Auditory attention switching and judgment switching: Exploring multicomponent task representations

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Abstract

An auditory attention-switching paradigm was combined with a judgment-switching paradigm to examine the interaction of a varying auditory attention component and a varying judgment 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 judgment that had to be executed (Experiment 2). Hence, the attentional selection criterion switched independently between speaker sexes (or between ears), while the judgment alternated between letter categorization and number categorization. The data indicate that auditory attention criterion and judgment were not processed independently, regardless of whether the attention criterion or the judgment was cued. The partial repetition benefits of the explicitly cued component suggested a hierarchical organization of the auditory attention component and the judgment component within the task set. We suggest that the hierarchy arises due to the explicit cuing of one component rather than due to a “natural” hierarchy of auditory attention component and judgment component.

Keywords Attention: selective · Attention: space-based · Audition

Studies showed that switching between different judgments is costly in terms of reaction times and error rates. Such judgment switch costs are usually measured as the performance difference between judgment repetition trials and judgment switch trials and are supposed to represent, at least partly, the additional time required for judgment reconfiguration in a switch trial (i.e., the costs; Jersild, 1927; for reviews, see Kiesel et al., 2010; Koch, Poljac, Müller, & Kiesel, 2018; Vandierendonck, Liefoghe, & 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 judgment repetitions may as well contribute to the performance differences score. Therefore, we use performance in judgment

switches as a baseline (see similar ways of reporting task-switching data also in Dreisbach, Haider, & Kluwe, 2002; Koch, 2001, 2005; Oberauer, Souza, Druey, & Gade, 2013; Ruthruff, Remington, & Johnston, 2001; Schmidt & Liefoghe, 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 Liefoghe (2008) used a cued switching paradigm in which an additional cue indicated whether participants had to perform a judgment (parity judgment or magnitude judgment) 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 to or did not correspond to the number at the global dimension). Thus, in every trial, a repetition (or switch) of the judgment, 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, 2004; Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001, 2002; Murray, De Santis, Thut, & Wylie, 2009; Philipp & Koch, 2010;

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Sandhu & Dyson, 2013). The pattern of the interaction of judgment component and stimulus dimension component in Vandierendonck et al.'s (2008) study was very similar to that of other multicomponent switching studies and will be described using performance in complete switches (judgment switch and stimulus dimension switch) as a baseline.

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

We always used the term *component* when taking about, for example the varying stimulus dimension of Vandierendonck et al.'s (2008) setup. The term was employed because we consider stimulus dimension and the judgment components of a “task set,” which, according to Oberauer et al. (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 judgment 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 reused (see a 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 multicomponent 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, Töllner, Müller, & Zehetleitner, 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 (RTs) were even shorter in complete switches than in partial repetitions, aside from the findings of similar RTs and findings of slightly higher RTs 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, 2004; Kleinsorge & Heuer, 1999; 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 judgment switches were dominant to stimulus dimension switches (Kleinsorge, 2004) and dominant to response mapping switches (Kleinsorge & Heuer, 1999). It was argued that the judgment is dominant because the participant communicated the judgment's results by the responses. However, it is not clear whether this argument also generalizes to other components and whether also the fact that both components were cued simultaneously in the studies of Kleinsorge and colleagues contributed to the result pattern. For example, Philipp and Koch (2010) found that the sequential cuing (early and late in the cue-stimulus interval [CSI]) of a judgment 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 multicomponent switching studies

Fig. 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

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 multicomponent 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; Moray, 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, and 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 (judgment 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 judgment was cued implicitly. Namely, the judgment needed to be identified based on the type of the selected target. It was not predictable based on the attention cue in which judgment was required so that the participants could not actively prepare for a specific judgment, unlike in other multicomponent 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 judgment 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). To see whether

such spatial inertia could also modulate the expected interaction of an attention component and a judgment component in the present study, we compared performance in an experimental block with speaker-sex cuing to performance in a block with ear cuing.

Method

Participants Earlier studies on multicomponent switching used sample-sizes of fewer than 12 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 between 19 and 35 years of age ($M = 23.9$, $SD = 3.8$) 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 one to nine, except for five, 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 (Koch & Lawo, 2014; Lawo et al., 2014; Seibold, Nolden, Oberem, Fels, & Koch, 2017). In the speaker-sex cuing 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-cuing block, the German word *links* (“left”) or the symbol of a leftward-pointing arrow indicated that the target would be presented to the left ear, and the word *rechts* (“right”) or the

symbol of a rightward-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, respectively. 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, respectively. The stimulus–response 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 of either 100 ms or 1,000 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 response-cue interval (RCI) of either 1,100 ms or 200 ms, which was varied inversely to the previous CSI duration.¹ 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 Fig. 2 for an illustration).

