandhu & Dyson, 2013). The pattern of the interaction of judgement component and stimulus dimension component in Vandierendonck et al.’s (2008) was very similar to that of other multi-component switching studies and will be described using performance in complete switches (judgement switch and stimulus dimension switch) as a baseline.

Typically, large performance benefits are obtained in complete repetitions (judgement and stimulus dimension repeat). In partial judgement repetitions (judgement repetition and stimulus dimension switch) and partial stimulus dimension repetitions (judgement switch and stimulus dimension repeat) small repetition benefits for the repeating components are often obtained (see Figure 1 for an exemplary interaction pattern of two switching components).

We always used the term *component* so far, when taking about, e.g. the varying stimulus dimension of Vandierendonck et al.'s (2008) setup. The term was employed since we consider stimulus dimension and the judgement components of a "task set", which, according to Oberauer, Souza, Druey and Gade (2013), is a set of bindings between representations of stimuli, instructed rules, responses, and goals associated with each other. It is assumed that in every trial, updating processes are run for those features of the task set that change, like the stimulus or the whole "subset" of judgement demands. The consistently observed large repetition benefits in complete repetitions and the small benefits in partial repetitions indicate that parts of the previous trial's episode can be re-used (see similar idea of episodic event file retrieval in Hommel, Proctor, & Vu, 2004).

We think these small, yet often persistent repetition benefits in partial repetitions can tell us more about how the components are related within the proposed task set. Partial repetition benefits were not discussed extensively in previous studies on multi-component switching, although they were obtained quite frequently (for repetition benefits in partial repetitions see e.g., Hahn et al., 2003; Kieffaber, Kruschke, Cho, Walker & Hetrick, 2013; Philipp & Koch, 2010; Rangelov et al., 2013). In the following, we will describe two prominent accounts of multi-component switching and suggest how they could explain the partial repetition benefits.

Vandierendonck et al. (2008) suggested that as soon as any mismatch (i.e., a component switches) is detected in the current trial, all parts of the task set get updated. Hence, performance in partial repetitions and complete switches should be very similar – that is, a *flat* interaction pattern should be present and partial repetition benefits should always be small and nonsignificant (see such patterns in e.g., Philipp & Koch, 2010; Rangelov et al., 2013; Vandierendonck et al., 2008).

Alternatively, Kleinsorge and Heuer (1999) and Kleinsorge (2004) proposed that the components are *hierarchically* organized within the task set. The component hierarchy causes that a switch of a higher-level component facilitates a switch of the lower-level component, but not vice versa. By that, findings can be explained in which reaction times (RT) were even shorter in complete switches than in partial repetitions, aside from the findings of similar RT and findings of slightly higher RT in complete switches. Namely, the higher-level component creates a switch bias for the lower-level component, although the lower-level component is supposed to repeat (e.g., Kleinsorge & Heuer, 1999; Kleinsorge, 2004; and for partial response repetitions, e.g., Altmann, 2011). Hence, the switch bias for the lower-level component needs to be overcome to perform the lower-level repetition and select the correct response. Specifically, for partial repetitions, the hierarchical account implies that a higher-level component repetition benefit should be present despite a lower-level component switch. In contrast, a lower-level partial repetition should not elicit a repetition benefit and might even incur costs.

The component hierarchy was proposed based on the observation that judgement switches were dominant to stimulus dimension switches (Kleinsorge, 2004) and dominant to response mapping switches (Kleinsorge & Heuer, 1999). It was argued that the judgement is dominant because the participant communicated the judgement's results by the responses. However, it is not clear whether this claim would generalizes to other components and whether also the fact that both components were cued simultaneously in the studies of Kleinsorge and Heuer (1999) and Kleinsorge et al. (2001, 2002) contributed to the result pattern. For example, Philipp and Koch (2010) found that the sequential cueing (early and late in the CSI) of a judgement component and a response modality component modulated the interaction pattern at least numerically.

In the present study, the variations of performance in partial repetitions are examined, since they could provide information about whether the partial repetition benefits in performance occur systematically, or whether they are unsystematic and indicate a flat component representation. Moreover, the majority of the previous multi-component switching studies used visual stimulus material or at least partly visual stimuli (e.g. in stimulus modality switching experiments: Hunt & Kingstone, 2004; Sandhu & Dyson, 2013). We therefore intended to replicate the interaction of switching components in an auditory paradigm, as there is some evidence that visual and auditory perception and processing differ in terms of object formation and spatial resolution (e.g., Bertelson, & Aschersleben, 2003; for a review on auditory attention, see Shinn-Cunningham, 2008).

Thus, an auditory multi-component switching paradigm was applied. The instructed task set contained an auditory attention component (Koch, Lawo, Fels, & Vorländer, 2011; based on a dichotic listening task like in Cherry, 1953; Morey, 1959; for reviews see Bronkhorst, 2015; Shinn-Cunningham, 2008) and a judgment component (e.g., Rogers & Monsell, 1995), which both alternated independently between trials. The setup looked as follows: Two simultaneously spoken stimuli were presented via headphones – one stimulus per ear. One of the stimuli was always spoken by a female speaker, the other was spoken by a male speaker. A cue in the beginning of each trial indicated whether the participant had to attend to the female or male speaker in the upcoming stimulus pair (attention component). The two spoken stimuli were a letter and a number in each trial (judgement component). Whenever the attention target was a letter, the participant had to decide whether this letter was a consonant or a vowel. Whenever the target was a number, the participant needed to decide whether the number was even or odd. This means that the attention target was explicitly indicated by the cue, whereas the target's category (letter or number) and thereby the judgement was cued implicitly. Namely, the judgement needed to be identified based on the type of the selected target. It was not predictable based on the attention cue which judgment was required so that the participants could not actively prepare for a specific judgement, unlike in other multi-component switching studies, in which both components were explicitly cued (e.g., Kleinsorge, 2004; Philipp & Koch, 2010; Vandierendonck et al., 2008).

## Experiment 1

In Experiment 1, the main goal was to explore whether the varying attention component and the independently varying judgement component interact in our auditory paradigm. Furthermore, an earlier study on auditory attention switching compared performance with speaker sex cues to that of blocks with ear cues and found larger attention repetition benefits with ear cues (Lawo, Fels, Oberem & Koch, 2014). These were attributed to high spatial inertia of auditory attention (see also Best, Ozmeral, Kopco & Shinn-Cunningham, 2008; Best, Shinn-Cunningham, Ozmeral & Kopco, 2010, for demonstrations of auditory spatial inertia). In order to see whether such spatial inertia could also modulate the expected interaction of attention component and judgement component in the present study, we compared performance in an experimental block with speaker-sex cueing to performance in a block with ear cueing.

### Methods

**Participants.** Earlier studies on multi-component switching used sample-sizes of less than twelve participants (Hübner et al., 2001; Kleinsorge, 2004; Kleinsorge, & Heuer, 1999), but more studies on the topic used higher sample sizes of 20 to 24 participants (Kleinsorge et al., 2002; Philipp, & Koch, 2010; Vandierendonck et al., 2008). Hence, we decided to follow along these lines by testing 24 participants, which were students (19 women) from the RWTH Aachen University. They were aged between 19 and 35 years ($M$ = 23.9, $SD$ = 3.8) and received partial course credit or 8 € for their participation. Hearing problems were detected neither in the self-report nor in an audiogram that was conducted on a Maico MA33 audiometer.

**Apparatus and stimuli.** The experiment was developed in PsychoPy 2.0 (Peirce, 2008) and run under Linux. The auditory stimuli were the spoken number-words from 1 to 9, except for 5, with an adjusted duration of 600 ms. Aside from the number-words, the spoken vowels A, E, I, U and consonants G, K, M, R with an adjusted duration of 400 ms were used as stimuli. All stimuli were recorded at the Institute of Technical Acoustics of the RWTH Aachen University in an anechoic chamber from one male and one female speaker, respectively. The stimulus material was also adjusted for subjective loudness (DIN 45613). The stimuli were presented via headphones (Sennheiser PMX 95) in dichotic pairs, of which one stimulus was spoken by a male speaker and the other stimulus was spoken by a female speaker. Each stimulus pair consisted of one letter and one number (e.g., A7).

A visual cue at the beginning of each trial indicated the criterion for the target selection. The cue (height 4 cm; average width: 8.2 cm) was presented in black color in the center of a white screen of a 22-inch computer monitor (LG 22MB65PM). We used a 2:1 cue-to-attention-criterion mapping and the experimental program did not allow for direct cue repetitions, to avoid visual cue repetition priming and isolate the effects of component repetition priming (Lawo et al., 2014; Koch & Lawo, 2014; Seibold, Nolden, Oberem, Fels, & Koch, 2017). In the speaker-sex cueing block, a female speaker was either cued by the German word "Frau" (German for "woman") or the symbol "♀", whereas a male speaker was either cued by the word "Mann" ("man") or the symbol "♂". In the ear cueing block, the German word "links" ("left") or the symbol of a leftwards pointing arrow indicated that the target would be presented to the left ear and the word 'rechts' ('right') or the symbol of a rightwards pointing arrow indicated a target presentation to the right ear.

The participants were seated at about 70 cm viewing distance from the monitor and were instructed to press left and right arrow keys on a German computer keyboard (QWERTZ) with the index fingers of their left and right hand. Whenever the selected target stimulus was a letter, the participants were asked to classify the letter by pressing either the left or right key for a vowel or a consonant. Whenever the selected target stimulus was a number, the participants were asked to classify the number by pressing either left or right key for an even or an odd number. The S-R mappings were counterbalanced between participants.

**Procedure.** The experiment started with a questionnaire asking for age, gender, hearing, and visual impairments. It was followed by a hearing sensitivity test, and by the experimental instructions on the computer screen. The experiment consisted of two blocks with 256 trials each, resulting in 512 experimental trials. In one of the two blocks, participants had to attend to the cued speaker sex to select the target stimulus, whereas in the other block they had to attend to the cued left or right ear. Both experiment halves were preceded by a short practice block that consisted of 16 trials each and the order of the halves was counterbalanced between participants. The experimental session took approximately 60 minutes.

In the beginning of each trial, a cue appeared and after a CSI (cue-stimulus interval) of either 100 ms or 1000 ms the stimuli were presented via headphones. The CSI varied randomly on a trial-by-trial basis. The cue stayed on the screen until a response was given, and the response was followed by a RCI (response-cue interval) of either 1100 ms or 200 ms, which was varied inversely to the previous CSI duration.[5] In case of an incorrect response, the word 'Fehler' (German for 'error') was printed in red on the screen for 500 ms immediately after the response, lengthening the RCI (see Figure 2 for an illustration).

**Design.** The independent variables were attention transition (repetition vs. switch), judgement transition (repetition vs. switch), and cueing dimension (speaker sex vs. ear cueing; block-wise). The dependent variables were reaction times (RT) and percentage of errors (PE).

**Results and discussion**

For the analysis, we excluded the first trial of each block, and all trials following on an error (9.1%). For the analysis of the RT, we additionally excluded all RT outlier trials above three standard deviations from a participant's mean RT (1.8%), as well as all erroneous trials (8.8%). We conducted separate analyses of variance (ANOVA) for repeated measurements for RT and PE.

The analysis of the RT revealed a main effect of attention transition, $F(1, 23) = 39.42$, $p < .001$, $\eta_p^2 = .63$, with attention repetition benefits of 122 ms, and a main effect of judgement transition, $F(1, 23) = 15.49$, $p = .001$, $\eta_p^2 = .40$, with judgement repetition benefits of 64 ms. Attention transition and judgement transition also interacted, $F(1, 23) = 4.78$, $p = .039$, $\eta_p^2 = .17$.

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[5] Please note that this was a programming error, which led to three-different possible RSI (response stimulus interval) lengths (i.e., RCI+CSI: 200+100, 200+1000, 1100+100, 1100+1000), since a CSI always determined the length of the subsequent RCI in a sequence of trials. Therefore, the effect of the CSI manipulation cannot be separated from RSI effects. Hence, we refrain from an analysis and interpretation of the CSI effects in terms of active preparation. However, the temporal intervals were manipulated entirely independently from cueing dimension, attention transition, and task transition, so that the effects of these latter variables can still be interpreted.

Repetition benefits of 186 ms, $t(23) = 6.93$, $p < .001$, were found in complete repetitions relative to complete switches. In partial attention repetitions, RT benefits of 96 ms were found, $t(23) = 4.51$, $p < .001$, and in partial judgement repetitions benefits of 39 ms were obtained, $t(23) = 2.80$, $p = .010$. The manipulation of cueing dimension did not elicit any reliable effect, *F*s < 3.0, *p*s > .10 (see also Figure 3 and Table 1).

The analysis of the percentage of errors confirmed the RT pattern. A main effect of attention transition was present, $F(1, 23) = 8.76$, $p = .007$, $\eta_p^2 = .28$, with attention repetition benefits of 1.8%. Judgement transition also elicited a main effect, $F(1, 23) = 12.60$, $p = .002$, $\eta_p^2 = .35$, with judgement repetition benefits of 3.3%. Attention transition and judgement transition also interacted, $F(1, 23) = 6.71$, $p = .016$, $\eta_p^2 = .23$. With respect to complete switches, repetition benefits of 5.5% were present in complete repetitions, $t(23) = 4.09$, $p < .001$, while partial attention repetitions led to a nonsignificant benefit of 0.3%, $t(23) = 0.34$, $p = .740$, and partial judgement repetitions to a benefit of 1.8%, $t(23) = 1.94$, $p = .065$. Cueing dimension did not elicit any significant effect, *Fs* < 1.6, *ps* > .22.

In summary, we obtained attention repetition benefits and judgement repetition benefits as well as an interaction of both independently varying components. We propose that the interaction indicates that processing of the components was not independent. Moreover, the component processing was not affected by whether the cues indicated the speaker-sex of the target presentation, or the ear. Thus, the interaction seems to arise on a non-perceptual, supposedly more abstract level.

Like earlier studies, we obtained partial repetition benefits for both components, which were at best slightly more pronounced for partial attention repetitions than for partial judgement repetitions. This speaks against a flat component representation of the varying components and might indicate a hierarchical representation, in which the attention component is at a higher level than the judgement components. However, so far, the possibility remains that the component processing was independent, and the interaction just arose because a cost of coordination occurred when both components are processed in parallel (see componential account by Hübner et al., 2001, discussed by Vandierendonck et al., 2008). This account can explain partial repetition benefits and predicts that the highest RT and error rates should be obtained in complete switches.

## Experiment 2

As we stated above, a hierarchical component representation should elicit larger partial repetition benefits for the higher-level component than for the lower-level component, which was at least numerically the case for the attention component in Experiment 1. Yet, since it is unclear how such a hierarchy would arise within the task set, we wanted to put two possibilities to the test, which were similarly suggested by Kleinsorge (2004). One option is that a hierarchy of attention component and judgement component arises due to a "natural" hierarchy of attention criteria and judgements. The other option is that a hierarchy arises due to the trial structure that we used, in which only one component was cued explicitly and therefore possibly became dominant, while the other was only implicitly indicated by the target itself.

Thus, we used a similar setup as in Experiment 1, but we exchanged the ear-cueing block by a block in which the judgement was cued in order to compare the attention cueing block (speaker sex cueing) to a judgement cueing block. In case of a "natural" hierarchy of attention component and judgement component, the result pattern should be similar in the attention cueing block and in the judgement cueing block – and the interaction pattern should resemble to that of Experiment 1. Alternatively, when the hierarchy depends on which component is cued explicitly, we would expect a modulation of the interaction of the two varying components by the cue type (attention cueing vs. judgement cueing), which should show up as the three-way interaction of cue type, attention transition, and judgement transition.

Technically, the introduction of the judgement cueing block required an extension of the mapping-rules. When cueing the judgement, attention switches (i.e., speaker sex switches) would be entirely irrelevant for response selection. In contrast, in the attention cueing block, speaker sex and judgement are both relevant for response selection, since the target judgement could only be identified when participants listened to the speaker sex indicated by the cue. Thus, to make speaker sex similarly relevant for response selection in the judgement cueing block as it was already in the attention cueing block, a speaker sex response rule was added: When the target was spoken by a male speaker, participants had to respond with two response keys operated by their left hand, whereas when the target was spoken by a female speaker, participants had to press keys operated by right hand.

### Method

**Participants.** A new group of 24 German-speaking students (19 women) from the RWTH Aachen University, aged between 18 and 25 years (*M* = 21.3, *SD* = 2.3), took part and received partial course credit or 12€ (8 € per hour) for their participation in the experiment.[6] The participants were right-handed, except for two left-handers. Hearing problems were detected neither in the self-report, nor in an audiogram, which was conducted on a Maico MA33 audiometer.

