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Research Article

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Expanding dual-task research by a triple-task

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Abstract: Multitasking research in the laboratory is dominated by extremely simplistic dual-task paradigms. Although dual-tasks allow for some variations, they do not compare well to more complex everyday task settings. This study expands a classical dual-task paradigm by adding a third task. The dual-tasks and the triple-task always consisted of the same three single tasks. The aim was to investigate the effects of the combinations of the three single-tasks and in which manner response times and costs increased. Stimulus-response pairings were varied either once within participants (E1) or between participants (E2). Our results showed that the increase in response time from dual-tasks to triple-tasks was only 43% of the increase from single-tasks to dual-tasks suggesting a non-linear cost of adding tasks. Moreover, response times in each subtask were higher in triple-task situations compared to single-task or dual-task situations. This is in contrast to classical dual-tasks, in which typically only one of the two responses is delayed. Cognitively, for costs in triple-tasks, unlike in dual-tasks, task coordination seems to play a larger role compared to the classically suggested relationships between stimulus and response in terms of their modality- and ideomotor-compatibility which we will discuss. Overall, the study demonstrates that current multitasking research is limited in its generalizability by focusing only on dual-tasks and would benefit from research with more complex task settings.

Keywords: dual-task; triple-task; task coordination; multitasking.

1 Introduction

Multitasking can be found in different areas of everyday life. When driving a car, several tasks have to be performed simultaneously, such as navigating, steering, braking, and keeping an eye on the environment. Problems may arise if the driver, for example, is also taking a phone call while driving, leading to longer response times, or issues completing one of the two tasks successfully (Nijboer et al., 2016; Strayer & Johnston, 2001). However, under which circumstances can we talk about *multitasking*? Is driving a car really a form of multitasking, or have several tasks merged into one big task with several subtasks?

The term *task* refers to a cognitive or behavioral goal, which is given by instructions (Monsell, 1996). Instructions provide a clear specification of how a task must be processed. In addition, people must also be willing to accept these instructions as their task (see, Hackman, 1969; Künzell et al., 2018 for a discussion on task definition). Classical studies on multitasking using clearly defined and isolated stimuli, such as sounds or visually presented forms. This allows manipulating the time between the presentation of the first and second stimulus on a millisecond level. A common way to investigate human multitasking with such simple tasks is the dual-task paradigm (see, e.g., Koch et al., 2018, for a review). Studies based on the dual-task paradigm investigated the performance of participants in

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a dual-task in relation to their performance in single-tasks (Pashler & Sutherland, 1998). In a dual-task, two stimuli are to be processed simultaneously, which often results in poorer performance (response time) and higher error rates (Kahneman, 1973; Koch et al., 2018; Norman & Bobrow, 1975; Pashler, 1994; Wickens, 2008). The combination of two simple tasks into a dual-task is still the dominant paradigm in multitasking research and reflects the lowest level of multitasking complexity. Multitasking research based on dual-tasking started with Welford (1952), who examined the effect of the psychological refractory period (PRP) with two stimuli, and since then several research aspects such as task performance limiting factors (Norman & Bobrow, 1975), different paradigms (Monsell, 2003; Pashler, 1984, 1994), modalities (Pashler, 1990; Schumacher et al., 2001), automatization (Maquestiaux et al., 2018; Strobach & Schubert, 2017b), processing order (Strobach et al., 2018), attention control (Hirst et al., 1980; Kramer et al., 1995), inhibition (Koch et al., 2010), long-term training effects (Bherer et al., 2005; Liepelt, Fischer, et al., 2011; Schumacher et al., 2001; Strobach & Schubert, 2017a), and transfer effects (Bherer et al., 2008; Liepelt, Strobach, et al., 2011; Strobach et al., 2012) have been investigated. Though, increasing the task's complexity by adding one or even more additional tasks was not systematically studied yet.

Multitasking can be classified in both a time and an application dimension. The time dimension distinguishes between concurrent and sequential multitasking while the application dimension distinguishes between the laboratory and the real world (Salvucci & Taatgen, 2010). Aforementioned dual-tasks are concurrent and take place in laboratory settings, whereas (driving) simulators (Nijboer et al., 2016; Watson & Strayer, 2010; Wechsler et al., 2018) or other complex tasks (Gutzwiller et al., 2019; Santiago-Espada et al., 2011) are closer to real-world tasks. In this area, there are also multitasking tasks for purely diagnostic aspects (Schuhfried, 1991) or studies that combine real-world aspects (such as a walking task) with laboratory tasks (Laessoe et al., 2008). There are only selected studies that extended the classical dual-task paradigm by adding a simple third task to form a basic triple-task paradigm. Recently, Konishi and colleagues (2021) have also extended a dual-task (Konishi et al., 2020) to a triple-task (Konishi et al., 2021) to determine whether participants have the ability to track their performance based on self-evaluation (metacognitive sensitivity). They used an adaption of the MATB (Santiago-Espada et al., 2011), but at the end of each trial, participants had to self-evaluate their performance. Konishi et al. (2021) could observe an increase in multitasking costs and that the number of tasks (dual-task vs. triple-tasks) had a great impact on further cognitive processes, such as metacognition. Consequently, adding a third task can grant valuable insight into how interference change when demands increase and can give a better approximation of how handling multiple concurrent tasks might be realized in complex every-day situations.

The current research in the field of dual-/ multi-tasking does not allow straightforward hypotheses about the effects of a third task on dual-task performance. Theories, such as the resource theory of Wickens (see also Tombu & Jolicøeur, 2003; Wickens, 1981), Pashler's (1984, 1990, 1994) response selection bottleneck (RSB), or the executive-process interactive control (EPIC) architecture of Meyer and Kieras (1997b, 1997a) are based exclusively on studies with two tasks. Even in dual-tasks, those theories fall short in one way or the other. The RSB model does not account for why some dual-tasks can be completed simultaneously without costs while others don't (Schumacher et al., 2001). This shortcoming was partly resolved in resource models (Tombu & Jolicøeur, 2003), but these models also leave the exact processes open. Exact modeling of task execution by a program specifying variables, operators, sequences, and loops is not possible. For example, Hommel (2020) also criticizes their "lack of mechanistic detail". For instance, it is not possible to explain why some subtasks are prioritized, or why different interferences occur in different modules (effector systems). The EPIC architecture also fails to explain the latter (Hoffmann et al., 2019). The Theory of Event Coding (TEC) advocated by Hommel (2019; Hommel et al., 2001) ventures on an extended approach, even though it has not yet found any concrete application in multitasking research (Hommel, 2020). According to TEC, a single, common representation medium for perceived events and the intended reaction or action forms the core structure of the functional architecture for perception and reaction planning. Its key assumption is that stimulus representations and action intentions are not differently coded, rather they are part of a common code, a common representational medium. If such a feature code (e.g., a location) is already bound in Task 1 but is also needed in Task 2, it needs to be unbound, which incurs costs in the form of time and errors. Koch (2009) showed that such overlapping response codes resulted in higher response times, an effect described as "strong crosstalk between the two tasks".

