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Selective Impairment of Auditory Selective Attention Under Concurrent Cognitive Load

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Load theory predicts that concurrent cognitive load impairs selective attention. For visual stimuli, it has been shown that this impairment can be selective: Distraction was specifically increased when the stimulus material used in the cognitive load task matches that of the selective attention task. Here, we report four experiments that demonstrate such selective load effects for auditory selective attention. The effect of two different cognitive load tasks on two different auditory Stroop tasks was examined, and selective load effects were observed: Interference in a nonverbal-auditory Stroop task was increased under concurrent nonverbal-auditory cognitive load (compared with a no-load condition), but not under concurrent verbal-auditory cognitive load. By contrast, interference in a verbal-auditory Stroop task was increased under concurrent verbal-auditory cognitive load but not under nonverbal-auditory cognitive load. This double-dissociation pattern suggests the existence of different and separable verbal and nonverbal processing resources in the auditory domain.

Keywords: cognitive load, selective attention, auditory Stroop, cognitive resources, double dissociation

Multitasking, although a demand in everyday life, commonly incurs costs in performance. Dual-task paradigms in which two tasks are to be performed simultaneously help us to understand why some tasks can be concurrently performed without noticeable performance costs, whereas other tasks suffer from being performed along each other. Recently, dual-task paradigms have been used to examine the circumstances that impair selective attention, that is, the ability to focus on relevant information while ignoring irrelevant and potentially interfering distracters. Performance in selective attention tasks under concurrent cognitive load has been compared with a condition in which the selective attention task is performed alone (no-load condition), providing a measure of dual-task interference. An impairment of selective attention in the load condition compared with the no-load condition has frequently been observed (e.g., Lavie, 2005; Lavie & De Fockert, 2005; Lavie, Hirst, De Fockert, & Viding, 2004).

A prominent explanatory approach for this influence of cognitive load on selective attention is the load theory (for recent reviews, see Lavie, 2005, 2010). Cognitive load, imposed by a task taxing executive cognitive control processes such as working memory, is thought to render executive cognitive control processes unavailable for other tasks. Those executive cognitive control processes are, however, assumed to be required in selective attention tasks to actively maintain stimulus-processing priorities. Without the availability of those control processes, distracters should not as easily be ignored or suppressed, resulting in a decrease in performance in selective attention tasks.

Recent findings suggest, however, that not all kinds of cognitive load reduce selective attention equally: Selective attention is specifically impaired when the content of the cognitive load task matches the content of the selective attention task (Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007). For instance, Park et al. (2007) demonstrated a performance decrease in a flanker-like task only under specific concurrent working memory loads: Performance was reduced only when the content of to-be-memorized material matched the target material in the flanker task. Similarly, Woodman, Vogel, and Luck (2001) and Woodman and Luck (2004) showed that search efficiency in a visual search task was only impaired by a concurrent spatial but not by a visual working memory task. The selective influence of cognitive load on selective attention has often been interpreted in terms of different processing resources: Tasks that share the same processing resources are more difficult to perform concurrently than tasks requiring different processing resources (Park et al., 2007; Woodman & Luck, 2004).

Whereas selective interference effects have been reported for visual material, evidence for selective load effects has not yet been found in the auditory domain. Moreover, whereas strong evidence for different and separable processing resources has been reported for the visual modality (e.g., Klauer & Zhao, 2004), no such evidence has been reported for the auditory domain (but see Deutsch, 1970; Pechmann & Mohr, 1992). The goal of the present research was therefore to investigate selective load effects in the auditory domain, and thereby, to provide evidence for the existence of different and separable cognitive processing resources in the auditory domain. We examined nonverbal-auditory as well as verbal-auditory selective attention under nonverbal-auditory and

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verbal-auditory cognitive load.[1] We expected and found selective load effects: Auditory selective attention was only impaired when the content of the cognitive load task matched the content of the selective attention task.

Our prediction of selective load effects in auditory selective attention follows from the assumption that the cognitive system consists of different processing resources (as in multiple resource theory; Navon & Gopher, 1979) and the hypothesis that different and separable processing resources exist in the auditory domain. Some evidence has been reported for separate auditory cognitive resources. Deutsch (1970) provided evidence for a possible dissociation of a memory for pitch from a memory for verbal material. She asked participants to compare the pitch of two tones, separated by a retention interval. Within this retention interval, participants heard either tones or digits. Memory for pitch was more affected by the interposition of tones than by the interposition of digits (see also Pechman & Mohr, 1992).

Although the results reported by Deutsch (1970) only represent single dissociations and are therefore far from conclusive (Dunn & Kirsner, 1988; Shallice, 1979), they suggest the existence of separate verbal-auditory and nonverbal-auditory cognitive resources. We built on this distinction and used verbal-auditory and nonverbal-auditory material in order to examine possible selective load effects in the auditory domain. The effects of two different cognitive load tasks (nonverbal-auditory, verbal-auditory) on the interference effect of two different auditory Stroop tasks (nonverbal-auditory, verbal-auditory) were examined. In Experiment 1A and 1B, the interference effect in a nonverbal-auditory Stroop task (Leboe & Mondor, 2007) was expected to increase under nonverbal-auditory cognitive load, compared with a no-load condition. The interference effect under verbal-auditory cognitive load was expected to be comparable to that under no-load conditions. In Experiment 2A and 2B, the interference effect of a verbal-auditory Stroop task (Green & Barber, 1981, 1983) was expected to increase under verbal-auditory cognitive load, compared with a no-load condition, but not under nonverbal-auditory cognitive load. This finding would strengthen a selective load account (e.g., Park et al., 2007) and extend it to the auditory domain. Such support for selective load would also suggest that, for load theory to provide a comprehensive account of attentional selection, it needs to be extended to explain material-specific selective load effects. Finally, this would be the first report of a double dissociation of verbal and nonverbal auditory processing resources.