**Apparatus and stimuli.** The apparatus and stimuli were the same as in Experiment 1, except for a change in the stimulus letter set from "G" to "L", to avoid confusions of "G" and "E", which participants reported in Experiment 1. The visual cue (height and average width: 3.2 cm and 11.9 cm) at the beginning of a trial indicated the target speaker's sex in the attention cueing blocks (like in Experiment 1), or the judgement (letter or number) in the judgement cueing blocks. This time, a 1:1 cue-to-target mapping was used to reduce the complexity the setup: for the attention cueing blocks, a female speaker was cued by the German word "Frau" (German for "woman"), whereas a male speaker was cued by the word "Mann" ("man"). For the judgement cueing blocks, the German word "Zahl" ("number") indicated that the target would be the number word, and the word "Buchstabe" ("letter") cued the letter word.

Due to the new response rule that was supposed to make the target speaker's sex similarly relevant for response selection in the judgement cueing block like it was in the attention cueing block, participants were instructed to respond with their left hand when the target was presented by a male speaker, whereas a female target speaker required a right hand response. Within the hands, the response-key mapping remained bivalent and was congruent between the two hands. In detail, participants were instructed to press the *Y*, *X*, *N* and *M* keys on a German computer keyboard (QWERTZ) with the index and middle fingers of their left and right hands, respectively. To help participants deal with the more complex mapping situation in this experiment, a small diagram of the response-key assignment was placed below the screen as a memory aid.

**Procedure.** The experimental procedure was like in Experiment 1, since the temporal intervals, the number of blocks, and trials remained the same as in the previous experiment. The attention cueing block and the judgement cueing block were preceded by a short practice block

[6] To see whether we had to change the sample size of Experiment 2 that was needed to replicate the interaction of attention transition and task transition, we conducted a post-hoc power analysis for the critical interaction based on the mean RTs of Experiment 1. A Monte Carlo Simulation of a 2x2 repeated measurements ANOVA with sample size, means, standard deviations, and within-participant mean correlations based on the data of Experiment 1 was conducted in R. The simulation was run 1000 times and in 98.7% of the runs, a significant interaction was present. Hence, we decided to stick to the sample size of 24.

that consisted of 16 trials, respectively, and the starting block was counterbalanced between participants. The experimental session took approximately 80 minutes.

**Design.** Independent variables were attention transition (repetition vs. switch), judgement transition (repetition vs. switch), and cue type (attention cueing vs. judgement cueing). The dependent variables were RT and PE.

**Results and discussion**

Like in Experiment 1, the first trial of each block, as well as trials directly following on an error (6.3%) were excluded from the analyses. For the analysis of the RT, all erroneous trials were also excluded as well as RT outliers (1.7%).

The analysis of the RT revealed a main effect of attention transition, $F(1, 23) = 51.27$, $p < .001$, $\eta_p^2 = .69$, with attention repetition benefits of 139 ms, and a main effect of judgement transition, $F(1, 23) = 48.47$, $p < .001$, $\eta_p^2 = .68$, with judgement repetition benefits of 138 ms. Attention transition and judgement transition interacted, $F(1, 23) = 56.96$, $p < .001$, $\eta_p^2 = .17$. A repetition benefit of 276 ms was found in complete repetitions with respect to complete switches. In partial attention repetitions, the repetition benefit was 23 ms, and in partial judgement repetitions it was 22 ms.

The manipulation of cue type led to a main effect, $F(1, 23) = 58.90$, $p < .001$, $\eta_p^2 = .72$, since RT were 248 ms shorter in the attention cueing block than in the judgement cueing block. Cue type, furthermore, modulated the attention repetition benefits, $F(1, 23) = 32.31$, $p < .001$, $\eta_p^2 = .58$, and the judgement repetition benefits, $F(1, 23) = 43.85$, $p < .001$, $\eta_p^2 = .66$, respectively. Namely, the attention repetition benefits were 117 ms larger in the attention cueing block than in the judgement cueing block, whereas the judgement switch costs were 126 ms larger in the judgement cueing block than in the attention cueing block. Also the three-way interaction was significant, $F(1, 23) = 10.65$, $p < .001$, $\eta_p^2 = .32$. Broken down by cueing sequence, the interaction of attention transition and judgement transition was significant in the attention cueing block, $F(1, 23) = 10.18$, $p = .001$, $\eta_p^2 = .31$, and in the judgement cueing block, $F(1, 23) = 82.89$, $p < .001$, $\eta_p^2 = .78$. In the attention cueing block, repetition benefits of 272 ms were obtained in complete repetitions, $t(23) = 7.14$, $p < .001$, with respect to complete switches. The partial attention repetition benefits had a size of 125 ms, $t(23) = 3.65$, $p = .001$, and the partial judgement repetitions revealed nonsignificant benefits of 27 ms, $t(23) = 0.95$, $p = .925$. In the judgement cueing blocks, complete repetitions elicited RT benefits of 281 ms, $t(23) = 8.03$, $p < .001$. Partial attention repetitions led to repetition costs (i.e., negative benefits) of 78 ms, $t(23) = -3.47$, $p = .002$, and partial judgement repetitions elicited nonsignificant benefits of 43 ms, $t(23) = 1.69$, $p = .104$.

The analysis of the error rates also revealed a main effect of attention transition, $F(1, 23) = 5.70$, $p = .026$, $\eta_p^2 = .20$, with attention repetition benefits of 1.2%. Likewise, a main effect of judgement transition was obtained, $F(1, 23) = 19.56$, $p < .001$, $\eta_p^2 = .46$, with judgement repetition benefits of 1.9%. Attention transition and judgement transition interacted, $F(1, 23) = 15.04$, $p = .001$, $\eta_p^2 = .40$. With respect to complete switches, repetition benefits of 3.2% were obtained in complete repetitions. Partial attention repetitions elicited costs of 0.7%, and partial judgement repetitions elicited benefits of 0.1%.

The main effect of cue type was significant, $F(1, 23) = 18.17$, $p < .001$, $\eta_p^2 = .44$, since error rates were 2.3% lower in the attention cueing blocks than in the judgement cueing blocks. Cue type also entered into the three-way interaction with attention transition and judgement transition, $F(1, 23) = 11.70$, $p = .002$, $\eta_p^2 = .34$. Broken down by cueing sequence, the interaction of attention transition and judgement transition was significant in the attention cueing block, $F(1, 23) = 6.06$, $p = .022$, $\eta_p^2 = .21$, and in the judgement cueing block, $F(1, 23) = 17.91$, $p < .001$, $\eta_p^2 = .44$. In the attention cueing block, complete repetitions elicited benefits of 2.5%, $t(23) = 3.24$, $p = .004$, with respect to complete switches. Partial attention repetitions led to nonsignificant benefits of 0.1%, $t(23) = 0.01$, $p = .994$, and partial judgement repetitions to nonsignificant benefits of 0.4%, $t(23) = 0.01$, $p = .510$. In the judgement cueing block, repetition benefits of 3.8% were obtained in complete repetitions, $t(23) = 4.58$, $p < .001$. In partial attention repetitions, repetition costs (i.e., negative benefits) of 1.4% were obtained, $t(23) = -1.42$, $p = .169$, and in partial judgement repetitions, repetition costs of 0.4% were present, $t(23) = -0.47$, $p = .644$. The other interactions were nonsignificant ($F$s < 1.9, $p$s > .190; see also Figure 2 and Table 1).

In sum, significant attention repetition benefits and judgement repetition benefits were again obtained. Please note that the repetition benefits could be slightly inflated relative to Experiment 1, due to the 1:1 cue-to-judgement mapping. More importantly, the interaction of the two switching components was replicated in Experiment 2, which may indicate that the auditory attention component and the judgment component were not processed independently. The cue type manipulation was successful, since in the attention cueing blocks the partial attention repetition benefits were larger than the partial judgement repetition benefits, whereas this was reversed in the judgement cueing blocks. In the latter, partial attention repetitions even elicited costs. Hence, the explicitly cued component elicited larger partial repetition benefits than the implicitly cued component, which suggests that the presumed integration of switching components into a task set depended on the cueing order rather than on a “natural” hierarchy of auditory attention component and judgement component.

## General Discussion

In this study, a novel auditory multi-component switching paradigm was used, which employed a combination of an auditory attention switching paradigm (Koch et al., 2011) and a judgement switching paradigm (e.g., Rogers & Monsell, 1995). The main aim was to examine whether and how an auditory attention component and a judgement component are integrated into a task set.

The results of the two experiments indicate that the attention component and the judgement component were not processed independently. Namely, besides auditory attention repetition benefits and judgement repetition benefits, the attention component and the judgement component interacted. When the cue indicated the auditory attention criterion, the interaction of the components revealed benefits in partial attention repetitions with respect to complete switches that were present despite the judgement switch. When the cue indicated the judgement rather than the attention criterion, larger repetition benefits were found for partial judgement repetitions, and even costs (i.e. negative repetition benefits) of partial attention repetitions. Thus, the explicitly cued component benefitted more from its repetition in subsequent trials than the implicitly cued component. The results of Experiment 1 furthermore showed that perceptual features of the attention criteria (i.e., speaker sex cues vs. ear cues for attentional target selection) did not reliably affect the interaction of the independently varying components.

The finding of an interaction of the auditory attention component and the judgement component in the present study indicates that different components were not processed independently and may be integrated into a common task set. In the following, the results are discussed with respect to different theoretical accounts of multi-component switching.

We suggest that our findings reflect a hierarchical component representation within the task set, as proposed by Kleinsorge (2004). We, furthermore, propose an extension to this account, since the hierarchy of the independently varying components seems to be determined by the cueing order in our Experiment 2. The obtained relative performance benefits of the explicitly cued component in partial repetitions imply that they could not be eliminated by the switch of the implicitly cued component. In contrast, no reliable repetition benefit was obtained for the implicitly cued component when the explicitly cued component switched. The cues seemed to have emphasized the switches of the component that they indicated, which may have created a more dominant representation of the cued component within the task set, relative to the implicitly cued component.

The results speak against the strict hierarchical account of Kleinsorge and Heuer (1999), in which higher-level component switches quasi-automatically induce lower level component switches. This mechanism would consistently lead to partial repetition costs when the higher-level component switches.

We suppose that our results are also not compatible with the predictions of a flat representation of components that was proposed by Vandierendonck et al. (2008). Namely, partial repetition benefits should not be obtained when any kind of component switch disrupts the entire episodic memory trace of the previous trial. Although the partial repetition benefits were often small and not always statistically reliable in the present study, they were consistently present in RT and at least numerically also in PE.

There are alternative explanations that also account for partial repetition benefits, which we did not outline in the introduction of this study. For example, Rangelov et al. (2013) proposed that a switch in one component leads to a more or less independent reconfiguration of the remaining subsequently processed components. For the present study's setup, this would predict that there should only be a relative benefit of a repetition of the explicitly cued component, but none of the implicitly cued component – which is in agreement with the present results. However, Rangelov et al.'s (2013) account would also predict that the longest RT and highest error rates should always be obtained in complete switches, which was not the case in the judgement cueing block of the present study.

The latter point also speaks against a componential account as introduced by Hübner et al. (2001) and was discussed by Vandierendonck et al. (2008). It was assumed that the varying components are processed independently, and that their interaction arises because an additional cost of coordination occurs in all trials containing a component switch.

Finally, we want to shortly discuss the finding that in the judgement cueing blocks, performance in complete switches was even superior to partial judgement switches. Here, participants did not know which response hand to use until the stimuli were presented. Possibly, reconfiguration of the judgement mapping could not be fully accomplished when participants did not know whether they had to link the mapping to left or right hand responses. The resulting more simultaneous reconfiguration of the judgement and the attention criterion could have led to more integrated processing of the components. This could have contributed to the more pronounced interaction pattern in this condition compared to the other conditions.

**Summary**

The present study examined the interaction of independently varying components in a setup with auditory stimuli. Replicating studies using visual stimuli, the employed auditory attention component and a judgement component interacted across different auditory selective attention criteria and across two component sequences within the trial. Hence, there seems to be an underlying mechanism in multi-component switching that causes that the varying components are not processed independently. This mechanism appears to be independent of component modalities, judgement, and perceptual features of the components. Since we obtained larger partial repetition benefits of the explicitly cued component than of the implicitly cued component, we suggest that the components were represented hierarchically within the task set, as proposed by Kleinsorge (2004), and that this hierarchy depended on the cueing order (i.e., the explicit and implicit cueing) rather than on a "natural" component hierarchy.


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## Figures and Tables

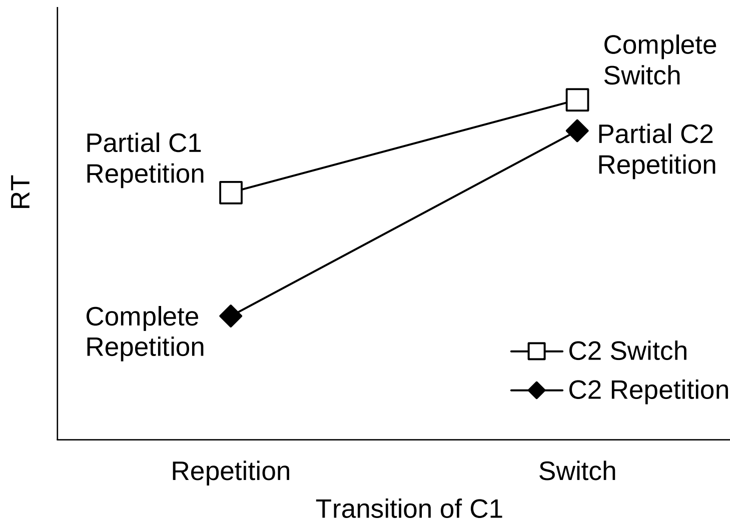


*Figure 1*. Example of the typical interaction pattern of two independently switching components (C1: component 1; C2: component 2). Four switch combinations are possible: complete repetitions, partial C1 repetitions, partial C2 repetitions, and complete switches.

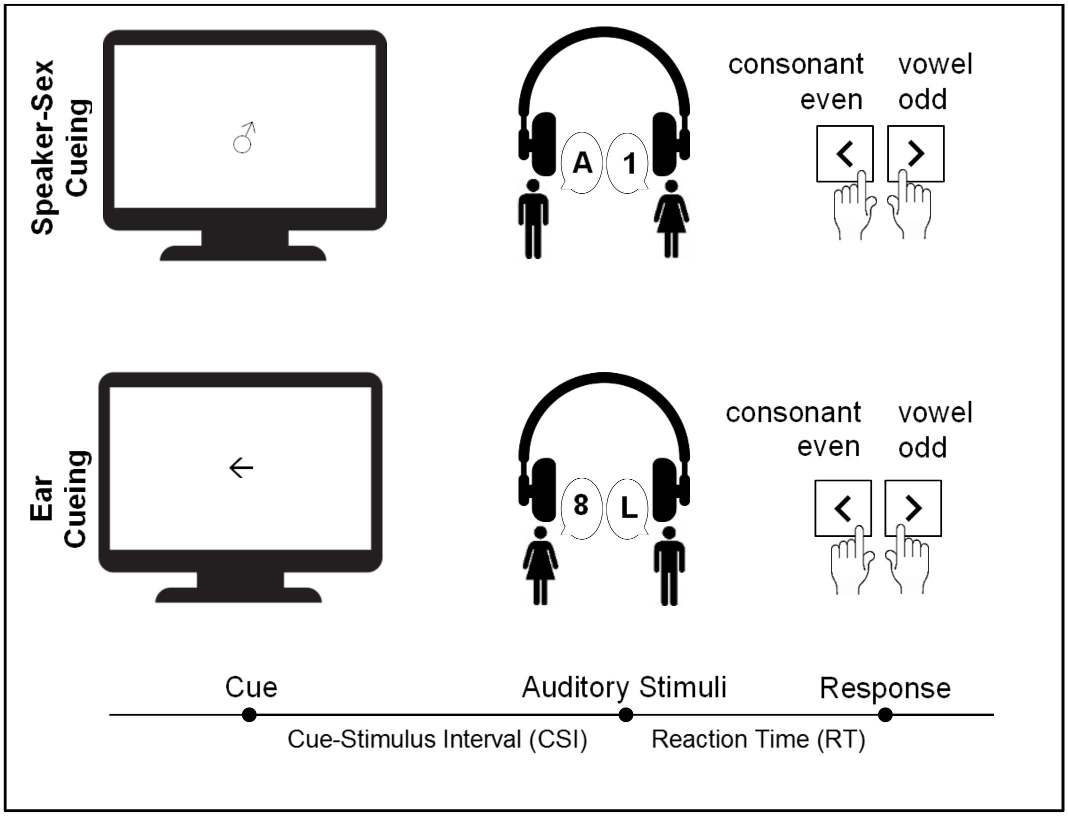


*Figure 2.* Examples of two trials from a block with ear cueing and a block with speaker sex cueing, respectively. The mapping of number and letter to left vs. right ear changed randomly from trial to trial.