Thus, not only do the stimuli themselves have an impact on multi-tasking costs, but also (the interaction of) their response modalities (Huestegge & Hazeltine, 2011). The bindings between stimulus and response can, in their modality or ideomotor feature, be compatible or incompatible (Stephan et al., 2021; Stephan & Koch, 2010). For example, a task is considered modality-compatible if a visual stimulus is responded to with a manual or a pedal effector. Modality incompatibility occurs when the visual stimulus must be responded to with a vocal effector. The characteristics of the stimulus influence the compatibility of the stimulus and response bindings. If the visual stimulus appears on the left side and is responded to with the right hand the binding is considered ideomotor incompatible (for a review see, Shin et al., 2010). Hazeltine et al. (2006; see also Hazeltine & Ruthruff, 2006) showed that the dual-task costs were more than twice as high in tasks with modality-compatibility than incompatibility. Göthe et al. (2016) broke this down even further: They did not only examine the modality-compatibility of stimulus and response (modality pairing) but also whether the features within a task were compatible (ideomotor compatibility), i.e. whether a location stimulus appearing on the left side of the screen must also be responded to with a left button (modality and ideomotor bindings are compatible). Essentially, dual-tasks were used to induce high versus low interference conditions by using two kinds of stimulus-response (S-R) pairings (Göthe et al., 2016; Hazeltine et al., 2006; Tombu & Jolicoeur, 2004). The high interference condition is realized by two visual-manual (S-R) pairing tasks, the low interference condition is realized by a combination of a visual-manual and auditory-vocal task.

If typical dual-tasks are extended by adding another task, several considerations stand to reason. As previously mentioned, it is difficult to construct three tasks that can be assigned to three completely independent S-R-pairings. For response modalities, in most classic dual-task studies investigating S-R pairings, hand and voice are used. They usually constitute the S-R pairings visual-manual and auditory-verbal, where the visual modality is defined as a location task (left or right) and the auditory modality as a pitch task (high or low). The response modalities foot (Hoffmann et al., 2019; Liepelt, Fischer, et al., 2011; Naefgen et al., 2017; Pashler & Christian, 1994; Sangals et al., 2007; Stephan et al., 2021) and eye movements (Hoffmann et al., 2019; Pieczykolan & Huestegge, 2014; Stephan et al., 2013), in contrast, received little attention. Even though previous results have shown that oculomotor responses (eye movements as response modality) are a good complement to previously employed response modalities, pedal tasks separate input and output modality more clearly even if manual and pedal tasks supposedly cannot be processed in parallel (Pashler & Christian, 1994). This was also suggested by the results of Hoffmann et al. (2019). In task switching, Stephan et al. (2021) were able to show that pedal responses produced the equivalent effects of manual responses. Dual-tasks with both response modalities demonstrated very high dual-task or switching costs. Furthermore, Hoffmann et al. (2019) showed that there is a task prioritization in response times of oculomotor < pedal < vocal < manual (we refer to this as response order 1). However, this prioritization is not in line with all dual-task studies (see Hazeltine et al., 2002; Schumacher et al., 2001), but the prioritization of (sub)task was observed in some studies (e.g. Hazeltine et al., 2006; Huestegge & Koch, 2013). Based on other studies using pedal responses (e.g., Liepelt, Fischer, et al., 2011), a prioritization of oculomotor < manual < pedal < vocal would also be plausible (response order 2). To be comparable to well-known dual-tasks studies, in the present study, we used similar stimulus-response mappings as Schumacher et al. (2001; see also Hazeltine et al., 2002; Hoffmann et al., 2019; Pashler & Christian, 1994). Stimuli remained as simple as possible with a location (left or right location), pitch (high or low pitch), and color task (green or turquoise color). The color discrimination task was comparable to the location task (Pisella et al., 1998) and should induce little interference with the location and pitch task due to the use of other ideomotor features (Shin et al., 2010). Thus, all three tasks were comparable to each other and similarly difficult. Consequently, the resulting triple-task was made up of a visual-manual, a visual-pedal, and an auditory-vocal task (with response modalities hand, foot, and voice).

In summary, the following assumptions about this triple-task can be made based on previous findings: First, we assume a clear prioritization of the subtasks, which will be either pedal < vocal < manual (Hoffmann et al., 2019, response order 1) or manual < pedal < vocal (Hazeltine et al., 2002; Liepelt, Fischer, et al., 2011, response order 2), which will be visible in the modality-specific response times. As in response order 2, we assume a high prioritization of the manual and pedal task, since both are important and elementary response modalities in everyday life. Second, we assume that there is some limited interference between the two visual tasks due to (weak) crosstalk (Koch, 2009) or due to a bottleneck in the visual system in terms of the dual-task framework (Tombu & Jolicøeur, 2003; Wickens, 1981). This could be circumvented by participants prioritizing tasks in response order 1 (pedal < voice < manual). By procedurally separating the manual and pedal task by the voice task, a bottleneck could be bypassed which in turn could show up in low costs for participants with response order 1. Third, since sub-task response times are higher for dual-tasks than comparable single-tasks (Schumacher et al., 2001, e.g.), we assume further increases in response times for triple-tasks. As an exploratory analysis, it will be interesting to see whether a linear, or non-linear increase of response time can be observed from single-task to dual-task to triple-task. The increase would be linear if the increase in cognitive demands from a single to the dual-task is comparable to the increase in cognitive demands from the dual-task to the triple-task and the increase would be non-linear accelerating, respectively decelerating, if the increase in cognitive demands from the dual-task to the triple-task is higher, respectively, lower compared to the increase from the single to the dual-task.

For our triple-task paradigm, as with the dual-task paradigm, all three stimuli were shown simultaneously. We also instructed equal prioritization of all three tasks (Schumacher et al., 2001; Stelzel et al., 2006). We focused on the comparison of single- and triple-tasks in the first experiment and on the comparison of single-, dual-, and triple-tasks in the second experiment. All tasks were presented in a mixed-block design to prevent task preparation (see, Kiesel et al., 2010 for a review).

2 Experiment 1

To directly compare the performance in the triple-task with the performance in each of the three single tasks, we exclusively used single-tasks and triple-tasks and we tested different S-R pairings for the two visual tasks. We switched response modality only in the visual task, as there have been very few comparable studies on the foot response modality, in contrast to the response modalities hand and voice. Thus, participants performed the tasks in a within subject design either with the S-R pairing location-hand and color-foot, or location-foot and color-hand, and each task pair was combined with pitch-voice.

2.1 Methods

2.1.1 Participants

19 students (9 females and 10 males, $M = 23.32$, $SD = 2.60$) took part in this experiment. All participants had normal or corrected-to-normal vision and no hearing impairments. They provided informed consent and were given course credit or ~9 € as compensation for their participation. Due to a technical equipment failure, four records were lost. Thus, 15 participants were included in the final analysis.