Experiment 1A and 1B

In Experiment 1, participants performed a nonverbal-auditory Stroop task (Leboe & Mondor, 2007) concurrently with either a nonverbal-auditory cognitive load task (Experiment 1A) or a verbal-auditory cognitive load task (Experiment 1B). In the nonverbal-auditory Stroop task, a complex high-pitched or low-pitched tone sounding from a high-positioned or low-positioned speaker was presented. Participants were instructed to attend to the pitch and to ignore the position of the presented tones. In a congruent trial, pitch and speaker position were compatible (i.e., a high-pitched tone sounding from a high-positioned speaker or a low-pitched tone sounding from a low-positioned speaker); in an incongruent trial, pitch and speaker position were incompatible (i.e., a high-pitched tone sounding from a low-positioned speaker or a low-pitched tone sounding from a high-positioned speaker). Analogous to the original Stroop task (Stroop, 1935), performance in incongruent trials is typically slower and more erroneous than in congruent trials. We expected that nonverbal-auditory processing resources would be required to process the target tone in this auditory Stroop task.

The cognitive load tasks required participants to maintain a sequence of tones (nonverbal-auditory load) or digits (verbal-auditory load) in memory while they performed the Stroop task. For each cognitive load task, we conducted separate pretests to keep the difficulty of the load tasks comparable. A small sample of participants (five participants for each cognitive load task) took part in these pretests; they did not participate in the experiments reported below. In the pretests, the number of to-be-memorized stimuli was sequentially adapted until participants made the same amount of errors in both cognitive load tasks. This resulted in a sequence of four short or long tones to be memorized in the nonverbal-auditory load task, and six to-be-memorized digits in the verbal-auditory load task.

We expected that interference in the nonverbal-auditory Stroop task would significantly increase under nonverbal-auditory but not under verbal-auditory cognitive load. Aside from these selective load effects, we expected a general increase in task difficulty under load: Reaction time and error rates in the Stroop task were expected to be always higher under cognitive load, compared with a no-load condition, because of task-coordination costs (Lavie et al., 2004; Olivers, Meijer, & Theeuwes, 2006).

Method

Experiments 1A and 1B are presented together. They differed only with respect to the cognitive load tasks that are described separately (Experiment 1A: nonverbal-auditory cognitive load; Experiment 1B: verbal-auditory cognitive load).

Design. Each experiment had a 2 (congruency: congruent, incongruent) × 2 (load: no-load, load) × 2 (order of task: load first, no-load first) design; the first two factors were varied within-subjects.

Participants. Participants were 48 University of Freiburg students (24 in each experiment) participating for course credit or as paid volunteers; mean age was 24.58 years, ranging from 19 to 42 years (Experiment 1A: mean age = 24.62, ranging from 20 to 42 years; Experiment 1B: mean age = 24.00, ranging from 19 to 35 years). Self-indicated normal hearing was required for participation and inquired by the investigator before the experiment started. In addition, participants had to indicate whether they had normal hearing in a demographic questionnaire at the beginning of the experiment presented on the computer screen. In Experiment 1A, two participants indicated that they had hearing impairments;

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[1] We use the broad term "nonverbal-auditory" to refer to auditory information that is distinct from spoken language. Whereas spoken language has been considered in working memory theories (e.g., Baddeley, 2003; Baddeley & Hitch, 1974), other types of auditory information have largely been neglected in this research tradition. It is still not clear which types of auditory information, aside from spoken language, can be stored in memory, and whether different material-specific resources exist for different types of nonverbal-auditory information.

those participants were excluded from analysis. One participant of Experiment 1B was excluded from analysis because this participant did not fill out the strategy questionnaire at the end of the experiment (see below).

Stimuli and apparatus. Tones were presented at a sound pressure level (SPL) of approximately 70 dB. Two loudspeakers were positioned approximately 11° above and below participants' visual angle. In order to keep head position constant for all participants, a chin rest was used that was approximately 57 cm away from the computer screen.

Nonverbal-auditory Stroop task. Comparable to the stimuli used by Leboe and Mondor (2007), a low-pitched and a high-pitched tone based on sine waves with duration of 120 ms was generated and stored as a sound file before the experiment started. The low-pitched tone consisted of a fundamental frequency of 362 Hz, a first (724 Hz), and a second harmonic (1086 Hz). Relative to the fundamental frequency, the intensity of the first and the second harmonics were set to 50% and 25%, respectively. Analogously, a high-pitched tone was generated that consisted of a fundamental frequency of 732 Hz plus the first (1,464 Hz) and the second (2,196 Hz) harmonics. These tones were either presented from the high-positioned or low-positioned loudspeaker. Participants' task was to decide whether tones were high or low by pressing "j" for high-pitched tones and "k" for low-pitched tones on a standard computer keyboard. In addition, they were instructed to ignore whether the tone was presented from the high-positioned or low-positioned loudspeaker. In order to allow participants to prepare for the Stroop task, the symbol "+" was displayed for 200 ms before the Stroop tone sounded (cf. Figure 1B).