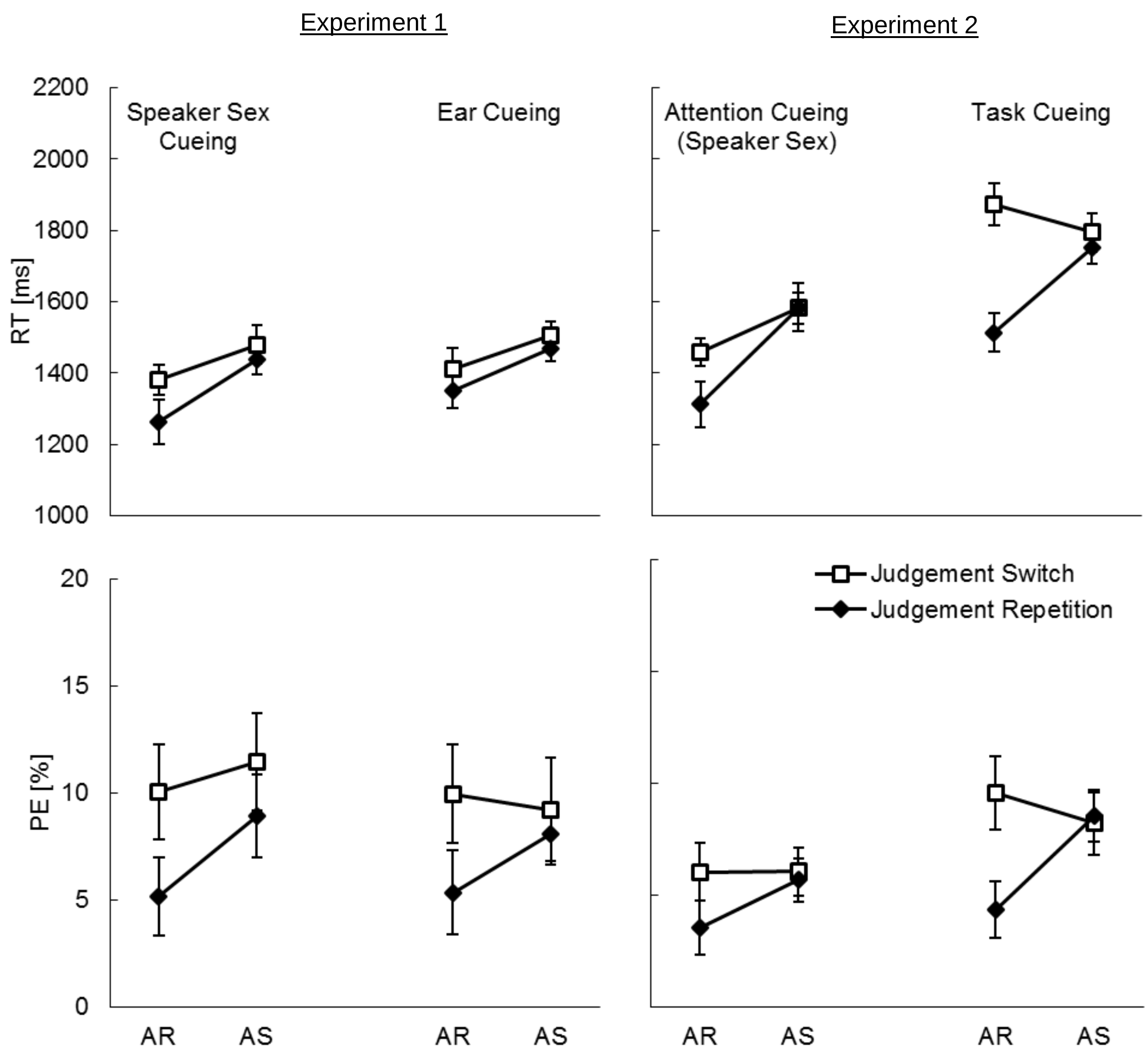


*Figure 3.* RT and PE of Experiment 1 and 2 as a function of attention transition (repetition [AR] vs. switch [AS]), judgement transition (repetition vs. switch), and cueing dimension (speaker sex cueing vs. ear cueing) in Experiment 1, which was exchanged by cue type (attention cueing vs. judgement cueing) in Experiment 2. Error bars reflect 95% Cousineau-Morey confidence intervals (Morey, 2008).

Table 1

*Mean RT and error rates.*

| | | Experiment 1 | | | | Experiment 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Speaker-Sex Cueing | | Ear Cueing | | Attention Cueing | | Judgement Cueing | |
| | | AR | AS | AR | AS | AR | AS | AR | AS |
| RT | Judgement Switch | 1380 (±42) | 1480 (±54) | 1412 (±60) | 1505 (±40) | 1460 (±38) | 1585 (±67) | 1872 (±59) | 1795 (±53) |
| | Judgement Repetition | 1262 (±62) | 1439 (±44) | 1350 (±50) | 1468 (±35) | 1313 (±65) | 1582 (±45) | 1513 (±55) | 1752 (±46) |
| PE | Judgement Switch | 10.1 (±2.2) | 11.5 (±2.3) | 10.0 (±2.3) | 9.2 (±2.4) | 6.0 (±1.2) | 6.0 (±1.1) | 10.0 (±1.7) | 8.2 (±1.4) |
| | Judgement Repetition | 5.2 (±1.8) | 8.9 (±1.9) | 5.3 (±2.0) | 8.1 (±1.4) | 3.5 (±1.2) | 5.7 (±1.0) | 4.4 (±1.2) | 8.5 (±1.4) |

Note. RT and PE of Experiment 1 and 2 as a function of attention transition (repetition [AR] vs. switch [AS]), judgement transition (repetition vs. switch), and cueing dimension (speaker sex cueing vs. ear cueing) in Experiment 1, which was exchanged by cueing type (attention cueing vs. judgement cueing) in Experiment 2. The 95% Cousineau-Morey confidence intervals (Morey, 2008) are provided in parenthesis.

## Study C

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*The binding of an auditory attention location and a judgment: A two-component switching approach.*

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# The binding of an auditory attention location and a judgement: A two-component switching approach

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ABSTRACT

In a two-component switching paradigm, in which participants switched between two auditory attention locations (attention component: left vs. right ear) and two judgements (judgement component: number vs. letter judgement), an interaction of the components was obtained. The judgement switch costs were large in attention repetitions, but small in attention switches (Seibold et al., 2018b). In previous two-component switching studies differently pronounced interaction patterns were obtained. In the present study, we explored whether the strength of the interaction pattern reflects the strength of the binding between the switching components. Specifically, we compared exogenous to endogenous attention location cueing, whether participants had explicit knowledge about the independence of attention switches and judgement switches, and whether the cue-stimulus interval for ear selection was short or long. Attention switches with auditory exogenous cues and explicit knowledge about the independence of the switching components did not affect the component interaction pattern, whereas a prolonged preparation interval did lead to a more pronounced pattern. We suggest that potential binding between attention location and judgement seems to be rather automatic and does not necessary require concurrent component processing. On the contrary, sufficient time for attention location switches during a long CSI may facilitate switches of the subsequent judgement.

*Keywords*: auditory attention, task switching, attention switching, underadditive switch costs

Daily life usually demands the management of multiple tasks and a flood of information. At any moment in time, it is important for us to separate currently relevant information from currently irrelevant information. Selective attention is a key mechanism in intentionally identifying relevant information. Yet, performance decrements in selective attention can occur when a switch of the selection criterion is required that makes previously relevant information irrelevant and vice versa. The performance decrements due to a switch in the selection criterion in comparison to an attention repetition are called attention switch costs and were reported in several studies (for auditory attention switch costs, see Koch, Lawo, Fels, and Vorländer, 2011; Lawo, Fels, Oberem & Koch, 2014; Seibold, Nolden, Oberem, Fels & Koch, 2018a; for visual attention switch costs see Logan, 2005; Longman, Lavric, Munteanu & Monsell, 2014; Longman, Lavric & Monsell, 2016; for crossmodal attention switch costs, see Kreutzfeldt, Stephan, Sturm, Willmes & Koch, 2015).

Like switching between selective attention criteria, also switching between judgements typically leads to switch costs (Jersild, 1927; Rogers & Monsell, 1995; see, e.g., Kiesel et al., 2010; Koch, Poljac, Müller & Kiesel, 2018, for reviews). Although attention switches have been studied separately in attention switching studies, there are a few studies in which attention switches and judgement switches have been distinguished and assessed within the same paradigm.

Seibold et al. (2018b) set up a switching paradigm, in which two auditory attention locations and two judgements switched randomly and independently between trials. Specifically, two simultaneously spoken stimuli were presented via headphones – one stimulus per ear. The stimuli were a spoken number and a spoken letter in each trial. A cue in the beginning of a trial indicated whether the participant had to attend to the left or right ear (attention switches between left and right ear) to identify the target in the upcoming dichotically presented stimulus pair - a technique that reliably produced auditory attention switch costs in the past (see, e.g., Koch et al., 2011; Seibold et al.,2018a). Whenever the target was a letter, a judgement about whether this letter was a consonant or a vowel, and a left or right respective key press, was required. Whenever the target was a number, participants needed to judge whether the number was odd or even and press the assigned left or right response key (judgement switches between number judgement and letter judgement).

Despite the absence of any experimental contingencies between the attention switches and the judgement switches (and repetitions), their processing was not independent. In attention repetitions (ear repetitions), large judgement switch costs were obtained, but in attention switches (ear switches), the judgement switch costs were reduced or even eliminated. In other words, when taking performance in complete repetitions as a baseline (attention location and judgement repeat), the costs of a simultaneous switch of attention location and of judgement (complete switch) were much smaller than the sum of attention switch costs and judgement switch costs as assessed in partial switch trials (judgement switch and attention repetition or vice versa). This finding resembles to those of other, so-called multi-component switching studies, in which different components (e.g. judgements, stimulus dimensions, response modalities, etc.) of a task set switch independently (e.g., Hübner, Futterer & Steinhauser, 2001; Kleinsorge, 2004; Kleinsorge & Heuer, 1999; Murray, De Santis, Thut & Wylie, 2009; Sandhu & Dyson, 2013; Vandierendonck, Christiaens & Liefooghe, 2008). The interaction of switching components is often described by its *underadditivitiy* of switch costs in complete switches (e.g., Allport, Styles, & Hsieh, 1994; Hahn, Andersen, & Kramer, 2003; Philipp & Koch, 2010). For simplicity, in the following, we will refer to it as the underadditive pattern.

Different explanations have been brought up for why the switching components interact and produce the underadditive pattern. Kleinsorge (2004), for example, suggested that the switching components are ordered *hierarchically* and that a higher-level component switch can facilitate lower-level component switches, but not vice versa. Vandierendonck et al. (2008) suggested that all components are equally weighted within a (*flat*) set of representations. This leads to strong repetition priming when all components repeat in subsequent trials, but as soon as one component requires to be switched, the whole representation gets discarded. Hence, both partial switches and complete switches require a complete update of the cognitive representation. Alternatively, Hommel, Proctor, and Vu (2004) suggested a feature integration account by assuming that the previous trial's component configuration is stored in an "event file." In complete repetitions, the event file can be re-used, and in complete switches participants perceive a complete mismatch which signals the opposite response. In partial switch trials, however, the repeated component retrieves the event file, creating a conflict with the (other) component that needs to be switched. The resolution of this partial switch conflict can be time-consuming and leads to errors, which outweighs the performance benefits of the individual repeated component.

The different theoretical explanations are based on findings of different underadditive interaction patterns in the respective studies: In Figure 1, we give examples of such interactions. An ordinal pattern, in which complete switches led to the longest RTs and highest error rates

(Figure 1 a), was obtained in Philipp and Koch's study (2010). In contrast, Vandierendonck et al. (2008) found a flat interaction pattern with equally high RTs and error rates in all conditions that contained a switch (Figure 1 b). In a study of Kleinsorge and Heuer (1999), complete switches led to even shorter RTs and lower error rates than partial switches (Figure 1 c), which qualifies the interaction pattern as disordinal. As visible in Figure 1, the underadditivity of switch costs in complete switches gets stronger from ordinal (a) to disordinal (c) pattern. In the component 1 (C1) switches, the ordinal pattern (a) still contains small component 2 (C2) switch costs, whereas in the flat pattern (b) C2 switch costs are eliminated, and in the disordinal pattern (c) C2 switch costs reversed (i.e. C2 switch benefits).

In Seibold et al.'s (2018b) Experiment 2, an ordinal component interaction was obtained when the cue indicated the auditory attention criterion, specifying the target's speaker-sex and thereby also the response hand, which the participants had to use to respond to the subsequent judgement. The attention component elicited a larger cost than the judgement component. Interestingly, this asymmetry was reversed when the cue indicated the judgement instead of the attention criterion, since then the judgement switch costs were larger than the attention switch costs. At the same time, the underadditive interaction pattern became more pronounced and disordinal in blocks in which the cue indicated the judgement. The authors argued that with judgement cues, the participants did not know which response hand to use (determined by target's speaker-sex) until the stimuli were presented. The participants may not have prepared the upcoming judgement when they did not know whether they had to link the mapping to left or right hand responses. The resulting more simultaneous reconfiguration of the judgement and the attention criterion could have led to more integrated processing of the components. This could have contributed to the more pronounced, even disordinal interaction pattern in this judgement cueing condition.

Based on this finding, we suggest that strength of the underadditivity of the interaction pattern could reflect the strength of the binding of C1 and C2 levels within a task set. The task set is assumed to be a set of bindings between representations of the task goal, instructed rules, and responses associated with each other (see e.g., Oberauer, Souza, Druey, & Gade, 2013; Koch et al., 2018). The term binding was defined as "temporal[…] coupling or synchronizing [of] the activation" (Hommel, Müsseler, Aschersleben, & Prinz, 2001, p.862) of representations (Singer, 1994; Treisman, 1996), and binding is supposed to "occur implicitly and automatically" (Zmigrod & Hommel, 2010, p. 143). The idea of binding seems to be compatible with the above mentioned accounts, since they all agree on the premise that some kind of association (i.e. binding) is built between the representations of the components within one trial. This binding leads to very short RTs and low error rates in complete repetitions, and may also affect the other switch conditions. However, due to the variety of different setups used to examine multi-component switching, it is unclear which features determine whether the underadditive interaction pattern of independently switching components is ordinal, flat, or even disordinal.

In the present study, we aimed to identify factors that determine the underadditive interaction pattern by manipulating the presumed binding of attention of components. To this end, we used an auditory two-component switching paradigm (like in Experiment 1 of Seibold et al., 2018b) with attention location (ear) switches and judgement switches. We examined the influence of three different manipulations that supposedly affect the binding of attention location and judgement. Based on results of Longman et al. (2016), in Experiment 1, we tested whether exogenous attention orienting, which should lead to less binding of the attention location and the judgement, would lead to less underadditivity of the interaction pattern than endogenous attention orienting. In Experiment 2, the influence of explicit knowledge about the independence of the switching components was assessed, and in Experiment 3, we tested whether cue-based preparation of attention orienting would make attention processing and judgement processing more sequential, reduce their binding and, therefore, lead to an attenuated underadditive interaction pattern.

## Experiment 1

Findings of Longman et al. (2016) suggested that the type of cue could lead to stronger binding of the attended ear to the judgement. In their eye-tracking studies, participants switched between three different judgement that were mapped to three different locations on the computer screen. A centrally presented cue indicated one of three locations and thereby also the respective judgement (i.e., attention location switches and judgement switches were correlated). Significantly longer delays of attention orienting and higher rates of incorrect fixations were obtained when an arbitrary single-letter cue indicated the attention location and required endogenous attention orienting, as compared to an explicit location cue (an arrow pointing to the target location), which presumably elicited exogenous attention orienting. At the same time, the judgement switch costs in reaction times (RTs) were increased with the explicit location cues. Longman et al. (2016) suggested that with the exogenous location cues, attention is guided quasi-automatically to the target location and therefore attention location and judgement are switched more independently, which resulted in less binding of attention location and judgement.