2.1.2 Setup

The experiment was programmed in MatLab® 2019a with the Psychtoolbox-3.013 (Brainard et al. 2016) on a PC running Linux OS® with Ubuntu 18.04 LTS. The study was conducted in noise-reduced medium-lit cabins. The visual stimuli were displayed on an EIZO® color monitor with a screen diagonal of 27 inches and a frame rate of 144 Hz at a resolution of 3840 × 2160 pixels. The BlackBox® toolkit response pad with a voice key feature was used to capture response time of the motor and the vocal responses. One visual task was completed with the index and middle finger of the dominant hand via two adjacent keys on the response pad. The other visual task was completed with both feet on the respective foot pedals. The Sennheiser® Model PC3 headset was used to record the participants' voice and reproduce the auditory stimuli.

2.1.3 Task

As an extension of the basic methodology of Schumacher et al. (2001; see also Hazeltine et al., 2002), participants performed three two-choice response time tasks: a visual-manual (color or location discrimination), a visual-pedal (location or color discrimination), and an auditory-vocal (pitch discrimination) task. Each task sequence was structured as follows: first, participants were presented a fixation screen for 500, 1000, or 1500 ms with a white square (3.7° side length) as a fixation object in the center of the screen. Second, the stimuli in the single-tasks were presented for 200 ms and the white fixation square stayed on the screen until the participant responded (see Fig. 1). In the location discrimination single-task, participants responded with their hand or feet, depending on the S-R pairing, to the location (and direction) of a white arrow (1.5° height) appearing randomly and equally distributed at the left or right side of the fixation square by pressing a button (left arrow with the index finger or left foot and right arrow with the middle finger or right foot). In the color single-task, participants responded with their hand or feet, depending on the S-R pairing, to the color that the fixation square (and the arrow shown if necessary) turned to. The color was either green (RGB: 0, 255, 0) or turquoise (RGB: 0, 255, 255). The participants responded with a button press (green square with the index finger or left foot and turquoise square with the middle finger or right foot). In the pitch single-task, participants responded vocally via the voice key to a heard sine wave tone at frequencies of either 350 or 1650 Hz by saying “TIEF” or “HOCH” (German for: “LOW”/ “HIGH”).

In the triple-task, participants had to respond to all three tasks simultaneously (tasks were presented with an SOA of 0 ms).

2.1.4 Design

Participants had to complete two S-R pairing conditions (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)) in the same session in two distinct S-R orders (order A with first S-R pairing: CF|LH|PV and order B with first S-R pairing: LF|CH|PV, see Fig. 1). One S-R pairing condition consisted of three different uniform blocks and five mixed blocks. A uniform block comprised of 20 trials of only one type of single-task in the order location (LH or LF), color (CF or CH), and pitch (PV). A mixed block consisted of the three single-tasks and the triple-task with a total of 12 single-tasks and 40 triple-tasks in each block. The tasks were randomly distributed in each block. In total, in uniform blocks, the participants completed 120 single-task trials. In mixed blocks, they completed 120 single-task trials and 400 triple-task trials. Half of the participants started with S-R order A, followed by S-R order B, and the other half vice versa. Participants were instructed to perform all the tasks as quickly and accurately as possible. They were told not to respond in a particular order and to give equal priority to all tasks. In total, participants had to participate in three sessions on three consecutive days. On each day, they completed both S-R pairing conditions.

2.1.5 Analyses

Vocal responses were analyzed at the time the voice key was triggered using the R-Package “VoiceExperiment” (Nett, 2017). For unclear cases in the analysis, trials were listened to and manually classified. RStudio 3.5 (RStudio Team 2016) was used with the tidyverse package version 1.2.1 (Wickham 2017) for data preparation and creating figures and jamovi version 1.1 (jamovi project 2018) to calculate repeated measure ANOVAs and post hoc analyses. For the analyses of all effects, we included single-task and triple-task trials only from mixed blocks (uniform blocks were only used for training the S-R pairings). Only correct trials were included in the analyses. This means that in the triple-task all three tasks had to be responded correctly (error rate in single-tasks: 4.9 %, triple-task: 10.2 %). All trials with response times faster than 80 ms and slower than 4500 ms were removed (single-tasks: 0.9 %, triple-task: 2.9 %). If not stated otherwise, we calculated mean response times per participant and S-R order. Post hoc tests were conducted on the estimated marginal means with Welch’s *t*-test and we used the Welch-Satterthwaite equation for computing degrees of freedom.

2.2 Results

In the following analysis, we considered the effects of the single-tasks (ST) and the triple-task (TT) in mixed-blocks. For the analyses, the response times of single-tasks and the triple-task were calculated separately in repeated measures ANOVAs. The effects were examined by post hoc comparisons.