Design The independent variables were attention transition (repetition vs. switch), judgment transition (repetition vs. switch), and cuing dimension (speaker sex vs. ear cuing; block wise). The dependent variables were reaction times (RTs) and percentage of errors (PEs).

¹ Please note that this was a programming error, which led to three-different possible RSI lengths (i.e., RCI + CSI: 200 + 100; 200 + 1,000; 1,100 + 100; 1,100 + 1,000), 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 cuing dimension, cue type, attention transition, and task transition, so that the effects of these latter variables can still be interpreted.

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 (ANOVAs) 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 judgment transition, $F(1, 23) = 15.49, p = .001, \eta_p^2 = .40$, with judgment repetition benefits of 64 ms. Attention transition and judgment transition also interacted, $F(1, 23) = 4.78, p = .039, \eta_p^2 = .17$. 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 judgment repetitions benefits of 39 ms were obtained, $t(23) = 2.80, p = .010$. The manipulation of cuing dimension did not elicit any reliable effect ($F_s < 3.0, p_s > .10$; see also Fig. 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%. Judgment transition also elicited a main effect, $F(1, 23) = 12.60, p = .002, \eta_p^2 = .35$, with judgment repetition benefits of 3.3%. Attention transition and judgment 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 judgment repetitions to a benefit of 1.8%, $t(23) = 1.94, p = .065$. Cuing dimension did not elicit any significant effect ($F_s < 1.6, p_s > .22$).

In summary, we obtained attention repetition benefits and judgment 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 nonperceptual, 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 judgment 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 judgment component. 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

Fig. 2 Examples of two trials from a block with ear cuing and a block with speaker-sex cuing, respectively. The mapping of number and letter to left versus right ear changed randomly from trial to trial

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 RTs 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 judgment component arises due to a “natural” hierarchy of attention criteria and judgments. 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 to that of Experiment 1, but we exchanged the ear-cuing block with a block in which the judgment was cued in order to compare the attention-cuing block (speaker-sex cuing) to a judgment-cuing block. In case of a “natural” hierarchy of attention component and judgment component, the result pattern should be similar in the attention-cuing block and in the

judgment-cuing block—and the interaction pattern should resemble 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 cuing vs. judgment cuing), which should show up as the three-way interaction of cue type, attention transition, and judgment transition.

Technically, the introduction of the judgment-cuing block required an extension of the mapping rules. When cuing the judgment, attention switches (i.e., speaker-sex switches) would be entirely irrelevant for response selection. In contrast, in the attention-cuing block, speaker sex and judgment are both relevant for response selection, since the target judgment 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 judgment-cuing block as it was already in the attention-cuing 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 their right hand.

Method

Participants A new group of 24 German-speaking students (19 women) from the RWTH Aachen University, between 18 and 25 years of age ($M = 21.3$, $SD = 2.3$), took part and received partial course credit or €12 (€8 per hour) for their

Fig. 3 RTs (reaction times) and PEs (percentage of errors) of Experiments 1 and 2 as a function of attention transition (repetition [AR] vs. switch [AS]), judgment 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. judgment cueing) in Experiment 2. Error bars reflect 95% Cousineau–Morey confidence intervals (Morey, 2008)

participation in the experiment.² 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, respectively) at the beginning of a trial indicated the target speaker's sex in the

attention-cuing blocks (like in Experiment 1), or the judgment (letter or number) in the judgment-cuing blocks. This time, a 1:1 cue-to-target mapping was used to reduce the complexity the setup: For the attention-cuing 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 judgment-cuing blocks, the German word *Zahl* (“number”) indicated that the target would be the number word, and the word *Buchstabe* (“letter”) cued the letter word.

Because of the new response rule that was supposed to make the target speaker's sex similarly relevant for response selection in the judgment-cuing block as it was in the attention-cuing 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

² To see whether we had to change the sample size of Experiment 2 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 2×2 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 1,000 times, and in 98.7% of the runs, a significant interaction was present. Hence, we decided to stick to the sample size of 24.