In Experiment 1, we similarly compared performance with exogenous location cues to that with endogenous location cues. Since Seibold et al. (2018b) used visual cues, we tested performance with visual exogenous and visual endogenous location cues, but also auditory exogenous and auditory endogenous cues. In view of Longman et al.'s (2016) findings, exogenous cueing should lead to less binding of attention location and judgement representation than endogenous cueing and therefore should lead to a more additive (i.e. ordinal or entirely additive) pattern.

**Methods**

**Participants.** We tested 24 students (21 women, 3 men) from the RWTH Aachen University, aged between 18 and 30 years ($M$ = 22.05, $SD$ = 2.99). We conducted a post-hoc Monte Carlo simulation based on the parameters of Experiment 1 of the previous study of Seibold et al. (2018b), which confirmed that a sample size of 24 participants is sufficient to replicate the interaction of attention switches and judgement switches with a power of 97% in the present study.

The participants gave their informed written consent and received partial course credit for their participation. Hearing problems were detected neither in the self-report nor in an audiogram that was conducted on a Maico MA33 audiometer.

**Apparatus and stimuli.** The experiment was run in PsychoPy 2.0 (Peirce, 2008) under Linux. The univalent spoken auditory stimuli were the number words from 1 to 9, except for 5, and the spoken vowels A, E, I, U, and consonants K, L, M, R. The duration of the numbers was adjusted to 600 ms, while the spoken vowels A, E, I, U and consonants K, L, M, R had an adjusted duration of 400 ms. All stimuli were recorded in an anechoic chamber and adjusted for subjective loudness (DIN 45613; 74.5 dbC) at the Institute of Technical Acoustics of the RWTH Aachen University. In each trial, one spoken number and one spoken letter were presented to one ear, respectively. They were presented via headphones (Sennheiser PMX 95), one stimulus was thereby always spoken by a male speaker and the other stimulus was spoken by a female speaker. The speaker sex-to-ear as well as the ear-to- judgement mapping varied randomly from trial to trial.

A cue at the beginning of each trial indicated the target location. The visual endogenous cues were “links” or “rechts” (German for “left” or “right”; average size: 10.0cm x 3.3 cm) presented to the center of a 22-inch computer monitor (LG 22MB65PM). The visual exogenous cue was an asterisk (1.6 cm x 1.6 cm), which was presented on the left or right side of the computer screen (distance from screen center: 19.5 cm), indicating the corresponding target ear. The auditory endogenous cues were a high- and a low-pitch tone (200 Hz and 800 Hz; 350 ms; 94 dbC). Analogously to a piano keyboard, a low-pitched cue indicated a left target, whereas a high-pitched tone indicated a right target. The auditory exogenous cue was a 500 Hz tone (350 ms; 94 dbC) presented to the ear of subsequent target presentation.

The participants responded by pressing the left and the right arrow key on a German computer keyboard (QWERTZ) with the index fingers of their left and right hand. When the target stimulus was a letter, the participants were asked to classify the letter as consonant or vowel (letter judgement) by pressing the left or right response key. When the target stimulus was a number, it should be classified as odd or even (number judgement) by pressing the left or right response key (this mapping was counterbalanced among the participants). In case of an incorrect response an error noise was presented auditory (white noise at 93 dbC).

**Procedure.** At the beginning of the experimental session, participants had to fill out a short questionnaire on age, gender, handedness, hearing, and visual impairments, and they had to pass a hearing sensitivity test. Subsequently, they were presented with the experimental instructions on the computer screen. The experiment consisted of four cueing blocks with 256 trials in each block, resulting in 1024 experimental trials. Sixteen practice trials preceded each cueing condition. Half of the participants started with the auditory cueing blocks, the other half started with visual cueing blocks. The order of endogenous and exogenous cueing blocks was counterbalanced across participants, but remained constant for each participant within experimental halves with auditory vs. visual cues, respectively. The experimental session took approximately 75 minutes.

In the beginning of each trial, a cue with a duration of 400 ms was presented and immediately afterwards or after another 400 ms (CSI of either 400 ms or 800 ms) the auditory stimuli were presented via headphones. The CSI varied randomly on a trial-by-trial basis. The visual cue stayed on the screen until a response was given, whereas the auditory cue was only played once and then disappeared before stimulus onset. A response key press was followed by a response-cue interval (RCI) 800 ms or 400 ms. The length of the RCI was determined by the previous CSI[7]. In case of an incorrect response, the error tone was presented for 500 ms immediately after the response, thus lengthening the RCI.

**Design.** The independent variables were attention transition (repetition vs. switch), judgement transition (repetition vs. switch), cue modality (visual vs auditory), and cue type (exogenous vs endogenous). The dependent variables were reaction times (RT) and percentage of errors (PE).

**Results**

The data of two participants were not analyzed due to very high error rates above 25%. For the analysis of the RTs, the first trial of each block, all erroneous trials (6%) and trials following an error, as well as RT outlier-trials above three standard deviations from a participant's mean RT were excluded (1.6%). For the analysis of the PE, only the first trial of each block and trials following an error were excluded.

**Analysis of RTs.** An ANOVA for repeated measurements on the RTs revealed a main effect of attention transition, $F(1, 21) = 74.92$, $p < .001$, $\eta_p^2 = .78$, with attention switch costs of 150 ms, and a main effect of judgement transition, $F(1, 21) = 27.92$, $p < .001$, $\eta_p^2 = .57$, with judgement switch costs of 59 ms. Attention transition and judgement transition interacted, $F(1, 21) = 14.64$, $p = .001$, $\eta_p^2 = .41$. The judgement switch costs of 92 ms in attention repetitions were reduced to 27 ms in attention switches.

Cue type elicited a main effect, $F(1, 21) = 11.75$, $p = .003$, $\eta_p^2 = .36$, with 103 ms shorter RTs with exogenous cues than with endogenous cues. Cue modality interacted with cue type, $F(1, 21) = 10.25$, $p = .004$, $\eta_p^2 = .33$, as the benefit of exogenous cueing with respect to endogenous cueing was only 45 ms with visual cues, but 162 ms with auditory cues. Cue modality showed a trend for an interaction with attention transition, $F(1, 21) = 3.37$, $p = .081$, $\eta_p^2 = .14$, and the three-way interaction of cue type, cue modality, and attention transition was significant, $F(1, 21) = 6.31$, $p = .020$, $\eta_p^2 = .23$.

When breaking this down by cue modality, the interaction of cue type and attention transition was nonsignificant in blocks with visual cues, $F < 1$, since the attention switch costs

[7] Please note that this was a programming error in our Experiments 1 and 2, which led to three-different possible RSI (response stimulus interval) durations (i.e., RCI+CSI: 400+400, 400+800, 800+400, 800+800). Thus, the effect of the CSI manipulation cannot be separated from RSI effects, and are therefore not analyzed. However, the temporal intervals were manipulated entirely independently from attention transition, judgement transition, cueing modality, and cue type, so that the effects of these latter variables can still be interpreted. Importantly, in Experiment 3, the programming was corrected so that the RSI was constant and an interpretation of CSI in terms of active preparation was possible.

were similar in blocks with exogenous and endogenous cues (177 ms vs. 162 ms). In blocks with auditory cues, however, the interaction was significant, $F(1, 21) = 9.72$, $p = .006$, $\eta_p^2 = .31$. Auditory exogenous cueing led to smaller attention switch costs than auditory endogenous cueing (101 ms vs.160 ms). All other effects were nonsignificant (*Fs* < 2.3, *ps* > .15; see Figure 2).

**Analysis of the PE.** The analysis of the error data revealed a pattern that largely resembled that obtained in the RTs. Namely, a main effect of attention transition was present, $F(1, 21) = 24.19$, $p < .001$, $\eta_p^2 = .54$, with attention switch costs of 2%. Judgement transition also elicited a main effect, $F(1, 21) = 9.05$, $p = .007$, $\eta_p^2 = .30$, with judgement switch costs of 1.8%. Attention transition and judgement transition interacted, $F(1, 21) = 9.92$, $p = .005$, $\eta_p^2 = .32$. In accordance with the RT data, judgement switch costs had a size of 2.8% in attention repetitions and 0.9% in attention switches.

Cue modality interacted with cue type, $F(1, 21) = 4.97$, $p = .037$, $\eta_p^2 = .19$, since the benefit of exogenous cueing with respect to endogenous cueing was 0.2% in blocks with visual cues, but 1.6% in blocks with auditory cues. Cue modality also interacted with attention transition, $F(1, 21) = 6.09$, $p = .022$, $\eta_p^2 = .23$, since the attention switch costs were 1.2% larger in blocks with auditory cues than in blocks with visual cues. Finally, the four-way interaction was significant, $F(1, 21) = 10.41$, $p = .004$, $\eta_p^2 = .33$. When breaking this down by cue modality, the interaction of attention transition, judgement transition, and cue type was significant in blocks with visual cues, $F(1, 21) = 73.71$, $p = .003$, $\eta_p^2 = .34$, but not in the blocks with auditory cues, $F < 2.9$, $p > .10$. In bocks with visual exogenous cues the judgement switch costs were large in attention repetitions and even negative in attention switches (3.4% vs. -1.1%; $F(1, 21) = 19.92$, $p = .001$, $\eta_p^2 = .49$), while in blocks with visual endogenous cues a nonsignificant, but numerically inverse (i.e. “overadditive”) pattern was obtained (1.9% vs. 2.6%; $F < 1$). In blocks with auditory exogenous and auditory endogenous cues, the expected underadditive patterns did only differ numerically but not reliably (exogenous cueing: 2.4% vs. 1.9%; $F < 1$; endogenous cueing: 3.4% vs. 0.2%; $F(1, 21) = 5.49$, $p = .029$, $\eta_p^2 = .21$). All other effects were nonsignificant (*F*s < 2.8, *p*s > .11; see Figure 2).

## Discussion

We replicated the ordinal underadditive interaction pattern of attention switches and judgement switches, obtained by Seibold et al. (2018b). In the auditory cueing blocks, auditory exogenous cueing led to the expected reduction of attention switch costs consistently in the RTs and in the error rates, indicating more automatic and faster attention switches. However, the exogenous cueing did neither in RTs nor in the error rates affect the underadditive interaction pattern of attention switches and judgement switches, which may indicate that endogenous attention control is not a necessary precondition to produce the underadditive interaction pattern. However, since the latter inference is based on a null-effect, it needs to be replicated in Experiment 2.

In comparison to the blocks with auditory cues, the influence of cue type in the blocks with visual cues was less clear and rather unsystematic. The cue type modulated the interaction of attention switches and judgement switches in the error rates, but an opposite numerical pattern was obtained in the RTs, indicating a speed-accuracy trade-off. Namely, in the error rates, the interaction pattern of attention switches and judgement switches was disordinal with visual exogenous cues, whereas no interaction was obtained (i.e. additive switch costs) with visual endogenous cues. When looking at the RTs in these visual cueing blocks, the underadditive pattern was present but numerically less pronounced with exogenous cues than with endogenous cues (83 ms vs. 46 ms; 118 ms vs. 9 ms; see also Figure 2). Therefore, the interpretation of the data of the visual cueing blocks in this experiment needs to be taken with caution. That is why we choose to only use auditory cues in the following Experiment 2 and 3.

## Experiment 2

In Experiment 2, we used a different manipulation that could affect the underadditive interaction pattern of attention switches and judgement switches. Namely, we interspersed 'pure' attention blocks, in which auditory selective attention was kept constant on one ear while the judgement still switched randomly. The pure attention blocks could be regarded as judgement switching training and such isolated judgement switching training may emphasize to the participants that attention location switches and judgement switches occurred independently of each other in the experiment. Such explicit knowledge could encourage participants to actively prevent the binding of attention location and judgement and would reduce or even eliminate the interaction of attention switches and judgement switches in the present mixed blocks compared to Experiment 1.

Furthermore, the pure attention blocks offered the possibility to calculate attention mixing costs (Koch & Lawo, 2015) by comparing attention repetitions in the mixed attention blocks to those in pure attention blocks (simply all trials of the pure attention blocks). Performance in mixed blocks is usually poorer than performance in pure blocks, and this performance difference is called mixing cost (Los, 1996; see, e.g., Kiesel et al., 2010, for a review). Mixing costs can be understood as a more global form of switch costs (e.g., Kray & Lindenberger, 2000; Mayr, 2001), which are due to additional sustained control processes that are needed in mixed blocks rather than in pure blocks (e.g., Rubin & Meiran, 2005; Vandierendonck, Liefooghe, & Verbruggen, 2010, for discussions). The control processes are needed to deal with the increased memory load when maintaining more than one attentional selection rule in working memory during the mixed blocks, as well as with less predictability and more ambiguity about the upcoming attention target (Mayr, 2001; Poljac, Koch, & Bekkering, 2009; Rubin & Meiran, 2005). Attention mixing costs in auditory attention switching when using visual spatial cueing have been reported before (Koch & Lawo, 2015). Yet, in the earlier study no judgement switches occurred, so that the present study was aimed to examine auditory attention mixing costs with concurrent judgement switches.

Since visual exogenous attention cueing did not elicit the expected reduction of attention switch costs with respect to visual endogenous attention cueing, we used only auditory exogenous and endogenous cues in Experiment 2. This allowed us to test whether we could replicate the findings in the auditory cueing blocks of Experiment 1 in the mixed blocks of Experiment 2.

**Method**

**Participants.** A new group of 24 German-speaking students (16 women, 8 men) from the RWTH Aachen University, aged between 19 and 31 years (*M* = 24.08, *SD* = 2.38) took part and received partial course credit for their participation in the experiment. The participants were right-handed, except for 6 left-handers. Hearing problems were detected neither in the self-report, nor in an audiogram, which was conducted on a Maico MA33 audiometer.

**Apparatus, stimuli, and procedure.** The apparatus and stimuli were the same as in Experiment 1, with the only difference that we exclusively used auditory cueing in the present experiment. The experiment consisted of 12 blocks of 60 trials resulting in a total of 720 experimental trials per participant. In four of the twelve experimental blocks, the auditory attention focus was constantly directed to one ear. Since performance in blocks with endogenous and exogenous cues was compared, there was one block exogenously cueing the left ear, one block endogenously cueing the left ear, and also two such blocks for the right ear. The remaining eight blocks consisted of four exogenously cued blocks and four endogenously cued blocks, in which attention locations and judgements switched independently between trials – thus exactly like in the auditory cueing blocks of Experiment 1. The order of cue types (exogenous vs.

endogenous cues) and block type (mixed vs. pure attention block) was counterbalanced among participants. Each pure block and each pair of mixed blocks was preceded by 8 practice trials, respectively. Altogether, the experimental session took approximately 60 minutes.

**Design.** The dependent variables were RTs and PE. We analyzed the data of Experiment 2 in two non-orthogonal contrasts. We first report the attention switch cost contrast, in which we analyzed only all trials from the mixed attention blocks. The independent variables were auditory attention transition (repetition vs. switch), judgement transition (repetition vs. switch), and cue type (exogenous vs. endogenous).

For the mixing cost contrast, all trials from the pure attention blocks were compared to the attention repetition trials of the mixed attention blocks. Hence, as there were no attention switches included, the independent variables were judgement transition (repetition vs. switch), cue type (exogenous vs. endogenous), and the additional independent variable of attention block (pure attention block vs. attention repetitions of mixed attention blocks [mixed attention block]).

**Results**

One participant was excluded from the analysis due to an error rate above 25%. Like in Experiment 1, the first trial of each block, all erroneous trials (5.4%), and trials following and error, as well as RT outlier-trials above three standard deviations from a participant's mean RT (2.0%) were excluded in the analysis of the RTs. For the analysis of the PE, only the first trial of each block and trials following an error were excluded.

**Attention switch cost contrast.** First, we conducted an analysis containing only the trials of the mixed attention blocks.

***Analysis of the RTs.*** The ANOVA for repeated measurements on the RT data revealed a main effect of attention transition, $F(1, 22) = 45.42$, $p < .001$, $\eta_p^2 = .67$, with attention switch costs of 136 ms, and a main effect of judgement transition, $F(1, 22) = 22.0$, $p < .001$, $\eta_p^2 = .50$, with judgement switch costs of 60 ms. The underadditive interaction pattern of attention transition and judgement transition was replicated, although the trend was not significant, $F(1, 22) = 3.58$, $p = .072$, $\eta_p^2 = .14$. The judgement switch costs were larger in attention repetitions than in attention switches (82 ms vs. 39 ms).