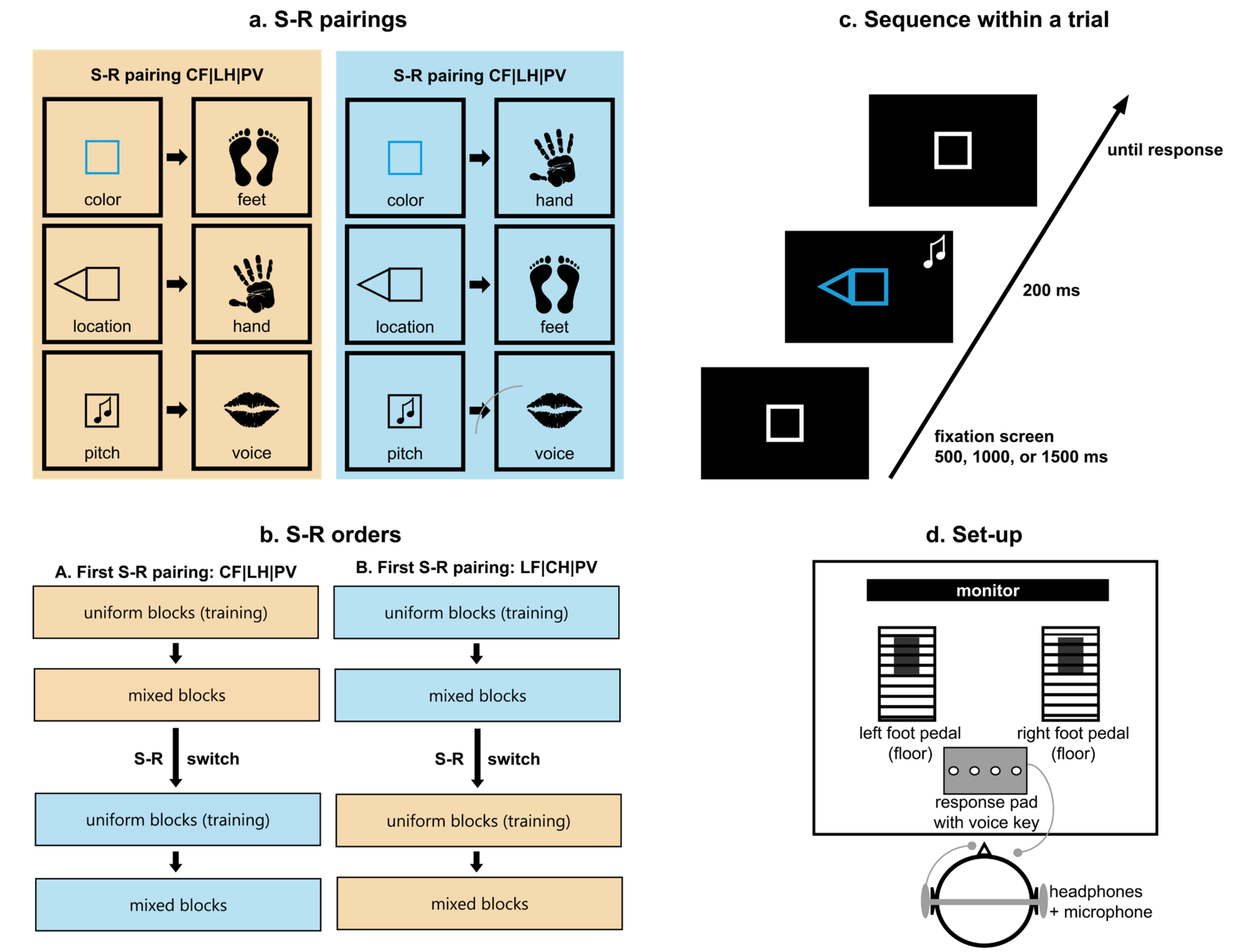

Figure 1: Schematic representation of the design and the tasks. a. shows both possible stimulus-response (S-R) pairings. In the S-R pairing CF|LH|PV, participants had to respond to the color (green or turquoise) of the fixation square with their feet, the location of the arrow (left or right) with their dominant hand, and to the pitch (low or high) with their voice. In the S-R pairing LF|CH|PV, the participants had to respond to the color with their hand, to the location of the arrow with their feet, and the pitch with their voice. b. shows both S-R orders which also represent the between-subject factor. In S-R order A, participants first had to perform the stimulus-response pairing (S-R pairing) color-foot, location-hand, and pitch-voice (CF|LH|PV) and then location-foot, color-hand, and pitch-voice (LF|CH|PV). In the S-R order B, the S-R pairings were reversed in order. In each S-R pairing, participants first practice each task separately in a uniform block. Mixed blocks consist of single-tasks and the triple-task. c shows the sequence of a triple-task trial. After the fixation screen, the stimuli appear for 200 ms. Until the response, the same screen as for the fixation screen is seen again. The note is visible only for illustration. d shows the set-up in the laboratory. Participants responded with their feet, dominant hand, and voice. The voice was timed with the voice key of the response pad and recorded with the microphone of the headphones.

2.2.1 Performance in single-tasks in mixed blocks

We analyzed single-tasks from mixed blocks to investigate how they are processed in the triple-task context. Single-tasks in uniform blocks were not analyzed in detail. They served only as a brief training to get used to the current S-R pairing. In general, the response times of single-tasks in mixed blocks increased considerably in comparison to single-tasks in uniform blocks.

A repeated-measures ANOVA was calculated for single-tasks in mixed-blocks with response modality (foot, hand, vs. voice) and S-R pairing (CF|LH|PV vs. LF|CH|PV) as a within-subject factor. The main effects for response modality, $F(2,28) = 2.99$, $p = .066$, $\eta^2_p = 0.176$, and S-R pairing, $F(1,14) = 1.44$, $p = .250$, $\eta^2_p = 0.093$, were not significant. The interaction of response modality and S-R pairing, $F(2,28) = 20.90$, $p < .001$, $\eta^2_p = 0.599$, was significant.

For the interaction response modality and S-R pairing we observed that response times depended on the stimuli (see Table 1. for descriptive values). In S-R pairing CF|LH|PV, location-hand (M = 733 ms) was faster than pitch-voice (M = 867 ms), M = -133 ms, $t(53.8) = -2.67$, $p = .01$, 95 % CI for M [-234 ms, -33 ms], and pitch-voice was faster than color-foot (M = 1052 ms), M = -185 ms, $t(53.8) = -3.7$, $p < .001$, 95 % CI for M [-286 ms, -85 ms]. In S-R pairing LF|CH|PV, location-foot (M = 849 ms) was faster than pitch-voice (M = 903 ms), M = -183 ms, $t(53.8) = -3.65$, $p < .001$, 95 % CI for M [-283 ms, -82 ms], and pitch-voice was faster than color-hand (M = 1032 ms), M = -129 ms, $t(53.8) = -2.59$, $p = .012$, 95 % CI for M [-230 ms, -29 ms].

Table 1: Response times and standard deviations in milliseconds for single-tasks and triple-task from mixed-task blocks and stimulus-response (S-R) pairings (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)).

Task	S-R pairing	Foot		Hand		Voice	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	CF|LH|PV	1052	229	733	155	867	148
	LF|CH|PV	843	145	1032	205	903	165
Triple-task	CF|LH|PV	1189	234	1158	213	1536	307
	LF|CH|PV	1208	235	1289	269	1650	424

In summary, regardless of the response modality, the location task was always responded to the fastest, followed by the pitch task, and finally by the color task. After the response modality switched for the location and the color task, the participants seemed to prioritize the response order according to the stimulus and not according to the response modality. Therefore, neither of the two hypothesized response orders (pedal < vocal < manual vs. manual < pedal < vocal) seems to be generally applicable for the single-tasks.

2.2.2 The performance in the triple-task in mixed blocks

A repeated-measures ANOVA was calculated for the triple-task in mixed-blocks with the within-subject factor response modality (foot, hand, vs. voice), and S-R pairing (CF|LH|PV vs. LF|CH|PV). Only the within-factor response modality was significant, $F(2,28) = 17.54$, $p < .001$, $\eta^2_p = 0.556$. Despite changing the S-R parings in the visual tasks, no effects could be observed, neither for the main effect S-R pairing, $F(1,14) = 3.70$, $p = .075$, $\eta^2_p = 0.209$, nor for the interaction between response modality and S-R pairing, $F(2,28) = 2.50$, $p = .100$, $\eta^2_p = 0.152$.

The response modalities hand (M = 1223 ms) and foot (M = 1198 ms) were equally fast (M = -25 ms, $t(28) = -0.339$, $p = .737$, 95 % CI for M [-178 ms, 127 ms]), and both were faster than the response modality voice (M = 1593 ms), (hand: M = -370 ms, $t(28) = -4.951$, $p < .001$, 95 % CI for M [-522 ms, -217 ms], foot: M = -395 ms, $t(28) = -5.291$, $p < .001$, 95 % CI for M [-548 ms, -242 ms]). Descriptively we could observe that in both S-R pairings the location task was slightly faster than the color task. Furthermore, the pitch task was much slower, as seen in the main effect of the response modalities.

The prioritization of response order according to stimuli found in the single-tasks was not evident in the subtasks of the triple-task. Instead of prioritizing the stimuli, the two response modalities hand and foot were prioritized in both S-R pairings, which is more in line with response order 2 (manual < pedal < vocal) but is not fully supported due to the equally fast execution of pedal and manual responses. Further, this seems to suggest that the two visual tasks do not interfere with each other.