Experiment 1A: Nonverbal-auditory load. In the nonverbal-auditory load task, participants heard a sequence of four to-be-memorized tones that were either short (90 ms) or long (150 ms). Tone length was randomly selected for each tone separately. These tones were presented from both loudspeakers simultaneously, and were separated by a silent inter-tone-interval of 800 ms. The tones' pitch was based on the mean frequency pattern of the high-pitched and low-pitched tones of the Stroop task, that is, a fundamental frequency of 547 Hz, a first (1,094 Hz), and a second harmonic (1,641 Hz). Relative to the fundamental frequency, the

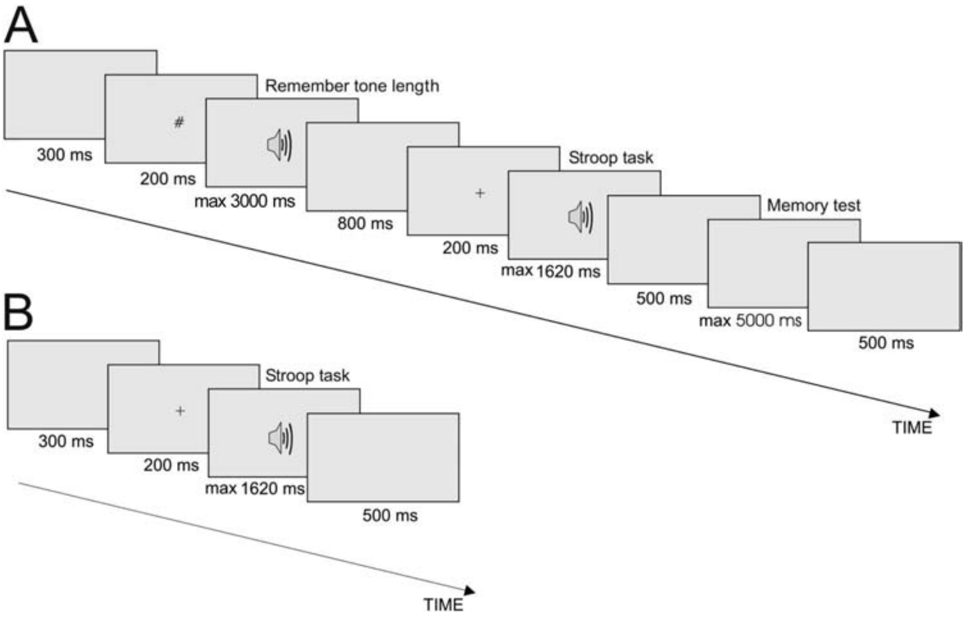

Figure 1. A) An illustration of a trial in the nonverbal-auditory load condition of Experiment 1A (nonverbal-auditory Stroop task). Each trial started with a blank screen for 300 ms followed by the symbol # for 200 ms, which indicated the beginning of the to-be-memorized stimuli: Participants heard four short or long tones with a maximal duration of 3,000 ms that they had to memorized (maximal four long tones of each 150 ms plus three inter-tone-intervals of each 800 ms). After a blank screen of 800 ms, participants saw the symbol + presented for 200 ms; this symbol indicated the beginning of the Stroop task. Participants then heard a high-pitched tone or a low-pitched tone (120 ms) presented from a high-positioned or low-positioned loudspeaker and had to indicate whether the tone was high- or low-pitched. After a response was given or 1,500 ms had passed, participants saw a blank screen for 500 ms before they were asked whether a specific tone of the memorized sequence was short or long. Participants had to respond within 5,000 ms. The next trial began after an inter-trial interval of 500 ms. In the verbal-auditory load task (Experiment 1B), participants were presented with, and had to memorize, a sequence of spoken digits instead of a sequence of short or long tones. B) In the no-load condition, the trial started with a blank screen for 300 ms followed by the symbol + presented for 200 ms; this symbol indicated the beginning of the Stroop task. The Stroop trial was then presented as described above. In Experiment 2, the word *Mann* (man) or *Frau* (woman) spoken in a male or female voice was presented (440 ms) instead of high- or low-pitched tones.

intensity of the first and the second harmonics were again set to 50% and 25%, respectively.

After a retention interval in which participants performed the Stroop task, they were asked to indicate whether a specific tone of the memorized sequence was short or long by pressing the key "a" for short tones and the key "s" for long tones on a standard computer keyboard. It was counterbalanced at which serial position the requested tone had been presented.

Experiment 1B: Verbal-auditory load. In the verbal-auditory load task, participants heard a sequence of recordings of six digits from one to nine vocalized by a male speaker. Within any sequence, only two digits occurred in a directly ascending or descending order (e.g., 3–4, but not 3–4–5). Each recording of any given digit was 560 ms long. Digits were separated by a silent interval of 150 ms. The fundamental frequency of the recordings was adjusted so that it was identical to the fundamental frequency of the nonverbal-auditory load tones and therefore identical with the mean of the fundamental frequency of the Stroop tones.

After a retention interval, in which participants performed the Stroop task, participants heard another digit and had to indicate whether it was one of the memorized digits (by pressing the key "a") or a new digit (by pressing the key "s"). It was counterbalanced whether the requested digit was a new or an old digit, and at which serial position the requested digit had previously been presented.

Procedure. The trial sequence is depicted in Figure 1. Each trial started with a blank screen of 300 ms. Subsequently, in the no-load condition (Figure 1B) the symbol "+" was presented for 200 ms to allow participants to prepare for the Stroop task. Participants then heard the Stroop tone (120 ms); they were instructed to respond within a response window of 1500 ms. After a response was registered or a response window of 1,500 ms had passed, the next trial started after an inter-trial-interval of 500 ms. In the load condition (Figure 1A), the initial blank screen was followed by the symbol "#" for 200 ms to indicate the presentation of the to-be-memorized material of the cognitive load task. Afterward, the to-be-memorized stimuli of the cognitive load tasks were presented. Subsequently, a blank screen was presented for 800 ms followed by the symbol "+" presented for 200 ms indicating the beginning of the Stroop task. The Stroop task was then presented as described above. After the response was registered or 1500 ms had passed, a blank screen was shown for 500 ms before the retrieval probe of the cognitive load task was presented. After a response was registered or 5000 ms had passed, the next trial started with an inter-trial-interval of 500 ms. In order to prevent possible trade-offs between the Stroop task and the load task, the instructions for the Stroop task and the load task were comparable in their emphasis on speed and accuracy.