The main effect of cue type was significant, $F(1, 22) = 11.24$, $p = .003$, $\eta_p^2 = .34$, indicating that RTs in blocks with exogenous cues were 158 ms shorter than in blocks with endogenous cues. Cue type interacted with attention transition, $F(1, 22) = 5.21$, $p = .033$, $\eta_p^2 = .19$, showing that attention switch costs were smaller with exogenous cueing than with endogenous cueing (101 ms vs. 170 ms). However, cue type did not interact with judgement transition, and also the three-way interaction with attention transition and judgement transition was nonsignificant, *F*s < 1. The remaining interactions were nonsignificant, too, *F*s < 1 (see also Figure 3).

***Analysis of the PE.*** The ANOVA on the errors rates revealed a main effect of attention transition, $F(1, 22) = 10.67$, $p = .004$, $\eta_p^2 = .33$, with attention switch costs of 1.8%, and a main effect of judgement transition, $F(1, 22) = 5.98$, $p = .023$, $\eta_p^2 = .21$, with judgement switch costs of 1.5%. Attention transition and judgement transition did not interact, $F < 1$. The main effect of cue type was significant, $F(1, 22) = 6.33$, $p = .020$, $\eta_p^2 = .22$, with 3.2% less errors in blocks with exogenous cueing compared to endogenous cueing. All other effects were nonsignificant, *F*s < 2.5, *p*s > .12 (see also Figure 3).

***Between-experiment comparison.*** To confirm the replication, we conducted a between-experiments comparison, in which we included blocks with auditory cues of Experiment 1 and the mixed blocks of Experiment 2. We added the between-participants variable experiment (Experiment 1 vs. Experiment 2). The critical interaction of attention transition and judgement transition was significant in the RTs, $F(1, 43) = 10.30$, $p = .003$, $\eta_p^2 = .19$, and marginally significant in the error rates, $F(1, 43) = 4.03$, $p = .051$, $\eta_p^2 = .09$. The main effect of experiment was nonsignificant in the RTs and error rates, *F*s < 1, and experiment did not enter into any interaction with the other independent variables in the RTs, *F*s < 1, and error rates, *F*s < 1.5, *p*s > .22. Hence, the explicit knowledge about the independence of attention switches and judgement switches did eliminate the underadditive interaction pattern.

**Attention mixing costs contrast.** Since the attention mixing cost was not a key element for the theoretical questions discussed in this study, we summarize it only briefly. To anticipate, reliable attention mixing costs were obtained, despite the independent judgement switches.

In detail, attention mixing elicited a main effect, $F(1, 22) = 36.42$, $p < .001$, $\eta_p^2 = .62$, with attention mixing costs of 199 ms. Judgement transition also elicited a main effect, $F(1, 22) = 26.10$, $p < .001$, $\eta_p^2 = .54$, with judgement switch costs of 79 ms. Attention mixing and judgement transition interacted, $F(1, 22) = 7.09$, $p = .014$, $\eta_p^2 = .24$, showing that the judgement switch costs were smaller in the attention repetitions in the mixed blocks than in the pure attention blocks (59 ms vs. 100 ms).

The manipulation of cue type elicited a main effect, $F(1, 22) = 7.22$, $p = .013$, $\eta_p^2 = .25$, revealing 106 ms shorter RTs with exogenous cueing than endogenous cueing. Cue type interacted with attention block, $F(1, 22) = 6.76$, $p = .016$, $\eta_p^2 = .24$. The benefit of exogenous cueing relative to endogenous cueing was larger in the mixed than in the pure attention blocks (161 ms vs. 52 ms). All other effects were nonsignificant, *F*s < 2.3, *p*s > .14.

The analysis of the error rates showed similar, yet less pronounced effects. Judgement transition elicited a main effect, $F(1, 22) = 9.61$, $p = .005$, $\eta_p^2 = .30$, with judgement switch costs of 2.6%, and it marginally interacted with attention block, $F(1, 22) = 4.22$, $p = .052$, $\eta_p^2 = .16$, since the judgement switch costs were smaller in the mixed than in the pure attention blocks (1.5% vs. 3.7%). Cue type elicited a main effect, $F(1, 22) = 4.87$, $p = .038$, $\eta_p^2 = .18$, with 2.7% less errors with exogenous cues than endogenous cues. All other effects were nonsignificant, *F*s < 1.

**Discussion**

In Experiment 2, we replicated the ordinal underadditive interaction pattern of attention switches and judgement switches. The underadditive interaction pattern did not differ reliably from that of Experiment 1, which implies that the explicit knowledge about the independence of attention switches and task switches did not prevent their presumed binding. Like in Experiment 1, the cue type manipulation was effective for the attention switch costs, since exogenous cueing led to smaller switch costs than endogenous cueing, and the underadditive interaction pattern of attention switches and judgement switches was again not affected. Besides, when comparing performance in pure attention blocks to performance in mixed attention blocks, the judgement switch costs were clearly affected by randomly switching attention locations in the mixed attention blocks. This, once more, indicates that the attention location and judgement were not represented and processed independently.

## Experiment 3

In Experiment 1 and 2, we tested whether the underadditive interaction pattern of attention switches and judgement switches could be modulated by the type of cueing, or by explicit knowledge about the independence of the two switching components. Clearly, the attention switch costs were affected by the cue type manipulation, but this did not affect the underadditive interaction pattern of attention switches and judgement switches very substantially.

In Experiment 3, we tested whether less simultaneous component processing would lead to less binding between attention location and judgement, as suggested by Seibold et al. (2018b). Namely, as defined earlier in this study, binding is supposed to be a “temporal[…] coupling or synchronizing [of] the activation" (Hommel et al., 2001, p.862). Longman et al.'s (2016) also expressed this idea, since in their study active preparation for visual attention location switches reduced the "coupling" of attention switches and judgement switches.

Thus, we manipulated the CSI to see whether it modulates the underadditive interaction pattern. Based on the findings of Longman et al. (2016), we would expect less binding and therefore an attenuated underadditive interaction pattern in trials with a long CSI. We used auditory endogenous cues to test preparation effects in a situation in which the attention switch costs should be relatively large.

## Method

**Participants.** A new group of this time 32 German-speaking students (25 women, 7 men) from the RWTH Aachen University, aged between 18 and 33 years (*M* = 21.5, *SD* = 3.21) took part and received partial course credit for their participation in the experiment.  We choose this larger sample size for Experiment 3 since the effects of active preparation on the underadditive interaction pattern might be small, like those of cue type. Hearing problems were detected neither in the self-report, nor in an audiogram, which was conducted on a Maico MA33 audiometer.

**Apparatus, stimuli, and procedure.** The apparatus and stimuli were the same as in the auditory endogenous cueing blocks of Experiment 1. The RSI was constant between trials so that the influence of the CSI manipulation could be isolated independent from the potential influences of the overall duration of the RSI. Namely, the RCI was short at 400 ms when the subsequent CSI was long at 800 ms, or vice versa. The experiment contained 3 blocks with 256 trials (total of 768 trials), respectively, and was preceded by 8 training trials. The whole experimental session took about 45 minutes.

**Design.** The independent variables were auditory attention transition (repetition vs. switch), judgement transition (repetition vs. switch), and CSI (400 ms vs. 800 ms). The dependent variables were RTs and PE.

## Results

Like in the previous experiments, the first trial of each block, all erroneous trials (10.9%) and trials following and error, as well as RT outlier-trials above three standard deviations from a participant's mean RT (1.5%) were excluded in the analysis of the RTs. For the analysis of the PE, only trials following an error and the first trial of each block were excluded.

**Analysis of the RTs.** The ANOVA for repeated measurements on the RT data revealed a main effect of attention transition, $F(1, 31) = 66.72$, $p < .001$, $\eta_p^2 = .68$, with attention switch costs of 164 ms, and a main effect of judgement transition, $F(1, 31) = 11.70$, $p = .002$, $\eta_p^2 = .68$, with judgement switch costs of 46 ms. Attention transition and judgement transition also interacted, $F(1, 31) = 40.18$, $p < .001$, $\eta_p^2 = .56$, showing that the judgement switch costs were larger in attention repetitions than in attention switches (111 ms vs. 20 ms).

CSI elicited a main effect, $F(1, 31) = 123.38$, $p < .001$, $\eta_p^2 = .80$, since RTs were 111 ms longer in trials with short CSI than in trials with long CSI, indicating a general preparation effect. Moreover, CSI interacted with judgement transition, $F(1, 31) = 4.20$, $p = .049$, $\eta_p^2 = .12$, since the judgement switch costs were reduced from 63 ms in short CSI trials to 28 ms in long CSI trials. This latter effect was qualified by a significant three-way interaction, $F(1, 31) = 5.49$, $p = .026$, $\eta_p^2 = .15$.

Contrary to our prediction, when tested separately for short and long CSI, the interaction of attention transition and judgement transition was less pronounced with short compared to long CSI. In trials with short CSI, the judgement switch costs were larger in attention repetitions than in attention switches (110 ms vs. 17 ms), $F(1, 31) = 12.39$, $p = .001$, $\eta_p^2 = .29$. In trials with long CSI, the judgement switch costs were again larger in attention repetitions than in attention switches, $F(1, 31) = 42.41$, $p < .001$, $\eta_p^2 = .58$, and they were even reversed in attention switches (112 ms vs. – 57 ms [i.e. negative judgement switch costs, $t(31) = -2.57$, $p = .015$]). The remaining interaction of attention transition and CSI was nonsignificant, $F < 1$ (see also Figure 4).

Visual inspection of the data pattern suggests that the benefit of long preparation time was largest in complete switches, which is why partial switches show even larger costs than complete switches ($ps \leq .001$; $\Delta M_{CompleteRepetition} = 99$ ms; $\Delta M_{JudgementSwitch} = 97$ ms; $\Delta M_{AttentionSwitch} = 87$ ms; $\Delta M_{CompleteSwitch} = 161$ ms).

The analysis of the error rates revealed a main effect of attention transition, $F(1, 31) = 20.84$, $p < .001$, $\eta_p^2 = .40$, with attention switch costs of 2.4% ms, and a main effect of judgement transition, $F(1, 31) = 28.86$, $p < .001$, $\eta_p^2 = .48$, with judgement switch costs of 2.5%. Attention transition and judgement transition interacted, $F(1, 31) = 18.83$, $p < .001$, $\eta_p^2 = .39$, showing that the judgement switch costs were larger in attention repetitions than in attention switches (4.8% vs. 0.2%). Moreover, like in the RT data, the three-way interaction was significant, $F(1, 31) = 5.45$, $p = .026$, $\eta_p^2 = .15$.

In trials with short CSI, the interaction of attention transition and judgement transition was only marginally significant, $F(1, 31) = 3.97$, $p = .055$, $\eta_p^2 = .11$, but in trials with long CSI, like in the RTs, it was clearly more pronounced, $F(1, 31) = 29.43$, $p < .001$, $\eta_p^2 = .49$. In trials with short CSI, judgement switch costs larger in attention repetitions than in attention switches (4.2% vs. 1.4%). The same trend was obtained also in trials with long CSI and, like in the RTs, the judgement switch costs were even reversed in attention switches (5.5% vs. -1% [i.e. negative judgement switch costs, $t(31) = -1.19$, $p = .242$]). All other effects were nonsignificant, *F*s < 1 (see Figure 4).

Since we inspected the interaction pattern visually in the RTs, we also looked at the preparation benefits, here (error rates in short CSI trials subtracted from error rates in long CSI trials). However, the numerical repetition benefits and costs were unsystematic and nonsignificant (preparation effects: *p*s > .300; $\Delta M_{CR} = 1.2\%$; $\Delta M_{TS} = 0\%$; $\Delta M_{AS} = -1.3\%$; $\Delta M_{CS} = 1\%$).

**Discussion**

Hence, in Experiment 3, we, once more, replicated the typical underadditive interaction pattern of attention switches and judgement switches. The CSI manipulation was successful because it elicited a general preparation effect in the RTs and it modulated the judgement switch costs. CSI also modulated the underadditive interaction pattern, but in the opposite way than expected. Namely, with enhanced preparation (i.e., long CSI), the underadditivity of the interaction became stronger and resulted in a disordinal pattern. In the RTs, especially the complete switches benefitted from a preparation. In the error rates only numerical preparation effects were present in the different conditions - from benefits in complete repetitions and complete switches to costs in partial attention.

## General Discussion

In the present study, we employed an auditory two-component switching paradigm in which participants had to switch between two auditory attention locations and between two judgements (like Seibold et al., 2018b). A robust finding in this paradigm is an interaction of the attention component and the judgement component, in which the switch costs of complete switches are underadditive. We suggested that this interaction arises due to the binding of attention location and judgement in each trial. Specifically, the underadditivity of switch costs in complete switches may reflect the binding strength. We tested three different manipulations that could potentially reduce the binding strength: Exogenous cueing could elicit quasi-automatic automatic attention switches and therefore could lead to less binding (Experiment 1 & 2).

Moreover, the participants' knowledge about the independence of the switching components (Experiment 2) could prevent the binding and therefore modulate the underadditive pattern. Finally also increased time for preparation of the attention location selection could reduce the binding of attention location and judgement and attenuate the underadditive interaction pattern due to more sequential component processing.

First, the results showed that the use of auditory exogenous cues reduced the attention switch costs in the RTs and error rates, but this modulation did not affect the underadditive interaction pattern of attention switches and judgement switches. This pattern was replicated in Experiment 2. In contrast, the results of the visual cueing blocks need to be regarded cautiously. Although visual exogenous cueing led to a more pronounced underadditive interaction pattern of attention switches and judgement switches in the error rates, the RTs showed an opposing pattern and there may indicate a speed-accuracy trade-off.

Second, the explicit knowledge about the independence of attention switches and judgement switches did not affect underadditive interaction pattern. However, as a third finding, a prolonged preparation interval in Experiment 3 did modulate the underadditive interaction pattern. When the CSI was long, the underadditive pattern of attention switches and judgement switches was more pronounced and resulted in a disordinal pattern, contrary to our predictions.

**The automaticity of the presumed binding**

The auditory exogenous cues, which were employed in Experiment 1 and 2, consistently led to reduced attention switch costs, due to probably more automatic attention orienting than auditory endogenous cues. However, the attention switch cost reduction did not affect the underadditive interaction pattern of attention switches and judgement switches. Our results therefore suggest that, at least for auditory cueing, endogenous object selection is not a necessary prerequisite for binding of attention location and judgement representation.

Earlier findings of Koch and Lawo (2014) go in line with this claim. In their auditory attention switching study in which cues indicated the speaker-sex of the target speaker, they also analyzed the irrelevant location (ear) switches of the target-speaker, which required no endogenous selection (i.e. intentional, self-initiated action). They found an underadditive ordinal interaction pattern of the cued speaker-sex switches and the irrelevant target-ear switched. Namely, speaker-sex switch costs in RTs and error rates were large when the target-ear repeated and small when the ear switched. The present findings extend these earlier observations to explicit judgement switches.

Hence, the present results do not go in line with the predictions based on the study of Longman et al. (2016), due to which the binding between attention location and judgment should be weaker with exogenous attention selection. This does not necessarily imply that the underadditive interaction pattern does not reflect the binding of attention location and judgement, but that their binding was rather automatic, like proposed by Zmigrod and Hommel (2010).

**Top-down regulation by explicit knowledge**

For Experiment 2, we argued that interspersed "pure" attention blocks with a constant attention location would make it explicit to the participants that attention location and judgement were unrelated. It was examined whether such explicit knowledge would lead to a top-down attenuation of binding, to reduce the performance decrements due to binding in trials with component switches. However, there was no evidence for such a top-down modulation of attention.

Still, supposedly top-down attentional control has been demonstrated to modulate the task-rule congruency effect in task-switching studies (see also Braverman & Meiran, 2015; Wendt, Luna-Rodriguez, Kiesel, & Jacobsen, 2013). Bugg and Braver (2016), for example, examined the task-rule congruency effect in a task-switching paradigm by a block-wise manipulation of the proportion of congruent to incongruent stimuli (requiring the same physical or different physical responses in two switching judgements) and found a smaller congruency effect in blocks with high proportions of incongruent trials.

In the present multi-component switching context, our manipulation of explicit knowledge might have been too weak to elicit a reliable modulation. Possibly, the independence of the component switches was already evident without the interspersed pure attention blocks. Introducing different contingencies between attention locations and judgements in the experimental blocks may have modulated the underadditive interaction pattern reliably. Thus, at this point, we can only state that the influence of our top-down control manipulation was at the most minimal.

**Cue-based preparation of attention location**

So far, we argued that the underadditive interaction pattern of attention switches and judgement switches in our experiments was mainly due to automatic associations of attention location and judgement within each trial. This, of course, raises the question of why specifically a prolonged CSI increased the underadditivity of the interaction pattern of attention switches and judgement switches.