2.2.3 The calculation of triple-task costs

The triple-task costs (differences in the mean values) in Experiment 1 were exclusively calculated from the difference of triple- and single-task (both from mixed blocks), e.g., for the response modality hand the response time of the subtask hand in the triple-task minus the response time of the hand in the single-task was calculated.

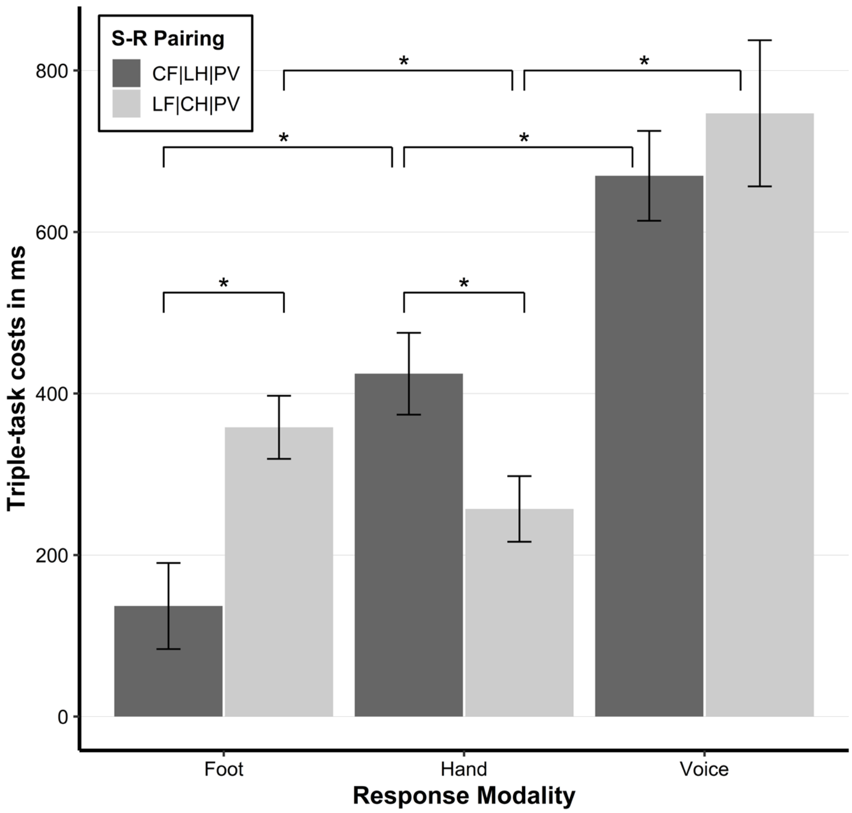

Figure 2: Triple-task costs in milliseconds to the foot (left), hand (middle), and voice response modality (right) as a function of the stimulus-response (S-R) pairings (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)). The values (costs) were calculated from the subtask in the triple-task minus the corresponding single-task. Asterisks indicate significance (α = .05) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

A repeated-measures ANOVA was calculated for triple-task costs with response modality (foot, hand, vs. voice) and S-R pairing (CF|LH|PV vs. LF|CH|PV) as a within-subject factor. The main effect for response modality, $F(2,28) = 32.80$, $p < .001$, $\eta^2_p = 0.701$, was significant. The main effect for S-R pairing, $F(1,14) = 3.02$, $p = .104$ $\eta^2_p = 0.117$, was not significant. The interaction of response modality and S-R pairing, $F(2,28) = 11.17$, $p<.001$, $\eta^2_p = 0.444$, was significant.

The triple-task costs did not differ between response modality with the same stimuli (e.g., foot from S-R pairing CF|LH|PV vs. hand from S-R pairing LF|CH|PV) but between stimuli with the same response modality (e.g., color from S-R pairing CF|LH|PV vs. location from S-R pairing LF|CH|PV). The lowest costs occurred with the color stimulus (with M_{Foot} = 137 ms, M_{Hand} = 257 ms). This was followed by the location stimulus (with M_{Foot} = 358 ms, M_{Hand} = 425 ms) and the pitch stimulus with the highest costs (with $M_{\text{Pitch-CF|LH|PV}}$ = 670 ms, $M_{\text{Pitch-LF|CH|PV}}$ = 747 ms) (see Fig. 2).

Comparing the single tasks and the triple-task, significant costs were observed in each subtask, which - turned out to be the higher the later the subtask was responded to. Averaged over the two S-R pairings, this meant a doubling of the response times from the fastest subtask to the second-fastest subtask and from the second-fastest subtask to the slowest subtask.

2.3 Discussion

The aim of Experiment 1 was to examine the effects of three simultaneous tasks, allowing us to quantify the behavior of single-tasks and triple-tasks in a triple-task context. The results showed that in mixed blocks the response times in both single-tasks and the triple-task strongly increased and were up to two times higher compared with single-tasks in uniform blocks or in single-tasks and dual-tasks in other studies (Schumacher et al. 2001; Tombu and Jolicoeur 2004; Maquestiaux et al. 2018). It was further observed that participants responded in single-tasks fastest to the location stimulus and slowest to the color stimulus.

However, in the triple-task, the response to the location and color stimulus were apparently grouped (response times differences *M* = -25 ms) and showed similar response times (see section “The performance in the triple-task in mixed blocks”). Regardless of S-R pairing, the triple-task costs were lowest with the color stimulus, followed by the location stimulus, and the pitch stimulus. The apparent grouping of the response modalities hand and foot in the triple-task could have several reasons. Either (1) both tasks are actually processed in parallel, (2) crosstalk of stimuli and response codes prevents separate processing, or (3) the complexity of the triple-task requires different cognitive strategies than dual-tasks. The results of Experiment 1 currently allow the conclusion that both visual subtasks were processed simultaneously in the triple-task. According to the feature-integration theory of attention (Treisman & Gelade, 1980), both stimuli (location and color) can be perceived and processed simultaneously. But, in other studies that used the response modalities hand and foot in dual-tasks, there was no grouping in response times but sequential processing (Hoffmann et al., 2019; Liepelt, Fischer, et al., 2011; Sangals et al., 2007). However, the assumption that the response modalities hand and foot were processed simultaneously is rather weak as Liepelt et al. (2011) was unable to achieve complete elimination of dual-task costs despite intensive training, which argues against simultaneous processing. Liepelt et al. (2011) listed as a possible reason the crosstalk between the two tasks. In their study, the response codes shared the same (spatial) dimension resulting in interference between the two tasks (Hommel, 1998, 2019; Koch & Prinz, 2002). In our Experiment 1, both tasks shared the same dimension not only in the response codes but also in the stimuli codes. Thus, S-S and R-R compatibility may have occurred, strongly linking CF|LH, and LF|CH and preventing them from being processed separately. In addition, it is possible that the higher demands within a triple-task simply led to a strategy adaptation to process all tasks as quickly as only possible if subtasks were grouped (as may be the response modalities hand and foot). Thus, similar to bimanual coordination, response 1 waits for response 2, and both are executed more or less simultaneously although response 1 could already have been executed. The prerequisites are given by the temporal (SOA = 0 ms) and spatial (spatial) overlap (Miller & Ulrich, 2008; Rinkenauer et al., 2001). However, to find more evidence for the assumption these dual-tasks have to be added to compare them with the triple-task. This was done in Experiment 2.