Table 1 Mean RT and error rates

		Experiment 1				Experiment 2			
		Speaker-sex cuing		Ear cuing		Attention cuing		Judgment cuing	
		AR	AS	AR	AS	AR	AS	AR	AS
RT	Judgment switch	1,380 (± 42)	1,480 (± 54)	1,412 (± 60)	1,505 (± 40)	1,460 (± 38)	1,585 (± 67)	1,872 (± 59)	1,795 (± 53)
	Judgment repetition	1,262 (± 62)	1,439 (± 44)	1,350 (± 50)	1,468 (± 35)	1,313 (± 65)	1,582 (± 45)	1,513 (± 55)	1,752 (± 46)
PE	Judgment 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)
	Judgment 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. RTs (reaction times) and PEs (percentage of errors) of Experiments 1 and 2 as a function of attention transition (repetition [AR] vs. switch [AS]), judgment transition (repetition vs. switch), and cuing dimension (speaker sex cuing vs. ear cuing) in Experiment 1, which was exchanged by cuing type (attention cuing vs. judgment cuing) in Experiment 2. 95% Cousineau–Morey confidence intervals (Morey, 2008) are provided in parentheses

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 that in Experiment 1, since the temporal intervals, the number of blocks, and trials remained the same as in the previous experiment. The attention-cuing block and the judgment-cuing block were preceded by a short practice block 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), judgment transition (repetition vs. switch), and cue type (attention cuing vs. judgment cuing). 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 judgment transition, $F(1, 23) = 48.47$, $p < .001$, $\eta_p^2 = .68$, with judgment repetition benefits of 138 ms. Attention transition and judgment 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 judgment 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 RTs were 248 ms shorter in the attention-cuing block than in the judgment-cuing block. Cue type furthermore modulated the attention-repetition benefits, $F(1, 23) = 32.31$, $p < .001$, $\eta_p^2 = .58$, and the judgment-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-cuing block than in the judgment-cuing block, whereas the judgment switch costs were 126 ms larger in the judgment-cuing block than in the attention-cuing block. Also the three-way interaction was significant, $F(1, 23) = 10.65$, $p < .001$, $\eta_p^2 = .32$. Broken down by cuing sequence, the interaction of attention transition and judgment transition was significant in the attention-cuing block, $F(1, 23) = 10.18$, $p = .001$, $\eta_p^2 = .31$, and in the judgment-cuing block, $F(1, 23) = 82.89$, $p < .001$, $\eta_p^2 = .78$. In the attention-cuing 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 judgment repetitions revealed nonsignificant benefits of 27 ms, $t(23) = 0.95$, $p = .925$. In the judgment-cuing 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 judgment 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 judgment transition was obtained, $F(1, 23) = 19.56$, $p < .001$, $\eta_p^2 = .46$, with judgment repetition benefits of 1.9%. Attention transition and judgment 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 judgment 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-cuing blocks than in the judgment-cuing blocks. Cue type also entered into the three-way interaction with attention transition and judgment transition, $F(1, 23) = 11.70$, $p = .002$, $\eta_p^2 = .34$. Broken down by cuing sequence, the interaction of attention transition and judgment transition was significant in the attention-cuing block, $F(1, 23) = 6.06$, $p = .022$, $\eta_p^2 = .21$, and in the judgment-cuing block, $F(1, 23) = 17.91$, $p < .001$, $\eta_p^2 = .44$. In the attention-cuing 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 judgment repetitions to nonsignificant benefits of 0.4%, $t(23) = 0.01$, $p = .510$. In the judgment-cuing 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 judgment 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 Fig. 2 and Table 1).

In sum, significant attention repetition benefits and judgment 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-judgment 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-cuing block the partial attention repetition benefits were larger than the partial judgment repetition benefits, whereas this was reversed in the judgment-cuing block. 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 cuing order rather than on a “natural” hierarchy of auditory attention component and judgment component.

General discussion

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

The results of the two experiments indicate that the attention component and the judgment component were not

processed independently. Namely, besides auditory attention repetition benefits and judgment repetition benefits, the attention component and the judgment 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 judgment switch. When the cue indicated the judgment rather than the attention criterion, larger repetition benefits were found for partial judgment 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 judgment 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 multicomponent 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 cuing 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 were 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 RTs and highest error rates should always be obtained in complete switches, which was not the case in the judgment-cuing 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 judgment-cuing block, performance in complete switches was even superior to partial judgment switches. Here, participants did not know which response hand to use until the stimuli were presented. Possibly, reconfiguration of the judgment 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 judgment 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 with 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 judgment 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 multicomponent switching that causes that the varying components are not processed independently. This mechanism appears to be independent of component modalities, judgment, 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 cuing order (i.e., the explicit and implicit cuing) rather than on a “natural” component hierarchy.

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