In a block consisting of 10 trials, participants first practiced the load task; instead of the Stroop task, a blank screen was presented for 1,000 ms between the presentation of the to-be-memorized material and the retrieval probe. Subsequently, participants practiced the Stroop task in a block of 20 trials. These trials were identical to the no-load condition in the experimental blocks. In the last practice block, participants practiced the load and Stroop tasks together in a block of 15 trials; these trials were identical to the load condition in the experimental blocks. In all practice blocks (but not in experimental blocks), participants received feedback. In the Stroop task, they received feedback about their reaction time. Additionally, the word "Fehler" (German for *error*) was presented in red in case of an error. In the load tasks, participants received the same error feedback in case of an incorrect response. Feedback for the Stroop task was presented for 1,500 ms, feedback for the load tasks was presented for 500 ms. After these three practice blocks, participants performed four experimental blocks with 60 trials each. Two of these blocks consisted of no-load trials only and the other two blocks consisted of load trials only. One half of participants performed the no-load blocks first; for the other half of participants, the order was reversed. At the end of the experiment, participants received a questionnaire in which they were asked to indicate any strategies they have used to memorize the presented material. Participation in the experiment took approximately 45 min.

Results

Reaction time served as the primary dependent variable.[2] Analyses of reaction time are based on trials in which no errors were made in the Stroop task and in the cognitive load task. Outliers in Stroop reaction times were omitted in each individual's distribution by Tukey's criterion (i.e., values below the first quartile minus 1.5 times the interquartile range or above the third quartile plus 1.5 times the interquartile range). This led to the exclusion of 1.6% of the trials for participants performing the nonverbal-auditory load task and of 1.3% of the trials for participants performing the verbal-auditory load task.

Error rates were also analyzed to check for possible problems because of speed–accuracy trade-off, but none were found. Analyses of error rates in the Stroop tasks are based on trials in which no errors were made in the cognitive load task; analyses of error rates in the cognitive load task are based on trials in which no errors were made in the Stroop task. The chosen significance level was $\alpha < .05$ for all analyses.

Mean correct reaction times and error rates of the nonverbal-auditory Stroop task and the two different load tasks are presented in Table 1. Figure 2 (upper panel) presents Stroop interference of reaction time and error rates of the nonverbal-auditory Stroop task as a function of load (no-load, load), and load task (nonverbal-auditory, verbal-auditory).

Stroop task. In a first step, Stroop performance in both Experiment 1A and 1B was jointly analyzed. Reaction time and error rates of the Stroop task were examined in two separate 2 (congruency) $\times$ 2 (load) $\times$ 2 (load task) analyses of variance with repeated measures on the first two factors.[3] The main effect of congruency was significant for reaction time, $F(1, 43) = 30.28$, $p < .001$, $\eta_p^2 = .41$, and error data, $F(1, 43) = 12.05$, $p < .01$, $\eta_p^2 = .22$, revealing faster responses and less errors in congruent trials. As indicated by a main effect of load, faster responses were also given in the no-load condition compared with the load condition, $M = 139$, $SD = 116$, $F(1, 43) = 63.16$, $p < .001$, $\eta_p^2 = .60$.

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[2] An additional set of analyses was conducted using log-transformed reaction time to rule out the possibility of artifacts because of general slowing of reaction times (Faust, Balota, Spieler, & Ferraro, 1999; Salthouse & Hedden, 2002). These analyses revealed the same pattern of results as those reported in the article. For ease of interpretation, analyses based on untransformed latencies are reported.

[3] An additional set of analyses was conducted including the between-subject variable order of task (load first, no-load first): No significant effects involving order of task were found, neither in Experiment 1 nor in Experiment 2; therefore, the data were collapsed across this factor.

Table 1
Mean Correct Reaction Time (ms) and Mean Error Rates (%) in the Stroop Tasks (Nonverbal-Auditory, Verbal-Auditory) and Load Tasks (Nonverbal-Auditory, Verbal-Auditory) Presented Separately for Experiments 1 and 2

	Stroop task				Load task			
	Reaction time		Error		Reaction time		Error	
Load	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Experiment 1: Nonverbal-auditory Stroop								
Nonverbal	464	63	4.45	2.57	1409	443	14.89	9.57
Verbal	453	107	6.01	4.88	1377	317	13.82	9.56
Experiment 2: Verbal-auditory Stroop								
Nonverbal	751	86	6.89	3.83	1416	329	15.85	9.24
Verbal	786	86	7.57	5.42	1313	203	16.61	9.64

Overall, the congruency effect in reaction time was larger in the load condition ($M = 17$ ms, $SD = 23$) compared with the no-load condition ($M = 10$ ms, $SD = 17$) as indicated by an interaction of congruency and load, $F(1, 43) = 4.14$, $p < .05$, $\eta_p^2 = .09$.

Most important, this interaction was moderated by load task, resulting in a significant three-way interaction of congruency, load, and load task, $F(1, 43) = 4.83$, $p < .05$, $\eta_p^2 = .10$. As revealed by follow-up analyses, this three-way interaction resulted from a congruency × load interaction under nonverbal-auditory load (Experiment 1A), $F(1, 21) = 8.86$, $p < .01$, $\eta_p^2 = .30$, while this interaction was not significant under verbal-auditory load (Experiment 1B), $F < 1$. In the nonverbal-auditory load condition (Experiment 1A), the congruency effect, although reliable in both load conditions, was greater with load, $t(21) = 4.23$, $p < .001$, than without load, $t(21) = 2.08$, $p = .05$. In contrast, as indicated by the absence of an interaction, congruency effects in the verbal-auditory load condition (Experiment 1B) were not affected by load; reliable interference effects of comparable size were found with load, $t(22) = 2.66$, $p = .01$, as well as without load, $t(22) = 3.18$, $p < .01$ (see upper panel of Figure 2).