3 Experiment 2

In Experiment 1, participants completed only single-tasks and triple-tasks. Unexpectedly, response times were very high in both the triple-task and the single-tasks, which complicated a comparison with other studies. Also, the costs (triple-task compared to single-tasks) were much higher than expected. The introduction of the three possible dual-tasks should provide a better explanation for the observed effects in Experiment 1. In the following Experiment 2, participants performed single-tasks, dual-tasks, and triple-tasks in a between-subject design either with the S-R pairing location-hand and color-foot, or location-foot and color-hand. Each pairing was combined with the pitch-voice pairing.

3.1 Methods

3.1.1 Participants

44 students (21 females, *M* = 22.30, *SD* = 2.35) took part in this experiment. Two participants were left-handed, 42 right-handed. All participants had a normal or corrected-to-normal vision and no hearing impairments. They provided informed consent and were given course credit or ~9 € as compensation for their participation. Due to error rates of up to 65 %, two participants were excluded. Thus, 42 participants were included in the final analysis.

3.1.2 Setup

For Experiment 2, we used the same setup as for Experiment 1.

3.1.3 Task

Dual-tasks were added in addition to the existing single-tasks and the triple-task. Any combination of single-tasks was possible. This resulted in the location + color, location + pitch, and color + pitch dual-task. Similar to Experiment 1, but in a between-subject design, stimulus-response mapping depended on the S-R pairing condition.

3.1.4 Design

Contrary to Experiment 1, in a between-subject design, participants completed only one of two S-R pairing conditions (color-foot, location-hand, and pitch-voice (CF|LH|PV) or location-foot, color-hand, and pitch-voice (LF|CH|PV)) in one session. The session consisted of seven different uniform blocks and six mixed blocks. A uniform block comprised of eight trials of only one type of single-tasks, dual-tasks, or the triple-task. All uniform blocks served only for the exercise of each trial type. The order was always single-task, dual-task, followed by the triple-task to allow participants to become familiar with the modified or additional tasks. A mixed block consisted of each of the three single-tasks and dual-tasks and the triple-task with a total of 24 single-tasks, 24 dual-tasks, and 24 triple-tasks in each block.

3.1.5 Analyses

As in Experiment 1, only correct trials were included in the analyses (error rate in single-tasks: 5.6 %, dual-tasks: 11.7 %, triple-task: 11.1 %). All trials with response times faster than 80 ms and slower than 4500 ms were removed (single-tasks: 1.7 %, dual-tasks: 3.8 %, triple-task: 5.9 %).

3.2 Results

In the following, we compared response times in all single- (ST), dual- (DT), and triple-tasks (TT) as well as task costs in the context of dual-task costs and triple-task costs. Based on Experiment 1, we did not focus on the analysis of the response modalities but the stimuli in a repeated-measures ANOVA with the within-subject factor task (single-tasks, location + color dual-task, location + pitch dual-task, color + pitch dual-task, and triple-task) as a factor and the between-subject factor S-R pairing (CF|LH|PV and LF|CH|PV) as for each stimulus (color, location, or pitch) individually, e.g. for the location stimulus the tasks single-task, location + color dual-task, location + pitch dual-task, and TT were included. All descriptive values except the between-subject factor stimulus-response Pairing (S-R pairing) are presented in Tables 2 and 3. As we found no significant influence of the between-subject factor S-R pairing in any of the subsequent analyses (all *p*s > .20), descriptive tables including this factor can be found in the supplementary material (see Tables S1 to S6 in the supplementary material).

3.2.1 Response order between single-, dual-, and triple-tasks

To compare response times, all single-, dual-, and triple-tasks were aggregated in each case. We calculated a repeated-measures ANOVA with the three tasks as within-subject factor (single-task, dual-task, tiple-task). The analysis showed a significant main effect, $F(2,82) = 370.0$, $p < .001$, $\eta^2_p = 0.900$. Single-task were significant slower than dual-tasks, M = -457 ms, t(41) = -19.2, p < .001, 95% CI [-505 ms, -409 ms], and the triple-task, M = -653 ms, t(41) = -21.4, p < .001, 95% CI

Table 2: Mean response times (calculated from participants' means) and standard deviations in milliseconds for single-task trials, dual-task trials, and triple-task trials from mixed blocks.

Task	Combination	Color		Location		Pitch	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	-	874	171	689	154	941	185
Dual-task	Location + Color	1240	263	1236	280	-	-
	Location + Pitch	-	-	981	291	1447	311
	Color + Pitch	1243	298	-	-	1602	355
Triple-task	-	1326	296	1316	306	1819	357

Table 3: Mean error rates (calculated from participants' means) and standard deviations for single-task trials, dual-task trials, and triple-task trials from mixed blocks. Numbers indicate % values.

Task	Combination	Color		Location		Pitch	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	-	6.5	6.4	5.3	7.6	3.0	3.7
Dual-task	Location + Color	7.5	6.6	3.8	4.6	-	-
	Location + Pitch	-	-	1.3	1.7	8.6	7.6
	Color + Pitch	7.8	7.5	-	-	8.0	6.9
Triple-task	-	4.9	4.2	1.7	1.9	4.2	3.9

[-715 ms, -591 ms]. The dual-task were also significant slower than triple-tasks, M = -196 ms, t(41) = -10.9, p < .001, 95% CI [-232 ms, -160 ms].

The average response times of all dual-tasks (*M* = 1292 ms) relative to all single-tasks (*M* = 834 ms) increased by *M* = 457 ms. For all triple-tasks (*M* = 1487 ms), this increased by 196 ms or ~43% relative to all dual-tasks. Thus, response times increased less than linearly. However, examination of these costs in relation to the stimuli revealed widely varying costs depending on the specific task.

3.2.2 Response order within single-, dual-, and triple-tasks

Single-Tasks. To identify prioritization of (sub-) tasks we calculated a repeated-measures ANOVA with the three single-tasks as within-subject factor (color task, pitch task, location task). The analysis showed a significant main effect, $F(2,82) = 43.0$, $p < .001$, $\eta^2_p = 0.512$. The location-single-task was on average processed fastest (689 ms), followed by the color-single-task (874 ms), location compared to color: *M* = -186 ms, $t(82) = -6.58$, $p < .001$, 95% CI [-242 ms, -129 ms], and the pitch-single-task (941 ms), color compared to pitch: *M* = -67 ms, $t(82) = -2.36$, $p = .021$, 95% CI [-123 ms, -10 ms] (see all results in Table S7 in the supplementary material).

In single-tasks, the response order was not stable across both experiments. Compared to Experiment 1, the participants now prioritized responses in a different order changed from location < pitch < color to location < color < pitch in Experiment 2.