First of all, the CSI manipulation elicited quite different effects than the cue type manipulations in Experiment 1 and 2. Notably, a prolonged CSI did not lead to reduced attention switch costs but to reduced judgement switch costs instead. When looking at previous studies on attention switching, switch-specific attention preparation was not a very systematic finding (Koch et al., 2011; Lawo et al., 2014; Seibold et al., 2018a). It was therefore not necessarily expected that a reduction of attention switch costs would be obtained. The general preparation effect indicates that participants used the cue to orient attention before stimulus onset – in attention switches and repetitions. Possibly, the selected attention location could not be maintained during the following judgement execution and therefore benefitted from a prolonged preparation interval even in the attention repetitions.

Yet, why did a prolonged CSI specifically reduce the judgement switch costs? In judgement switching, findings of switch specific preparation effects that lead to reduced judgement switch costs are often observed (see Kiesel et al., 2010). However, in our experiment, the cue was entirely uninformative about the judgement, and inserting uninformative warning signals to a random judgement sequences usually leads to only very weak preparation effects (Meiran et al., 2000; see also Meiran & Chorev, 2005). Since the RSI was constant between trials, passive processes during the RSI, such as task set "decay" (Allport et al., 1994), should also not have affected the judgement switch costs.

We believe that other explanations for the impact of CSI on judgement switch costs may be more appropriate. The reduction of judgement switch costs in long CSI trials may be a characteristic of multi-component switching situations, since this finding resembles results of Philipp and Koch (2010), in which independent judgement and response modality switches were examined. In Philipp and Koch's study (2010), both switching components were indicated by separate cues, which appeared randomly and independently - either early at 1000 ms or late at 100 ms before stimulus onset. Early response modality cueing led to a reduction of the judgement switch costs, whereas early judgement cueing led to a reduction of the response modality switch costs in the RTs. The authors named this finding "counter intuitive" (p. 403) and speculated that knowing about one component made it possible to expect the specification of the other component later on.

In our study, a cued attention repetition could retrieve also the judgement repetition that we assume to be bound to it - especially when there was sufficient time in trials with long CSI. Retrieval of the bound judgement should lead to preparation benefits in complete repetitions and to costs of unbinding the retrieved judgement in partial task switches. In the error rates, numerical preparation benefits were obtained in complete repetitions and complete switches, while numerical preparation costs were obtained in partial switches – possibly, though not significantly, indicating costs of unbinding (e.g., Schuch & Koch, 2004; Koch, Frings & Schuch, 2017). However, the numerical pattern of the RTs showed that especially the complete switches benefitted much more from a long CSI than the other conditions. Future research is needed to clarify this point.

Alternatively, Philipp and Koch (2010) suggested that the early cueing of one component could have led to more focused attention when the second component was cued at 100 ms before stimulus onset, because the participants could expect its specification at that point. Although such an explanation would also be compatible with our results, there was an important difference between their study's findings and those in the present study that we need to consider: we obtained a three-way interaction indicating that the CSI specifically modulated the underadditive interaction pattern of attention switches and judgement switches, whereas in the study of Philipp and Koch (2010), the underadditive interaction pattern of judgement switches and response modality switches was not modulated by early judgement cueing and early response modality cueing, respectively.

Either way, the modulation of the underadditive interaction pattern by CSI was opposite to our expectations of attenuated component binding due to less simultaneous attention location selection and judgement execution. Still, the result that a prolonged CSI for attention location preparation did have an impact on the judgement switch costs speaks in favour of binding within the paradigm.

**Implications for theoretical accounts**

Overall, the present findings speak against a flat representation of the components (Vandierendonck et al., 2008). Namely, this account provides no mechanism that would produce a disordinal interaction pattern of attention switches and judgement switches, as obtained in trials with a long CSI (Experiment 3).

In comparison, the hierarchical account (Kleinsorge, 2004) and the feature integration account (Hommel et al., 2004) would account for disordinal interaction patterns of the switching components. Both propose that the underadditivity of switch costs in complete switches is due to more or less combined switching of the components in this condition. Kleinsorge (2004) proposed that combined switching can only be initiated top-down by a hierarchically higher-level component, whereas Hommel et al. (2004) do not assume that a specific hierarchy between the components is crucial for the combined switch.

Still, finding an explanation for the modulation of the underadditive interaction pattern by CSI is not trivial within these latter two accounts. Seibold et al. (2018b) demonstrated that the order in which the components are processed within a trial determines which component is dominant (i.e., on a hierarchically higher-level). A long CSI could have reinforced this hierarchy of attention component and judgement component (i.e., component order), since a switch of the attention location might even be completed within the long CSI. A completed attention switch may have facilitated judgement switches for the subsequent stimulus processing relative to an uncompleted attention switch in a trial with short CSI.

Such a facilitation may have been due to the reduction of the condition alternatives. Kleinsorge and Scheil (2015) conducted experiments in which participants switched between four different judgements. A cue presented 800 ms before stimulus onset sometimes reduced the four judgement alternatives to two and this led to performance benefits especially in judgement switches benefitted, whereas judgement repetitions were relatively unaffected. The authors argued that in two-choice decisions, other than in four- or three-choice decisions, any evidence against one alternative directly favours the other alternative and therefore leads to faster decisions. Judgement repetitions, instead, were hardly affected by a reduction of the number of alternative judgements confirming repetition benefits from episodic retrieval and priming.

Still, at this point, we can only speculate how such a switch facilitation is created for the subsequent component. It could be as well the switch expectations (e.g., Philipp & Koch, 2010), or a retrieval of earlier episodes in which the “opposite” attention location and judgement were bound, or by negative priming (i.e. retrieving “the opposite event”) due to inhibition of the previous episode (e.g., Hommel et al., 2004). Future research is needed to identify what contributes to multi-component switching and the modulation of the underadditive interaction pattern by CSI and how partial switches and complete switches would be affected.

**Conclusion**

The present study tested whether the underadditive interaction pattern of attention switches and judgement switches can be due to binding of attention location and judgement representation within each trial. According to the results, such binding would occur rather automatically, since quasi automatic attention switches induced by auditory exogenous cues, as well as explicit knowledge about the independence of the attention switches and judgement switches, did not modulate the underadditive interaction pattern. Moreover, less concurrent component processing did not attenuate the presumed binding but led to a more pronounced interaction pattern implying even stronger binding. We suggest, on the basis of the hierarchical account of Kleinsorge (2004) that sufficient time for an attention location selection during a long CSI may more strongly retrieve the judgement repetition in an attention repetition but could also facilitate judgement switches – for example by a preliminary reduction of the possible component conditions.

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## Figures

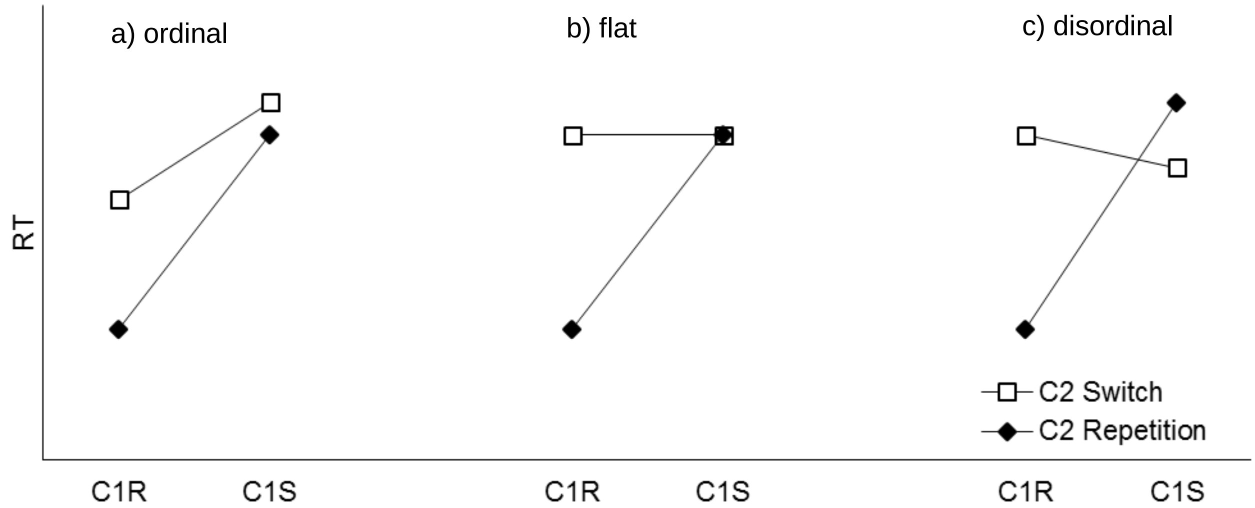


*Figure 1*. Exemplary ordinal (a), flat (b), and disordinal (c) patterns of the interaction of component 1 transition (repetition [C1R] vs. switch [C1S]) and component 2 transition (C2 repetition vs. C2 switch) in the RTs.

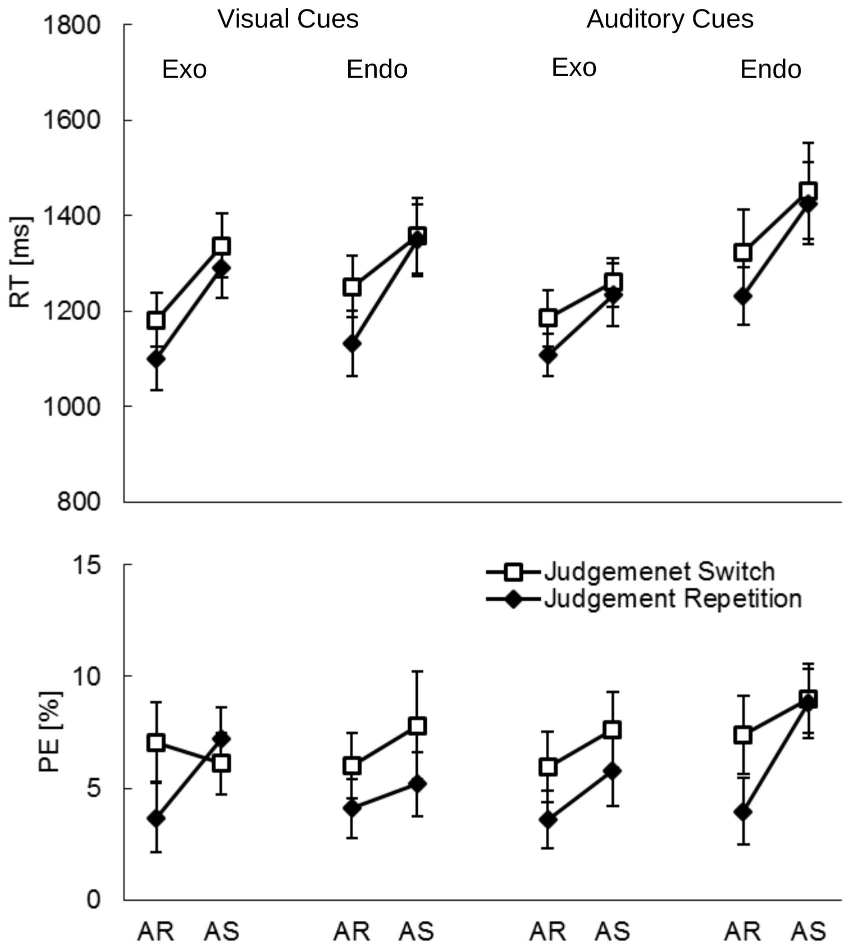


*Figure 2*. Descriptive results of the RT and PE data of Experiment 1 as a function of attention transition (repetition [AR] vs. switch [AS]), judgement transition (repetition vs. switch), cue modality (visual vs. auditory), and cue type (exogenous [Exo] vs. endogenous [Endo]). The error bars reflect 95% Cousineau-Morey Confidence Intervals (Morey, 2008).

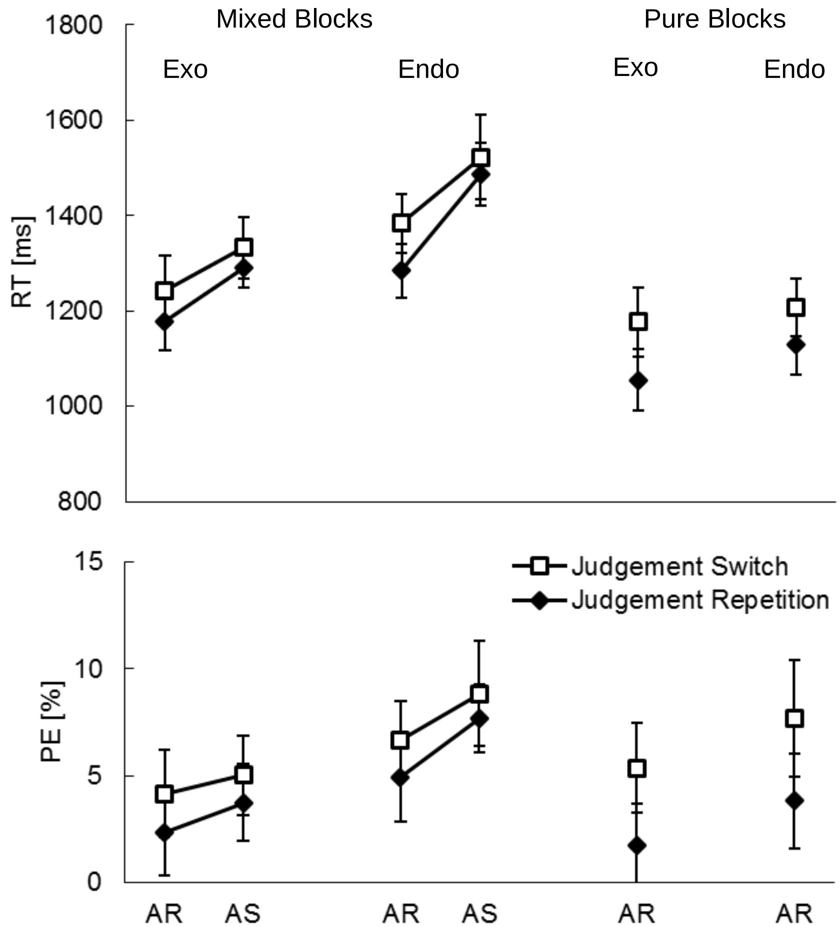


*Figure 3.* Descriptive results of the RT and PE data of Experiment 2 as a function of attention transition (repetition [AR] vs. switch [AS]), judgement transition (repetition vs. switch), cue type (exogenous cues [Exo] vs. endogenous cues [Endo]) and attention block (pure blocks vs. mixed blocks). The error bars reflect 95% Cousineau-Morey Confidence Intervals (Morey, 2008).

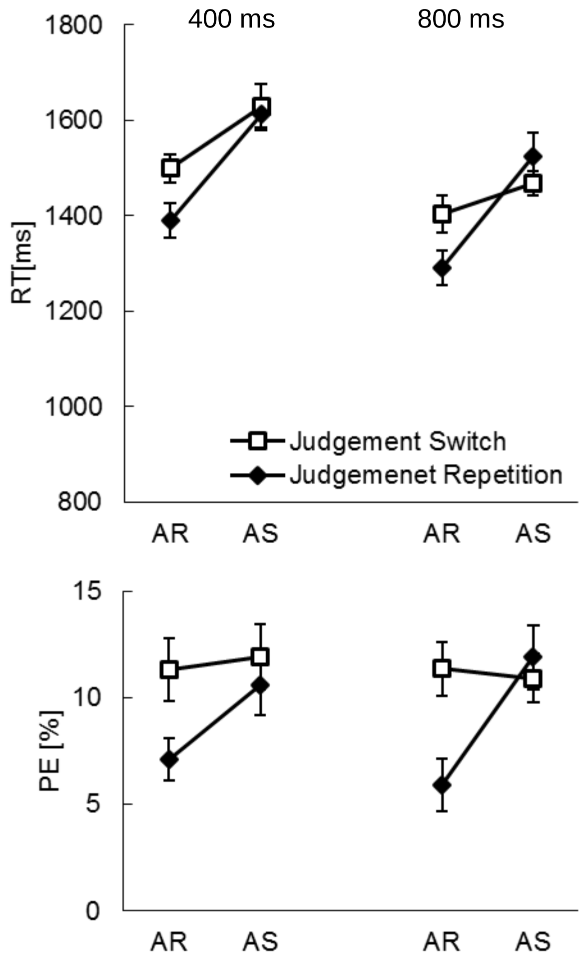


*Figure 4.* Descriptive results of the RT and PE data of Experiment 3 as a function of attention transition (repetition [AR] vs. switch [AS]), judgement transition (repetition vs. switch), and CSI (400 ms vs. 800 ms). The error bars reflect 95% Cousineau-Morey Confidence Intervals (Morey, 2008).