Load task. To assess possible trade-offs between the Stroop task and the cognitive load tasks, reaction time and error data of the *load task* were analyzed in analyses of variance with factor congruency (congruent, incongruent), for Experiment 1A and 1B separately.[4] Specifically, we wanted to rule out the possibility that a Stroop effect (i.e., better Stroop performance in congruent than incongruent trials) is paralleled by a pattern of better load task performance in *incongruent* (compared with congruent) Stroop trials. Such a trade-off would render our results difficult to interpret. However, no evidence for such trade-offs between the Stroop task and the load task was found, neither in reaction time nor in error data of both load tasks. To the contrary, the only finding was a significant main effect of congruency on the error data of Experiment 1B, $F(1, 22) = 16.76$, $p < .001$, $\eta_p^2 = .43$, revealing that fewer errors were made in the verbal-auditory load task after a *congruent* Stroop trial.

Data from the strategy questionnaire showed that the majority of participants have memorized the material in the load tasks as intended: 14 participants in Experiment 1A indicated that they had memorized the tones auditorily and 17 participants in Experiment 1B indicated that they had memorized the digits verbally.

Discussion

Nonverbal-auditory Stroop effects revealed the expected pattern: First, reliable Stroop interference effects were observed under load as well as in no-load conditions. Most important, Stroop interference was increased under concurrent nonverbal-auditory cognitive load, as compared with a no-load condition. By contrast, Stroop effects were not increased under verbal-auditory cognitive load. Performance in the cognitive load tasks did not reveal trade-offs. The expected selective interference effects in auditory selective attention were thus demonstrated.

At the end of the experiment, participants were asked to indicate any strategies they have used to memorize the presented material. This was done to verify that participants memorized the material in the expected way (i.e., that the tones in the nonverbal-auditory load task were memorized in a nonverbal manner). The majority of participants indicated that they have memorized the material in the load tasks in the intended manner.[5]

In Experiment 1, selective interference effects for nonverbal-auditory selective attention were found. If those selective interference effects were based on selective loading of separate processing resources, it should be possible to reverse this pattern: A task requiring verbal-auditory selective attention should only be impaired under verbal-auditory cognitive load but not under nonverbal-auditory cognitive load. If, however, selective load effects in Experiment 1 were based on general task-coordination

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[4] In the analyses of reaction time and error data of the load tasks, the within-subject factor *congruency* refers to congruent or incongruent Stroop trials. In the load tasks themselves, trials did not vary in congruency.

[5] These results suggest that the majority of the participants did not use a verbal strategy to memorize the tone length (only 6 out of 22 participants indicated a verbal strategy in Experiment 1A). One criticism that might be nevertheless raised is that the nonverbal-auditory load task might not require nonverbal-auditory processing resources, and that participants may have falsely indicated that they had memorized the tone length auditorily, because this was perceived as the required and correct strategy (i.e., because of experimenter demand). However, this assumption is not consistent with the results, as the nonverbal-auditory load task produced increased interference effects in the nonverbal-auditory Stroop task. If participants had indeed memorized the four tones verbally, as they have memorized the digits, one would have expected similar results under both the nonverbal-auditory and the verbal-auditory load task.

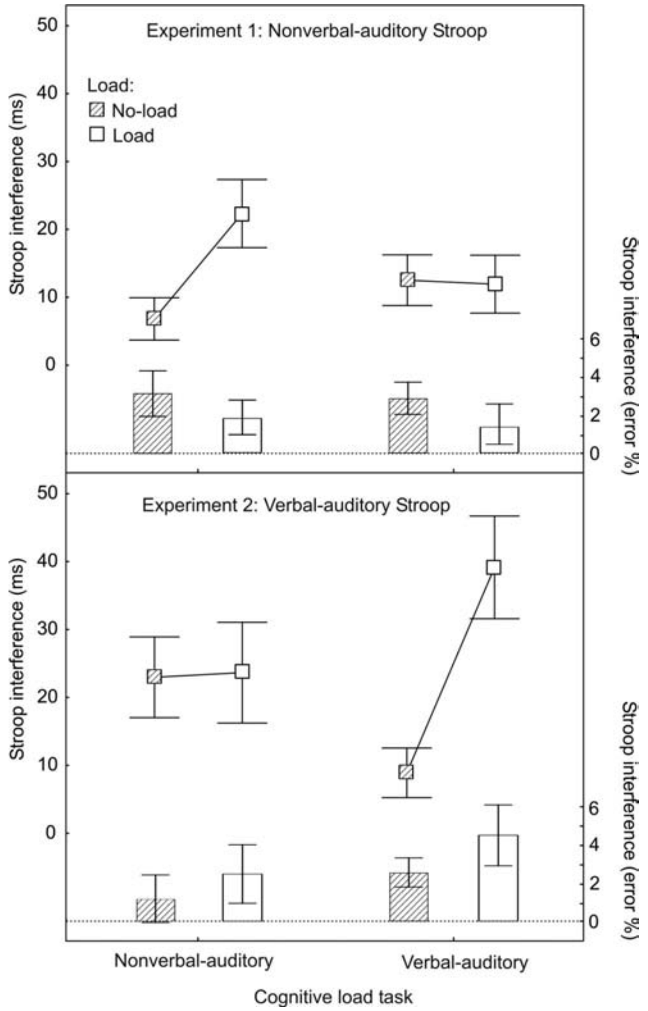

Figure 2. Stroop interference (incongruent minus congruent) for reaction times and error rates of the Stroop tasks from both experiments (upper panel: Experiment 1, nonverbal-auditory Stroop; lower panel: Experiment 2, verbal-auditory Stroop) as a function of cognitive load (no-load, load) and type of cognitive load task (nonverbal-auditory, verbal-auditory). Error bars show ± 1 *SEM*.

costs (that might have been larger for the nonverbal-auditory load task compared with the verbal-auditory load task), verbal-auditory selective attention should also be more impaired under nonverbal-auditory load.