Dual-Tasks. In the dual-tasks, the paired *t*-tests showed no difference between the color sub-task and the location sub-task in the location + color dual-task, *M* = 4 ms, $t(41) = 0.18$, $p = .859$, 95% CI [-40 ms, 48 ms]. However, a significant difference between two sub-tasks was observed in the location + pitch dual-task, *M* = -466 ms, $t(41) = -13.47$, $p < .001$, 95% CI [-536 ms, -396 ms], and in the color + pitch dual-task, *M* = -359 ms, $t(41) = -11.87$, $p < .001$, 95% CI [-420 ms, -298 ms].

In dual-tasks, we observed that neither the location task nor the color task was preferred when they appeared in the same dual-task. But in combination with the pitch task, the location and color tasks were always preferred.

Triple-Task. The same analysis as for the single-tasks was calculated for the triple-task with the three subtasks as within-subject factor, which revealed a similar pattern. We could observe a significant main effect, $F(2,82) = 103.0$, $p < .001$, $\eta^2_p = 0.714$, but the difference between the color and the location sub-tasks was not significant, $M = 10$ ms, $t(82) = 0.25$, $p = .805$, 95% CI [-70 ms, 90 ms]. The pitch task was still the slowest (see Table S7).

It seems that when combining the response modalities hand and foot in both the location + color dual-task and the triple-task, the responses times were equally fast. Consequently, we could not observe a clear task prioritization of the (sub-) tasks like Hoffmann et al. (2019) where participants responded fastest to oculomotor than pedal < vocal < manual (for a different response order see also Hazeltine et al., 2002).

3.2.3 Error rates within single-, dual-, and triple-tasks

Single-Tasks. For error rates in single-tasks the main effect was significant, $F(2,82) = 5.50$, $p = .006$, $\eta^2_p = 0.121$. We observed the lowest rates with the pitch stimulus ($M = 3.0$ %), pitch compared to color: $M = -3.5$ %, $t(41) = 4.16$, $p < .001$, 95% CI [-5.2 %, -1.8 %] followed, but without difference, by the color ($M = 6.5$ %) and location ($M = 5.3$ %) stimulus, color compared to location: $M = 1.2$ %, $t(41) = 0.94$, $p = .351$, 95% CI [-1.4 %, 3.9 %] (see all results in Table S8).

The error rates in the single-tasks showed the opposite pattern to the response times. While the response times in the pitch task were the highest, the error rates were now the lowest.

Dual-Tasks. Contrary to the response times in the location + color dual-task, significant difference in error rates were observed between the location ($M = 7.5$ %) and color ($M = 3.8$ %) stimulus, $M = 3.7$ %, $t(41) = 4.91$, $p < .001$, 95% CI [2.2 %, 5.2 %]. Furthermore in the location + pitch dual-task, the error rates with the location stimulus ($M = 1.3$ %) were lower than with the pitch stimulus ($M = 8.6$ %), $M = -7.4$ %, $t(41) = 4.91$, $p < .001$, 95% CI [-9.7 %, -5.1 %]. In the color + pitch dual-task, no difference in error rates between the stimuli were observed (($M_{color} = 7.8$ %, $M_{pitch} = 8.0$ %), $M = -0.4$ %, $t(41) = -0.34$, $p = .74$, 95% CI [-1.7 %, 1.2 %].

The error rates in the dual-tasks appeared very unsystematic in the current data sample. It should be emphasized, however, that the error rate in the location + color dual-task differed significantly, indicating interference between the two subtasks compared to the response times.

Triple-Task. In the triple-task, the main effect was significant, $F(2,82) = 23.2$, $p < .001$, $\eta^2_p = 0.361$. The location stimulus ($M = 1.7$ %) showed the lowest error rates followed by the color stimulus ($M = 4.9$ %), location compared to color: $M = -3.2$ %, $t(41) = 6.3$, $p < .001$, 95% CI [-4.2 %, -2.2 %], and pitch stimulus ($M = 4.2$ %) , color compared to pitch: $M = 0.7$ %, $t(41) = 1.61$, $p = .116$, 95% CI [-0.2 %, 1.5 %] (see all results in Table S8 in the supplementary material).

In comparison to the dual-tasks, the subtasks in the triple-task again showed a different pattern. The error rate increased comparable to the response times in the same subtasks (location < color < pitch).

3.2.4 Triple-task and dual-task costs

3.2.4.1 Response times

Based on the results of the single-task, dual-task, and triple-task trials, different dual- and triple-task costs could be calculated in Experiment 2. We always compared the occurring stimulus in the respective dual-task or triple-task to the single-task (e.g., in the dual-task location-color the sub-task with the color stimulus and the single-task with the color stimulus). The resulting costs can be seen in Fig. 3 and Fig. 4.

For each stimulus (color, location, and pitch), repeated-measures ANOVAs with the task as a within-subject factor (dual-task location + color, dual-task location + pitch, dual-task color + pitch, and the triple-task) were calculated. However, the corresponding task was only analyzed if the corresponding stimulus was also present in the task. Significant main effects were found for all stimuli (see Table S9 in the supplementary material).

For the *color stimulus*, participants showed equally high costs, in both dual-tasks (color + location $M_{color} = 366$ ms; color + pitch $M_{color} = 369$ ms), $M = -3$ ms, $t(82) = -0.11$, $p = .913$, 95% CI [-54 ms, 48 ms]. Only the triple-task costs ($M_{color} = 452$ ms) were significantly higher than both dual-task costs, location + color dual-task costs compared to triple-task

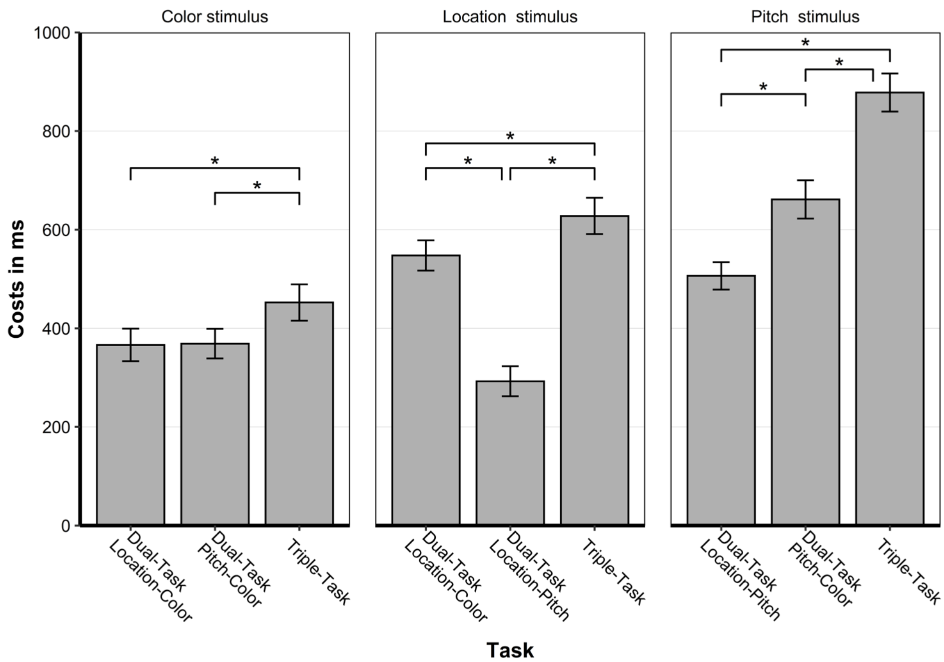

Figure 3: Dual-task costs and triple-task costs to the color stimulus (left), location stimulus (middle), and pitch stimulus (right) as a function of the task (location + color, color + pitch, location + pitch dual-task, and triple-task) in which they are appearing (e.g. in the leftmost bar, the cost was calculated from the location + color dual-task minus the color single-task). Thus, values represent dual-task costs and triple-task costs compared to single-tasks (averaged over stimulus-response (S-R) pairing condition). Asterisks indicate significance (α = .01) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