**Study D**

Seibold, J. C., Koch, I., Nolden, S., Proctor, R. W., Vu, K.-P. L., & Schuch, S. (2018).

*Exploring response repetition effects in auditory task switching: Response discriminability and task-set decay.*

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# Exploring response repetition effects in auditory task switching: Response discriminability and task-set decay

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ABSTRACT

In task switching studies, typically response repetition effects are obtained. Namely, when the task repeats, response repetitions are faster than response switches (response repetition benefit), but when the task switches, the opposite is found (response repetition cost). Previous studies mainly used visual stimulus material, but in the present study we examined whether the effects would also be obtained with auditory stimuli. Since spatial and temporal processing are assumed to be quite different in the auditory modality than in the visual modality, we manipulated spatial response distance and the response-stimulus interval (RSI). The results confirmed that response repetition effects can also be obtained in a setup with auditory stimuli and therefore seem to arise independent of stimulus modality. However, spatial response distance did not modulate the response repetition effects like it did in a previous study employing visual stimuli (Koch, Schuch, Vu, & Proctor, 2011). In contrast, the RSI manipulation was successful, since task switch costs were smaller in blocks of trials with long RSI than with short RSI, suggesting task set decay during the RSI. At the same time, a prolonged RSI led to more pronounced response repetition effects in the error rates, due to increased response repetition costs in task switches. We suggest that a long RSI provided more time for binding the selected task-specific response code to the physical response. Therefore, especially in task switches, the unbinding of the physical response from the previous task's response was more costly.

*Keywords*: response repetition effects, task switching, audition, response inhibition

When participants execute one of two randomly assigned tasks in each trial, typically, reaction times (RTs) and error rates are lower when the task of the previous trial repeats, compared to when it switches. The performance difference between such task switches and task repetitions is called *switch cost* (Jersild, 1927; for reviews, see Kiesel et al. 2010; Koch, Poljac, Müller, & Kiesel, 2018; Vandierendonck, Liefooghe, & Verbruggen, 2010).

Often, in task switching studies, the same two response keys are used for both tasks but have a different meaning in each task. For example, when participants categorize a number stimulus as odd vs. even (parity task), or as smaller vs. larger than five (magnitude task), a left key press is required for an "odd" response in the parity task and for a "smaller" response in the magnitude task.

When looking at response repetitions and switches, often only very small response switch costs occur overall, yet performance in response repetitions and switches varies as a function of task repetition and switch. Namely, in task repetitions, response repetitions are faster and more accurate than response switches (response repetition benefit), whereas in task switches, response repetitions are slower and more error prone than response switches (response repetition costs; see response repetition effects e.g. in Altmann, 2011; Brown, Reynolds, & Braver, 2007; Druey, 2014a; Druey, 2014b; Hübner & Druey, 2006; Kleinsorge, 1999; Kleinsorge & Heuer, 1999; Koch, Frings, & Schuch, 2018; Koch, Schuch, Vu, & Proctor, 2011; Schuch & Koch, 2004; Schuch & Koch, 2010; Rogers & Monsell, 1995; for a review see also Gade, Schuch, Druey, & Koch, 2014). In the following, we refer to this specific interaction pattern as response repetition effects.

The response repetition effects are assumed to arise on the response selection level (Druey, 2014b), since a study of Campbell and Proctor (1993) showed that response repetition effects can be obtained even across hands and fingers. It was, however, crucial that the coding of the responses was consistent across effectors (see also Pashler & Baylis, 1991). In line with that, Hübner and Druey (2006), as well as Schuch and Koch (2010) could demonstrate that response execution (i.e. executing the motor response) is not a necessary requirement for response repetition effects to arise in the subsequent trial, since the response only needed to be selected to produce the effects.

Moreover, spatial response distance modulated responding in general, across task switches and repetitions. Koch et al. (2011) compared performance in experimental blocks in which participants responded with adjacent left and right response keys to performance in blocks with separated response keys. In the blocks with separated response keys, smaller response repetition benefits and larger response repetition costs were found than in blocks with adjacent response keys, since the RTs of response repetitions increased across task repetitions and switches.

Koch et al. (2011) proposed that spatial response distance increased the response discriminability and therefore facilitated responding. According to the response inhibition account (see Druey, 2014b; Druey & Hübner; 2008; Grzyb & Hübner, 2013; Hübner & Druey, 2006; Hübner & Druey, 2008; Rogers & Monsell, 1995; Steinhauser, Hübner, & Druey, 2009), a response is generally inhibited after its execution to avoid response perseveration. The response inhibition leads to a general slowing of the repeated response in the subsequent trial. Response repetition benefits are proposed to be independent of response inhibition and arise from stimulus category priming in task repetitions (Druey, 2014b; Rogers & Monsell, 1995) – or from episodic binding that elicits priming due to similarities of the retrieval context to the encoding context (Koch, Frings, & Schuch, 2018). Referring to the proposed response inhibition, Koch et al. (2011) suggested that facilitated responding with separated response keys increased the risk for response perseveration and therefore elicited stronger response inhibition.

An alternative account suggests that task performance leads to stronger task-specific binding between responses and stimulus categories. Those bindings produce positive priming in task repetitions but negative priming in task switches (Schuch & Koch, 2004). Yet, within this account, there is no good explanation for the modulation of responding by spatial response distance.

To our knowledge, response repetition effects have been assessed within visual task switching paradigms so far. Therefore, the present study's aim was to examine response repetition effects in a paradigm with auditory stimuli. Although we think that the response repetitions effects should generalize to a setup with auditory stimuli, there are reasons to assume that the response distance effect obtained in Koch et al.'s (2011) study may not necessarily persist. Visual processing deviates in certain characteristics from auditory processing. Visual objects can be explored by strategic fixations and saccades to assess the relevant features, whereas an auditory object forms over time and is characterized more by its temporal dynamics than by its spatial features (see, e.g., Shinn-Cunningham, 2008). In line with that distinction, some studies suggest that spatial relations are more salient in vision than in audition (see e.g., Aschersleben & Bertelson, 2003; Lukas, Philipp, & Koch, 2010, 2014; Shams, Kamitani, &

Shimojo, 2000; Tomko & Proctor, 2017). On a neutral level, visual spatial relations are more or less directly projected to the primary visual cortex, whereas this seems to be less evident for spatial relations in the primary auditory cortex (King & Nelken, 2009).

Hence, the aim of the first experiment was to replicate response repetition effects in a paradigm with auditory stimuli. Moreover, we manipulated response distance by using blocks with different spatial response distances, like in Koch et al. (2011), to see whether responding was affected by response key distance despite the auditory stimulus processing requirements.

## Experiment 1

### Method

**Participants**. Twenty-four German-speaking students (20 female, 1 left-handed, *M* = 23 years, *SD* = 4.2, range from 18 to 28) from the RWTH Aachen University took part in the experiment and received partial course credit or 6 €. We planned our sample size based on Koch et al. (2011), who obtained a reliable interaction of task transition and response transition (i.e., the response repetition effects) and the modulation by spatial response distance in which we were interested.

**Apparatus, stimuli, tasks and procedure**. The experiment was run under Linux in PsychoPy 2.0 (Peirce, 2008). The stimuli were the spoken number words from 1 to 9, excluding 5, presented auditory via headphones (Sennheiser PMX 95) by a male speaker. The stimuli were recorded at the Institute of Technical Acoustics of the RWTH Aachen University in an anechoic chamber, and they were adjusted for subjective loudness (DIN 45613) as well as for duration (600 ms). Participants were seated at about 60 cm viewing distance from the monitor (22-inch LG 22MB65PM), on which visual cues (average height 3.3 cm, average width 3.0 cm) were presented centrally in black font on a white background.

The participants had to switch between a parity judgment (odd vs. even) and a magnitude judgment (smaller vs. greater than 5) of the number stimulus. At the beginning of each trial, a cue indicated which task to perform on the auditory stimulus. A dollar sign cue ($) required a magnitude judgment and a percentage sign cue (%) required a parity judgment. The participants responded by pressing one of two horizontally aligned response keys on a German computer keyboard (QWERTZ). Namely, in the magnitude judgment task, numbers smaller than five required a left response and numbers larger than five required a right response (compatible to the mental number line; see Dehaene, Bossini, & Giraux, 1993). The S-R mapping of the parity judgment was counterbalanced across participants (left response for an odd number and right response for an even number, or vice versa).

In the previous study of Koch et al. (2011), all immediate stimulus repetitions and direct stimulus-task repetition episodes (same stimulus when the task was executed the last time) were excluded from the experimental procedure to avoid stimulus repetition priming and measure ‘pure’ response repetition effects. The experiment was programmed in a way that while stimulus repetitions were not possible, it was still controlled that response repetitions and switches occurred equally often in each experimental condition, thus avoiding local switch biases (cf. Altmann, 2011). Here we took a slightly different approach; rather than excluding stimulus repetitions from the experimental procedure, we discarded them afterwards in the data analyses.

The spatial response distance was manipulated between blocks of trials, with either adjacent response keys ‘v’ and ‘b’, or spatially separated keys ‘x’ and ‘m’ (4 keys in-between[8]) on the bottom row of the keyboard. The response keys had to be pressed with the index fingers of both hands, respectively.

The experiment consisted of two halves, which differed by their response key distance. Each response distance condition was preceded by eight training trials and contained four blocks of 120 trials, each, which resulted in a total of 960 experimental trials. One experimental session took about 40 minutes. Each trial started with the presentation of the visual cue, which remained visible until a response was executed. After a cue-stimulus interval (CSI) of 200 ms the auditory stimulus was presented, which required a response. As soon as a response was registered, a response cue interval (RCI) of 200 ms followed. In case of an incorrect response, the word “Fehler” (German for “error”) was printed in red on the screen for 500 ms immediately after the response, thereby prolonging the RCI.

**Design.** The independent variables were task transition (repetition vs. switch), response transition (repetition vs. switch), and spatial response distance (adjacent keys vs. separated keys; block-wise). The dependent variables were RTs and PEs.

**Results and discussion**

For the analyses we excluded the training trials, the first trial of each block, the immediate stimulus repetitions and immediate task-stimulus combination repetitions (14.6%), and trials following an error (5.4%). For the analysis of the RT, we also excluded erroneous trials and RT

[8] The response key distance was smaller than in Koch et al. (2011), but since the conceptual spatial response distance (presence of intervening keys) seems to matter for response discriminability, rather than physical spatial response distance (e.g., Proctor & Chen, 2014), the distance should be sufficient to replicate the effects.

outliers that deviated more than three standard deviations from a participant's mean (2%). An analysis of variance (ANOVA) was conducted with the RT and error rate data.

In the RTs (see Figure 1, upper row),, task transition elicited a main effect, $F(1, 23) = 46.63$, $p < .001$, $\eta_p^2 = .68$, revealing task switch costs of 144 ms. Task transition interacted with response transition, $F(1, 23) = 10.75$, $p = .003$, $\eta_p^2 = .33$. In task repetitions, response repetition benefits of 40 ms were present, $t(23) = 2.94$, $p = .008$, and in task switches, response repetition costs of 23 ms, $t(23) = -1.75$, $p = .094$. Thus, we obtained the expected pattern of response repetition effects, which confirms that previous response repetition effect findings are generalizable to setups with auditory stimuli. Spatial response distance did not elicit any significant effect, and all other effects were nonsignificant, $F$s < 2.7, $p$s > .11.

The error rates (Figure 1, lower row) confirmed the pattern obtained in the RTs. Namely, a main effect of task transition was obtained, $F(1, 22) = 6.15$, $p = .021$, $\eta_p^2 = .22$, with task switch costs of 1.5%. Moreover, a response transition main effect was present, $F(1, 22) = 12.24$, $p = .002$, $\eta_p^2 = .36$, revealing overall response repetition costs of 2.2%. Like in the RTs, task transition interacted with response transition, $F(1, 23) = 15.59$, $p = .001$, $\eta_p^2 = .42$. In task repetitions, non-significant response repetition costs of 0.2% were found, $t(23) = -.24$, $p = .812$, and in task switches, response repetition costs of 4.3%, $t(23) = -5.66$, $p < .001$.

Spatial response distance only marginally interacted with task transition in the error rates, $F(1, 23) = 3.54$, $p = .073$, $\eta_p^2 = .14$, with 2.1% larger task switch costs in blocks with adjacent keys compared to blocks with separated keys. All other effects were nonsignificant, $F$s < 1.1, $p$s > .31.

This pattern of results means that although spatial response distance supposedly increased response discriminability, this difference did not modulate the response repetition effects reliably in the RTs or in the error rates. Such a null-effect must, of course, be interpreted cautiously, but it could indicate that response distance is less relevant in a paradigm employing auditory stimuli than in Koch et al.'s (2011) setup with visual stimuli. Still, a replication of this null effect in Experiment 2 is needed before drawing conclusions.

## Experiment 2

Experiment 2 was only partly a replication of Experiment 1, since we also introduced a block-wise manipulation of the response-stimulus interval (RSI). In Experiment 1, we used a relatively short RCI of 200 ms, which together with the cue-stimulus interval (CSI) of 200 ms resulted in an RSI of 400 ms. Koch et al. (2011), as well as many other studies on response repetition effects in task switching, used longer RSIs than we did (e.g., RSI of 1000 ms in Altmann, 2011; RSI of 1500 ms in Druey & Hübner, 2008; RSI of 1600 ms in Koch et al., 2011).

In task switching research, it was proposed that during the RSI, the previous task-set (i.e. the representation of task-specific goals, response rules and other operations demanded by the task; see Logan & Gordon, 2001) dissipates over time. A prolonged RSI usually leads to reduced task switch costs, presumably due to less interference between the previous and the present trial (Allport et al., 1994; Altmann, 2005; Meiran, 1996). Importantly, previous studies found that the RSI effect in randomly varying RSIs depends more on the ratio of the current RSI to the preceding RSI than on the absolute duration of the RSI (Horoufchin, Philipp & Koch, 2011).Therefore, in the present study we used a blocked manipulation of RSI. However, in an earlier study using an auditory attention switching paradigm with auditory number stimuli, no signs of task set decay were detected (Koch & Lawo, 2014). Thus, it is unclear whether the task-set decay also affects response repetitions effects.

Rogers and Monsell (1995) suggested that response inhibition, which according to the response inhibition account (Druey, 2014b) is supposedly applied after each response selection, may decay during the RSI. Hence, one would expect larger response repetition benefits and smaller response repetition costs with long RSI relative to with short RSI. Alternatively, a prolonged RSI could also increase the temporal response discriminability (i.e. the time interval between two subsequent responses is prolonged). Such increased temporal response distance could facilitate responding like the spatial response distance supposedly did in the visual setup of Koch et al. (2011). Hence, potentially increased *temporal* response discriminability should lead to a higher risk for response perseveration and therefore to stronger response inhibition (which was the rationale for spatial response discriminability in the study of Koch et al., 2011). Thus, an increase of the overall response repetition RTs in blocks with long RSI would be expected.

**Method**

**Participants**. Twenty-four new German-speaking students (20 female, 1 left-handed, *M* = 20.6 years, SD = 2.1, range from 18 to 28) from the RWTH Aachen University took part in the experiment and received partial course credit or 8 €.

**Apparatus, stimuli, tasks and procedure**. The setup apparatus and stimuli were the same as in Experiment 1. The RSI manipulation was implemented by comparing experimental blocks with the short RCI of 200 ms, as in Experiment 1, to blocks with a long RCI of 1400 ms (Koch et al., 2011). The CSI was kept constant at 200 ms.

The experiment consisted again of two halves, which differed by their response key distance, and they were each preceded by eight practice trials. Blocks with short and long RCI alternated, and it was counterbalanced between participants whether the starting block contained a long or short RCI. Each experimental block consisted of 120 trials, and since there were two blocks per spatial response distance and RCI length, the experiment contained in a total of 960 experimental trials.

**Design.** The independent within-subjects variables were task transition (repetition vs. switch), and response transition (repetition vs. switch) as well as spatial response distance (adjacent keys vs. separated keys; block-wise), and RSI (400 ms vs. 1600 ms; block-wise). The dependent variables were RTs and PEs.

**Results and discussion**

For the analyses, the training trials, the first trial of each block as well as the above mentioned immediate stimulus repetitions (11.9%), and trials following on an error (7.6%) were excluded. For the analysis of the RT, we also excluded all erroneous trials and RT outliers that deviated more than three standard deviations from a participant's mean (1.9%).