Experiment 2A and 2B

In Experiment 2, participants performed a verbal-auditory Stroop task (Green & Barber, 1981, 1983) concurrently with one of the two cognitive load tasks reported in Experiment 1 (Experiment 2A: nonverbal-auditory cognitive load; Experiment 2B: verbal-auditory cognitive load). In the verbal-auditory Stroop task, participants heard the word “Mann” (man) or “Frau” (woman) articulated either by a male or a female speaker. Participants were asked to judge the word meaning and to ignore the speaker’s gender. We expected that verbal-auditory processing resources would be required to perform this Stroop task. In line with the assumption of selective load effects, we expected interference in this Stroop task to increase only under verbal-auditory cognitive load but not under nonverbal-auditory cognitive load.

Method

Procedure and design was identical to Experiment 1 except for the differences indicated below. All auditory stimuli were presented via headphones at approximately 70 dB SPL. A chin rest was not used in this experiment.

Participants. Participants were 48 University of Freiburg students (24 in each experiment), participating for course credit or as paid volunteers; mean age was 24.22 years, ranging from 19 to 42 years (Experiment 2A: mean age = 24.24, ranging from 19 to 42 years; Experiment 2B: mean age = 22.96, ranging from 19 to 34 years). In Experiment 2A, two participants were excluded from analyses: one participant indicated hearing impairments; another participant was an extreme outlier according to Tukey’s criteria (i.e., mean load-task RT was 3380 ms in a sample with $M = 1484$ and $SD = 552$). In Experiment 2B, one participant was excluded from analyses because this participant was identified as an extreme outlier according to Tukey’s criteria (i.e., mean Stroop error rate was .35 in a sample with $M = .08$, $SD = .06$).

Verbal-auditory Stroop task. The words “Mann” (man) and “Frau” (woman) articulated in a male and in a female voice were stored as sound files before the experiment started. All four stimuli had the same length of 440 ms. Participants had to decide whether the word man or woman was spoken by pressing “j” (indicating *man*) or “k” (indicating *woman*) on a standard computer keyboard. They were instructed to ignore the gender of the speaker.

Results

Data were preprocessed as reported above (see Experiment 1). Mean correct reaction times and error rates of the verbal-auditory Stroop task and the two different load tasks are presented in Table 1. Figure 2 (lower panel) presents Stroop interference of reaction time and error rates of the verbal-auditory Stroop task as a function of load (no-load, load), and load task (nonverbal-auditory, verbal-auditory).

Stroop task. A combined analysis of both Experiment 2A and 2B was conducted analogous to that reported for Experiments 1A and 1B. Reaction time and error rates of the Stroop tasks in both conditions were examined in separate 2 (congruency) × 2 (load) × 2 (load task) analyses of variance with repeated measures on the first two factors. A significant main effect of congruency revealed faster responses, $F(1, 43) = 54.85$, $p < .001$, $\eta_p^2 = .56$, and fewer errors, $F(1, 43) = 17.39$, $p < .01$, $\eta_p^2 = .29$, in congruent trials. A main effect of load revealed that reaction times were faster under the no-load condition than under load, $M = 131$, $SD = 115$, $F(1, 43) = 61.14$, $p < .001$, $\eta_p^2 = .59$. Furthermore, a congruency × load interaction was observed in reaction time, $F(1, 43) = 5.02$, $p < .05$, $\eta_p^2 = .11$: Overall, larger congruency effects were found under load ($M = 32$ ms, $SD = 38$) compared with the no-load condition ($M = 16$ ms, $SD = 25$). Additionally, the interaction between load and load task was significant in reaction time, $F(1, 43) = 4.25$, $p < .05$, $\eta_p^2 = .09$, revealing larger load effects in Experiment 2B (verbal-auditory load; $M = 164$ ms, $SD = 110$) compared with Experiment 2A (nonverbal-auditory load; $M = 96$ ms, $SD = 112$).

Most important, however, the three-way interaction between congruency, load, and load task was again significant in reaction time data, $F(1, 43) = 4.58$, $p < .05$, $\eta_p^2 = .1$. As revealed by follow-up analyses, this three-way interaction resulted from a congruency × load interaction under verbal-auditory load (Experiment 2B), $F(1, 22) = 10.90$, $p < .01$, $\eta_p^2 = .33$; this interaction was not significant under nonverbal-auditory load (Experiment 2A), $F < 1$. In the verbal-auditory load condition (Experiment 2B), the congruency effect was greater with load, $t(22) = 4.93$, $p < .001$, than without load, $t(22) = 2.35$, $p < .05$. In contrast, as indicated by the absence of an interaction with load, congruency effects in the nonverbal-auditory load condition (Experiment 2A) were of comparable size with load, $t(21) = 3.03$, $p < .01$, and without load, $t(21) = 3.67$, $p < .01$ (see lower panel of Figure 2).

Load task. To assess possible trade-off between the load task and the Stroop task additional analyses of reaction time and error data in the cognitive load task were again conducted (see Experiment 1). In Experiment 2A, these analyses did not reveal any significant effects. For Experiment 2B, a significant main effect of congruency on the error data was again found, $F(1, 22) = 7.65$, $p < .05$, $\eta_p^2 = .26$: Fewer errors were made in the load task following a congruent Stroop trial. Thus, no evidence for trade-offs between the Stroop and load tasks was found.

Most participants indicated having used the intended strategy for memorizing the respective material in the cognitive load tasks: 18 participants in Experiment 2A indicated that they had memorized the tones auditorily and 15 participants in Experiment 2B indicated that they had memorized the digits verbally.

Discussion

Results revealed the expected pattern: Interference in the verbal-auditory Stroop task was increased under verbal-auditory load, compared with a no-load condition. In contrast, interference was not increased under nonverbal-auditory load. Accordingly, an interference increase was only found under expected resource overlap. Performance in both load tasks did not reveal trade-offs, and verbal-auditory Stroop interference was reliable under both no-load and load conditions. The results thus demonstrate the expected pattern of selective interference.

General Discussion

In Experiment 1 and 2, participants performed a nonverbal-auditory Stroop task or a verbal-auditory Stroop task. In a concurrent cognitive load task, participants were either asked to memorize nonverbal-auditory or verbal-auditory stimuli. As expected, interference in the nonverbal-auditory Stroop task was significantly increased only under nonverbal-auditory load (compared with a no-load condition), whereas interference in the verbal-auditory Stroop task was significantly increased only under verbal-auditory load.

These findings contradict the notion that all kinds of cognitive loads equally disrupt (auditory) selective attention (e.g., Lavie, 2005; Lavie et al., 2004). Instead, they support the existence of selective load effects that depend on the overlapping recruitment of cognitive resources: Whereas interference was increased in conditions in which a resource overlap was expected, no comparable increase was found in load conditions without such resource overlap. Because the selective interference effects of Experiment 1 were reversed in Experiment 2, these selective load effects seem to reflect overlapping demands on specific processing resources; clearly, the present findings cannot be explained by assuming that either the nonverbal-auditory or verbal-auditory load task was more demanding and thus yielded higher general load effects.

Note that the present results are consistent with the existence of general load effects. In addition to selective load effects, we also found a strong general impairment of performance under load: Reaction times were increased under load in all experiments, compared with the respective no-load conditions. These general performance costs are likely based on task-coordination (Lavie et al., 2004; Olivers et al., 2006) and might be comparable to general load effects reported in other studies (e.g., Lavie et al., 2004; Lavie & De Fockert, 2005).

The present study is not the first to investigate load effects in the auditory domain (Dalton, Santangelo, & Spence, 2009). Yet, previous studies did not find evidence for selective load effects. Dalton et al. (2009) asked participants to make speeded elevation discrimination responses of a continuous white noise presented from one of four spatially arranged loudspeakers. Concurrently, participants had to ignore three white noise bursts (distracters) presented either at the same spatial elevation (congruent trial) or at the opposite elevation (incongruent trial). In the cognitive load task, participants had to memorize six digits in random order (high load) or in ascending numerical order (low load). Dalton et al. (2009) found distracter interference to be more pronounced under high than under low digit load.

One possible interpretation of this finding is that nonverbal-auditory selective attention is impaired by any type of cognitive load, that is, general load effects may dominate in the auditory domain; an interpretation that would be in direct contrast to the present findings. But the findings reported by Dalton et al. (2009) can also be interpreted differently. Note that their task resembled a perceptual discrimination task, rather than being a classical interference paradigm such as the flanker-like task used by Park et al. (2007), or the Stroop-like task used here: The to-be-ignored white noise burst might have degraded the perceptual strength of the auditory target stimulus, thereby locating interference at a purely perceptual level. Interference by load might thus have affected different processes than in typical selective attention tasks.

Another possible interpretation of Dalton et al.'s (2009) findings is in terms of the level of load. In their study, as well as in other studies in which general load effects were obtained, more demanding load tasks might have been used (e.g., recall of a digit sequence) than in studies in which selective load effects were found (e.g., recognition of a digit from a memory set).[6] In other words, the former paradigms might have implied stronger requirements on central-executive processes such as task-coordination, which might in turn have resulted in general load effects. Such an interpretation is in line with Olivers et al.'s (2006) suggestion that ". . . just having to coordinate two tasks puts a strain on visual attentional control processes, regardless of whether these tasks are high or low in memory load and regardless of whether they overlap" (p. 1263; see also Lavie et al., 2004, for a discussion of task-coordination). This interpretation predicts that a gradual increase in the level of load would cause a qualitative shift

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[6] We thank an anonymous reviewer for suggesting this interpretation.

away from a pattern of selective load toward a general load effect, perhaps at a point where central-executive capacity limits are reached. In this way, the qualitatively different result patterns might be explained as a consequence of different levels of loads imposed on a single resource.

In our view, however, there is converging evidence that the qualitatively different patterns likely result from qualitatively different underlying processes. On the one hand, we think that increases in task-coordination costs lead to a stronger recruitment of central-executive processes, yielding general load effects. On the other hand, concurrent or overlapping demands on material-specific processes of stimulus representation are responsible for selective load effects. This account assumes that, besides perceptual and central-executive processes, working memory processes responsible for stimulus representation also contribute to selective attention. These resources are material-specific, and their selective recruitment can yield selective load effects. This view is consistent with current evidence regarding the brain structures and mechanisms supporting working memory and attention, which assume that executive control processes are supported by prefrontal cortex, whereas stimulus representation and maintenance processes are supported by material-specific areas in temporal and parietal cortex (for recent reviews, see Fuster, 2009; Jonides et al., 2008; Knudsen, 2007).

In sum, whereas our findings cannot be fully explained by load theory, neither are they incompatible with it. Whereas general load effects are thought to reflect reduced availability of central executive control resources, we think that selective load effects result from impaired performance because of the overlapping recruitment of task-specific processing resources. We propose an extension of load theory along the lines suggested above that might be able to explain the present pattern of selective load effects. Future research will have to investigate whether selective load effects are the result of overlapping recruitment of material-specific resources, or whether the different result patterns might be because of the cognitive load tasks used here being less demanding than the load tasks used in previous studies (e.g., Dalton et al., 2009): Perhaps selective load effects occur under weaker load, whereas general load effects occur under heavier load.