The analysis of the RTs (see Figure 2, upper row) revealed a main effect of task transition, $F(1, 23) = 56.46$, $p < .001$, $\eta_p^2 = .71$, with task switch costs of 101 ms. Task transition interacted with response transition, $F(1, 23) = 17.03$, $p < .001$, $\eta_p^2 = .43$. In task repetitions, response repetition benefits of 27 ms were obtained, $t(23) = 3.54$, $p = .002$, and in task switches, response repetition costs of 34 ms, $t(23) = -2.62$, $p = .015$. Hence, the response repetition effects were successfully replicated.

The new manipulation of RSI elicited a main effect, $F(1, 23) = 17.42$, $p = .001$, $\eta_p^2 = .43$, with 79 ms longer RTs in blocks with long RSI than in blocks with short RSI. RSI also interacted with task transition, $F(1, 23) = 18.51$, $p = .001$, $\eta_p^2 = .46$, showing a task switch cost reduction of 53 ms in blocks with long RSI compared to those with short RSI. The latter finding is in agreement with the idea of task-set decay (Altmann, 2005; Koch, 2001; see review of Kiesel et al., 2010).

The spatial response distance elicited a trend for a three-way interaction with RSI and response transition (see Figure 2), $F(1, 23) = 4.10$, $p = .055$, $\eta_p^2 = .15$. Although, this latter interaction was nonsignificant, we conducted post-hoc comparisons to see whether the results are comparable to those of Experiment 1. In blocks with short RSI, spatial response distance did not interact significantly with response transition, $F(1, 23) = 1.74$, $p = .200$, $\eta_p^2 = .07$, which replicates the pattern in Experiment 1. Namely, adjacent response keys led to overall response repetition costs of 11 ms and separated keys to benefits of 9 ms. In blocks with long RSI, the interaction was significant, $F(1, 23) = 4.68$, $p = .041$, $\eta_p^2 = .17$. Here, adjacent keys led to overall response repetition benefits of 18 ms, and separated keys to costs of 13 ms (both *p*s > .110). Hence, in the RTs of blocks with long RSI, the pattern replicates roughly the pattern obtained by Koch et al. (2011). However, since the spatial response distance elicited the opposite trend in blocks with short RSI, one should be cautious when interpreting this effect. Besides, in Experiment 1, no significant modulation of the RTs by spatial response distance was obtained. All other effects were nonsignificant, *F*s < 2.8; *p*s > .10.

The analysis of the error rates (Figure 2, lower row) confirmed and extended the findings in the RTs. It revealed a main effect of task transition, $F(1, 23) = 18.92$, $p < .001$, $\eta_p^2 = .53$, with task switch costs of 2.3%. Response transition also elicited a main effect, $F(1, 23) = 50.79$, $p < .001$, $\eta_p^2 = .69$, with overall response repetition costs of 4.8%. Task transition interacted with response transition, $F(1, 23) = 25.48$, $p < .001$, $\eta_p^2 = .53$. Response repetition costs of 1.5% were obtained in task repetitions, $t(23) = -1.97$, $p = .061$, and response repetition costs of 8.1% in task switches, $t(23) = -7.66$, $p < .001$. These results confirm the generalizability of the response repetition effects to setups with auditory stimuli.

Like in the RTs, RSI elicited a main effect, $F(1, 23) = 25.82$, $p < .001$, $\eta_p^2 = .53$, with 1.8% more errors in blocks with long RSI than in blocks with short RSI. Differently than in the RTs, RSI did not interact with task transition, but with response transition, $F(1, 23) = 9.65$, $p = .005$, $\eta_p^2 = .30$. The overall response repetition costs were 3.8% with short RSI, $t(23) = -5.10$, $p < .001$, and increased to 6.0% with long RSI, $t(23) = -7.51$, $p < .001$. Such a finding speaks against a decay of response inhibition, because that should have led to reduced rather than increased response repetition costs with long RSI (see Rogers & Monsell, 1995).

Moreover, unlike in the RTs, RSI modulated the interaction of task transition and response transition. The three-way interaction was significant, $F(1, 23) = 4.91$, $p = .037$, $\eta_p^2 = .18$. Broken down by RSI, the interaction of task transition and response transition was significant with short and long RSI, $F(1, 23) = 10.55$, $p = .004$, $\eta_p^2 = .31$, and $F(1, 23) = 34.96$, $p < .001$, $\eta_p^2 = .60$, but more pronounced in blocks with long RSI. In blocks with short RSI, response repetition costs of 1.1% were obtained in task repetitions, $t(23) = -1.17$, $p = .255$, and increased to

6.1% in task switches, $t(23) = -5.07$, $p < .001$. In blocks with long RSI, response repetition costs of 2% were obtained in task repetitions, $t(23) = -2.18$, $p = .040$, and response repetition costs of 10.1% in task switches, $t(23) = -8.58$, $p < .001$. Hence, especially the response repetition costs in task switches were increased in blocks with long RSI.

Spatial response distance elicited a significant interaction with RSI, $F(1, 23) = 9.33$, $p = .006$, $\eta_p^2 = .29$, since in trials with short RSI 1.6% fewer errors were obtained with adjacent than with separated keys, whereas in blocks with long RSI 0.8% more error were present with adjacent keys than with separated keys. Moreover, spatial response distance showed a numerical tendency to interact with task transition, $F(1, 23) = 3.48$, $p = .075$, $\eta_p^2 = .13$, with 1.5% smaller task switch costs in the blocks with adjacent keys. All other effects were nonsignificant, *F*s < 2.7, *p*s > .11.

## General Discussion

In the present study, we investigated whether response repetition effects in task-switching are generalizable to a setup with auditory stimuli. Moreover, we examined the impact of spatial response distance and RSI on response repetition effects.

### Response repetition effects

We obtained response repetition effects (i.e. response repetition benefits in task repetitions and response repetition costs in task switches) in both experiments, in the RTs and error rates, which means that the response repetition effect pattern was successfully replicated in our setup with auditory stimuli. Moreover, in the error rates of both experiments, pronounced response repetition costs were obtained in task switches, but no response repetition benefits in task repetitions. In fact, the response repetition costs were also obtained in task repetitions, albeit much smaller than in task switches (see similar patterns reported by Koch, Frings, & Schuch, 2018, and Rogers & Monsell, 1995).

### Spatial response distance

In the previous study of Koch et al. (2011), the response repetitions were modulated by spatial response distance – namely, separate keys led to longer response repetition RTs than adjacent keys. In the present study, in Experiment 2 increased spatial response distance only numerically increased the response repetition RTs in blocks with a long RSI. In blocks with a short RSI, the opposite pattern was found, and in Experiment 1 no trend in either direction was obtained.

One could criticize that we used a smaller key distance in the separate keys condition in our experiment than that used by Koch et al. (2011; 9.5 cm vs. 21 cm). Yet, we do not see any good reason why our response distance was not sufficient to elicit a potential modulation of the response repetitions and switches, since the conceptual distance (e.g., the presence of intervening keys) seems to affect responding more than the physical distance (Chen & Proctor, 2014). Moreover, the opposing pattern with respect to response distance was obtained in blocks with a short RSI, which suggests that spatial response distance may not affect response repetitions and switches in general – at least not with auditory stimuli. We believe that our use of auditory stimuli may serve best as an explanation for the null effects with respect to spatial response distance. It could have attenuated attention to spatial features of the setup and thereby attenuated the impact of the spatial response key distance on responding.

Besides, we think it is worth noting that spatial response distance, at best, slightly affected responding, whereas it did not modulate task switches and repetitions in any way in both experiments. Within the additive factors logic (Sternberg, 1969) it is assumed that an interaction of two variables is obtained when they affect the same processing stage. The absence of a modulation of the task switch costs by spatial response distance does, of course, not necessarily in reverse imply that the variables affected different processing stages and were independently processed - yet, this possibility should be considered.

**Task-set decay**

The RSI manipulation elicited more pronounced effects than spatial response distance, since a long RSI increased RTs and error rates in general. This is opposite to the trends found in other task switching studies that also manipulated the RSI and found shorter RTs or no change with long RSI (e.g., Kleinsorge, 1999; Rogers & Monsell, 1995; but see also Experiment 3 of Altmann, 2005). Moreover, a long RSI led to a reduction of the task switch costs, which is compatible with the assumption that the task set decays between trials (Altmann, 2005; Koch, 2001; see Horoufchin et al., 2011, for an extensive discussion). However, the response repetition effects did not show any sign of decay, since the error rates of response repetitions became higher when the RSI was long, especially in task switches. This finding implies that the presumed response inhibition that is said to contribute to the response repetition costs did not decay during the long RCI, as suggested by Rogers and Monsell (1995; but see for opposite predictions Duncan & Lewandowsky, 2005). In line with that, there was also no reliable effect of a decay of response repetition priming in task repetitions either, as it was earlier described by Rogers and Monsell (1995; see also Altmann, 2005; Kleinsorge, 1999).

The increased response repetition costs in task switches (in error rates) also seem to speak against the idea that the RSI increases temporal response discriminability, since the response discriminability hypotheses predicts similar response repetition performance decrements in task repetitions and switches (Koch et al., 2011). Moreover, the fact that the RSI manipulation also affected the task switch costs suggests that the modulation of response-repetition effects by spatial response distance processing and by RSI are likely to stem from different mechanisms.

The present study's results with respect to the RSI manipulation may rather be interpretable in terms of the episodic binding account of Schuch and Koch (2004). Namely, a long RSI could provide the possibility for the formation of stronger bindings of the features of the previous trial's episode. Such an idea was proposed by Philipp and Koch (2010), who found a more pronounced interaction pattern of task switches and response modality switches when there was more time for binding within a trial. We believe that this idea could also be applied to the present study. Namely, the resulting stronger bindings might especially have elicited more pronounced costs of "unbinding," which are basically failures of unbinding in the error rates. The little variation that was obtained in response repetition error rates between the different experimental blocks when the task repeated could reflect a floor effect of the episodic priming.

**Conclusion**

The present study demonstrated that response repetition effects in task-switching found with visual stimuli are generalizable to auditory stimuli. However, with auditory stimuli, the spatial response distance did not modulate responding, unlike in the previous study of Koch et al. (2011) that used visual stimuli. We suggest that the auditory modality-specific stimulus processing attenuated the relevance of spatial relations and thereby the impact of spatial response distance. Moreover, a prolonged RSI led to generally increased RTs and error rates and specifically to increased response repetition costs in the error rates of task switches. This finding is incompatible with the predictions based on response inhibition, which is presumed to decay over time (Druey, 2014b). We therefore proposed that a prolonged RSI provided more time for binding of the previous trial's features, and that this may have especially increased the probability for failed unbinding of the response in response repetitions of task switches.

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**Figures and Tables**

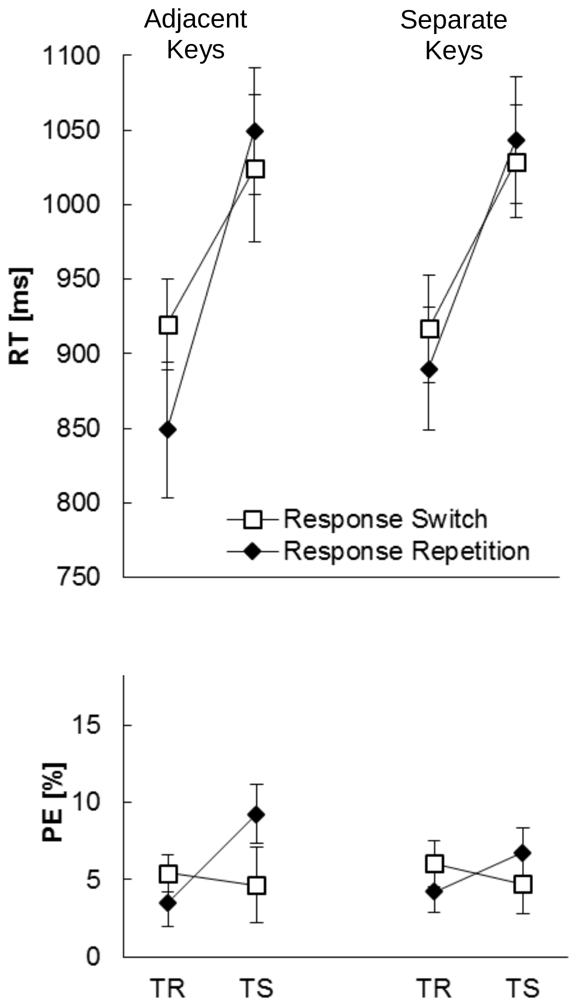


*Figure 1.* RT (upper row) and PE (lower row) of Experiment 1 as a function of task transition (repetition [TR] vs. switch [TS]), response transition (repetition vs. switch), and spatial response distance (adjacent vs. separate keys). The error bars reflect 95% Cousineau-Morey Confidence Intervals (Morey, 2008).

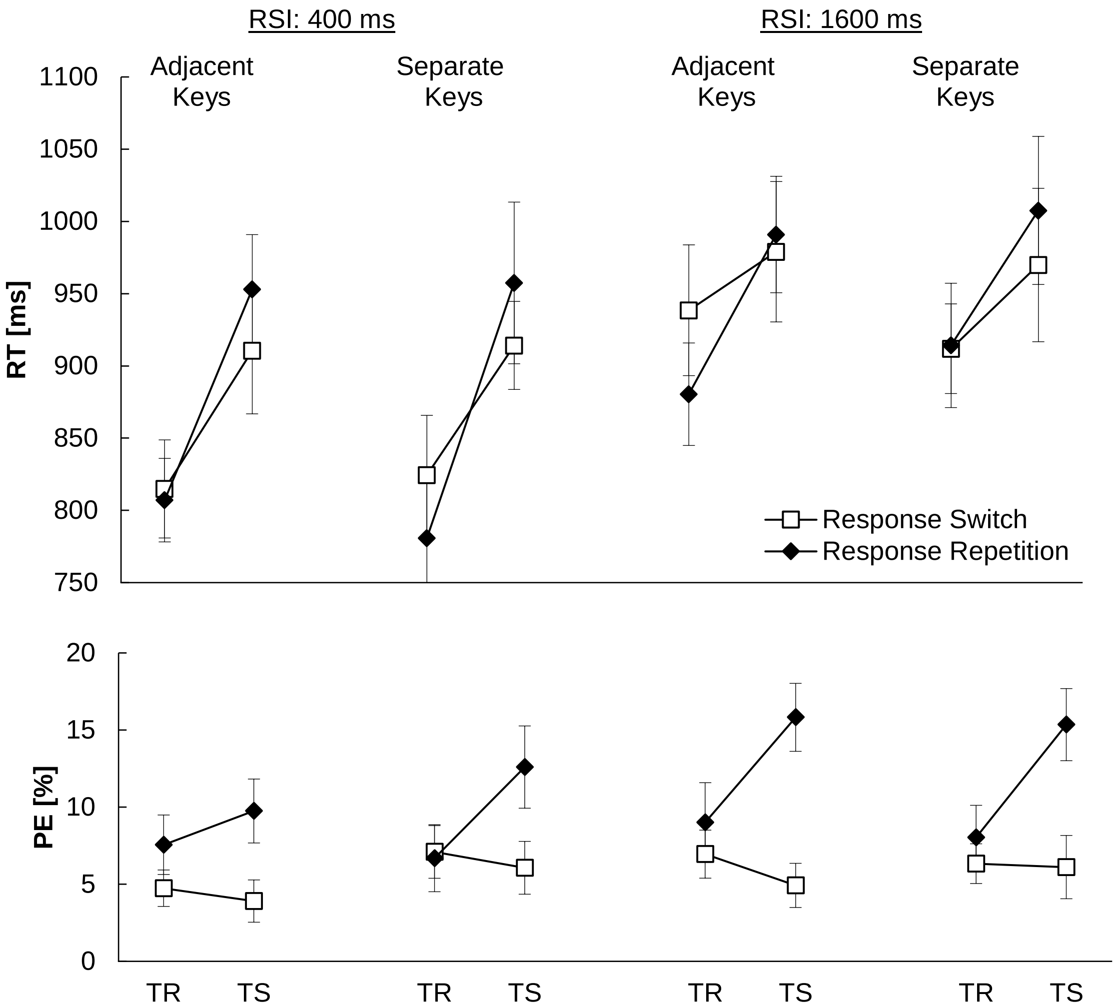


*Figure 2.* RT (upper row) and PE (lower row) of Experiment 2 as a function of task transition (repetition [TR] vs. switch [TS]), response transition (repetition [RR] vs. switch [RS]), spatial response distance (adjacent vs. separated keys), and RSI (400 ms vs. 1600 ms). The error bars reflect 95% Cousineau-Morey Confidence Intervals (Morey, 2008).