In explaining selective load effects, it has not only been argued that selective attention is specifically reduced when the content of the selective attention task matches the content of the cognitive load task. More precisely, it is assumed in the specialized load account (Park et al., 2007) that selective attention should be impaired when the same processing resources are required to perform the load task and to process the *target stimulus* of the selective attention task. In the nonverbal-auditory Stroop task, the target consists of the tones' pitch; in the verbal-auditory Stroop task, the target consists of the word meaning. We expected that nonverbal-auditory processing resources would be required to process the target in the nonverbal-auditory Stroop task; we therefore expected a target-load overlap when that task was combined with the nonverbal-auditory load task. Similarly, we expected that verbal-auditory processing resources are required to process the word meaning in the verbal-auditory Stroop task; we therefore expected a target-load overlap when that task was combined with the verbal-auditory load task. In Experiment 1A and Experiment 2B, such an interference increase was indeed demonstrated.

Park et al. (2007) even found an interference *decrease* under cognitive load when overlapping processing resources are required for performing the load task and for processing the *distracter stimulus* of the selective attention task. Future research using the present dual-task setup might help clarify whether an overlap between the resources required for processing the distracter and the cognitive load task can also improve auditory selective attention. Note, importantly, that Park et al. (2007) as well as other studies examining cognitive load effects (e.g., Lavie & De Fockert, 2005; Lavie et al., 2004) used paradigms with clearly distinguishable distracters and targets; in contrast, in the present experiments, target and distracter information was presented as two features of the same stimulus. Research on perceptual load has shown that selective processing of target and distracter information requires their clear separation into separate stimuli (Chen, 2003; Lavie, 2005). More research is needed to clarify whether selective overlap with target versus distracter processing can also reveal selective load effects when target and distracter are part of the same stimulus.

Whereas Park et al. (2007) have demonstrated improved visual selective attention under conditions of distracter–load overlap, recent research has shown that auditory selective attention can also be improved when task-irrelevant tones (that are to be ignored) are presented before the Stroop stimulus (Dittrich & Stahl, 2011). This interference reduction may reflect dilution effects caused by task-irrelevant stimuli (Kahneman & Chajczyk, 1983). It remains to be seen whether nonconcurrently presented irrelevant stimuli reduce distraction in a general manner, or whether a pattern of selective dilution can be observed: Interference in a nonverbal-auditory Stroop task might only decrease with irrelevant nonverbal-auditory stimuli (as has been shown by Dittrich & Stahl, 2011), but might not decrease with irrelevant verbal-auditory stimuli.

Aside from their relevance for load theory, the present results are also relevant for theories of working memory. To our knowledge, they demonstrate the first double dissociation of nonverbal-auditory and verbal-auditory processing resources. Single dissociations of nonverbal-auditory and verbal-auditory processing resources have already been demonstrated (Deutsch, 1970; Pechmann & Mohr, 1992). However, given a single dissociation, numerous alternative explanations for the result patterns can be devised aside from the notion of separate processing resources (Dunn & Kirsner, 1988). More unequivocal evidence for multiple processing resources is provided by double dissociations (Dunn & Kirsner, 1988; Shallice, 1979; Teuber, 1955).[7] Such a double dissociation is given when Task A (i.e., the nonverbal-auditory

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[7] Still, alternative explanations of double dissociations aside from separable processing resources are conceivable (Dunn & Kirsner, 1988, 2003; Klauer & Zhao, 2004). Probably the most often considered alternative explanation is the assumption that selective interference is induced because of similarity of the materials used in the different tasks (i.e., tasks interfere to the extent to which the material is similar; Nairne, 1990; Oberauer & Kliegl, 2006). Although dissimilar stimuli were used for the selective attention tasks and the cognitive load tasks in the present experiments, the possibility of a similarity-based modulation of interference appears plausible, as in multiple resource theory it is also assumed that tasks are more or less similar depending on whether the same or different processing resources are required. The question whether modulation of interference is similarity-based or resource-based will probably remain unsolved as long as the relevant features on which similarity is based are not specified, and the predicted consequences of stimulus similarity for cognitive processes are not spelled out.

Stroop) is only disrupted by Condition 1 (i.e., nonverbal-auditory load) but not by Condition 2 (i.e., verbal-auditory load) while Task B (i.e., the verbal-auditory Stroop) is only disrupted by Condition 2 (i.e., verbal-auditory load) and not by Condition 1 (i.e., nonverbal-auditory load; conditions can either be other tasks or concurrently presented stimuli). This is what we found.

Until now, working memory theories have largely concentrated on verbal-auditory information (Baddeley, 2003; Baddeley & Hitch, 1974); beyond spoken language, auditory information has been neglected in research on working memory, despite evidence for nonverbal-auditory short-term memory (e.g., Clément, Demany, & Semal, 1999; McKeown & Wellsted, 2009; Semal & Demany, 1993). The current findings emphasize the fact that theories of working memory and selective attention are incomplete, and that the structure of auditory working memory is more complex than previously thought. It remains to be seen whether the present results can inspire similar research activity and theoretical developments as comparable dissociations that have been demonstrated for the visual modality (e.g., Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Klauer & Zhao, 2004).

Irrespective of the underlying mechanisms that caused the reported selective load effects, it can be concluded that tasks do not always interfere with each other to the same extent. Support for this conclusion has previously been reported for the visual domain (Park et al., 2007); the present experiments are the first to demonstrate similar effects for the auditory domain. As evidence for general load effects was also found, we can conclude that multitasking generally incurs performance costs, but that this is specifically true when similar things have to be dealt with concurrently.

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