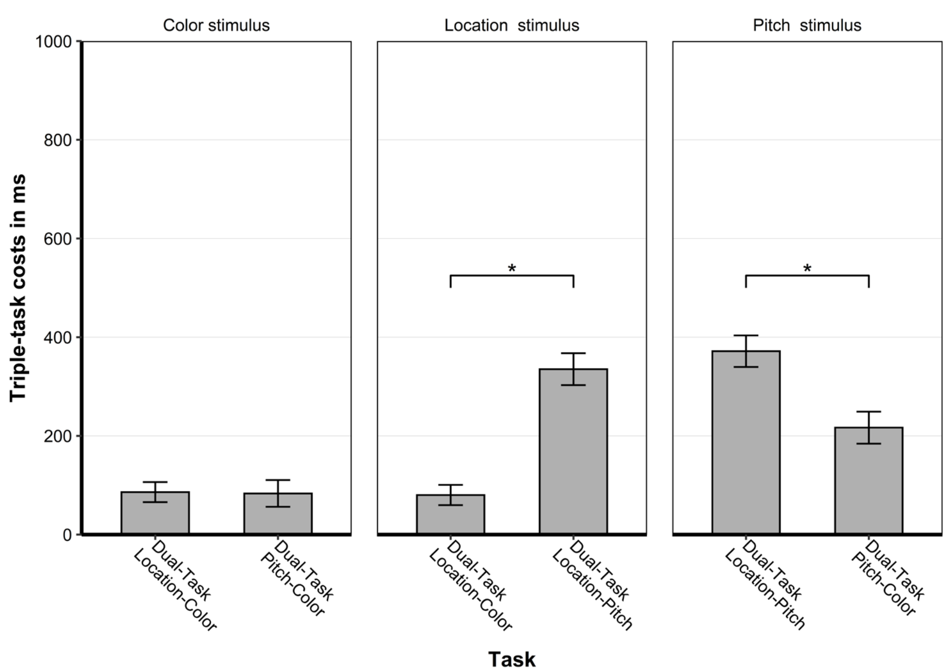

Figure 4: Triple-task costs to the color stimulus (left), location stimulus (middle), and pitch stimulus (right) as a function of the task (location + color, color + pitch, and location + pitch dual-task) in which they are appearing (e.g., the leftmost bar, the response time was calculated from the color task from the location + color dual-task minus the triple-task with a color stimulus). Thus, response times represent triple-task costs compared to dual-tasks (averaged over stimulus-response (S-R) pairing condition). Asterisks indicate significance (α = .01) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

costs: M = -86 ms, $t(82)$ = -3.37, p = .001, 95% CI [-137 ms, -35 ms] and color + pitch dual-task costs compared to triple-task costs: M = -83 ms, $t(82)$ = -3.26, p = .002, 95% CI [-134 ms, -32 ms].

For the *location stimulus*, the lowest costs were found for the location + pitch dual-task ($M_{location}$ = 293 ms), which were significantly lower than the costs for the location + color dual-task ($M_{location}$ = 548 ms), M = -255 ms, $t(82)$ = -8.69, p < .001, 95% CI [-313 ms, -197 ms]. As with the color stimulus, the triple-task costs were highest ($M_{location}$ = 628 ms), location + color dual-task costs compared to triple-task costs: M = -80 ms, $t(82)$ = -2.73, p = .008, 95% CI [-139 ms, -22 ms].

For the *pitch stimulus*, a comparable pattern as for the location stimulus emerged. In the location-pitch dual-task (M_{pitch} = 506 ms) participants showed the lowest costs. Significantly higher costs were again observed in the color-pitch dual-task (M_{pitch} = 661 ms), M = -155 ms, $t(82)$ = -4.74, p < .001, 95% CI [-220 ms, -90 ms], and with the highest costs in the triple-task (M_{pitch} = 878 ms), color + pitch dual-task costs compared to triple-task costs: M = -217 ms, $t(82)$ = -6.63, p < .001, 95% CI [-282 ms, -152 ms].

Depending on the dual-task, there were different costs in relation to the respective single-task. For the color stimulus, each response modality produced the same costs. However, dual-tasks that required responding to location or pitch showed that the stimulus combination of location and pitch had the lowest costs, and in combination with color, the higher costs were incurred. For all possible combinations, the triple-task costs relative to the single-tasks were always higher than triple-task costs relative to dual-task costs (meaning the triple-task always produced additional costs). These increased much less than the dual-tasks except when compared to tasks with the pitch stimulus. This argues against purely additive increase from dual-task costs to triple-task costs. To test this, we analyzed the costs of the subtasks within the three dual-tasks.

The triple-task costs of the location and color stimuli in the location + color dual-task, showed no differences, M = -6 ms, $t(41)$ = -0.69, p = .494, 95% CI [-24 ms, 12 ms], also the comparison of triple-task costs between the location and pitch stimuli in the location + pitch dual-task, M = -37 ms, $t(41)$ = -1.45, p = .156, 95% CI [-87 ms, 14 ms]. This means that the response times increased from the dual-task to the triple-task by the same amount in both subtasks. Only in the color-pitch dual-task the costs increased more for the pitch stimulus task than for the color stimulus task in the color + pitch dual-task, M = -133 ms, $t(41)$ = -5.36, p < .001, 95% CI [-184 ms, -83 ms].

3.2.4.2 Error Rates

We calculated the same ANOVAs for the triple-task costs and dual-task costs of error rates. Significant main effects emerged across all three stimuli (see Table S10 in the supplementary material). The descriptive is reported in Table 4. For the *color stimulus*, M = -0.3 %, $t(41)$ = -0.21, p = .838, 95% CI [-3.1 % 2.5 %], and pitch stimulus, M = 0.6 %, $t(41)$ = 0.45, p = .653, 95% CI [-2.1 % 3.4 %], we observed high costs with dual-task, but they were equal compared to each other. The costs for the triple-task (< 1.6%) was significantly lower compared to both dual-tasks costs (see details in Table S11 in the supplementary material). However, for the *location stimulus*, dual-task costs differed significantly between location + color dual-task (M = -1.4%) and location + pitch dual-task (M = -4.0 %), M = 2.6 %, $t(41)$ = 3.81, p < .001, 95% CI [1.2 % 3.9 %]. Here, location + pitch dual-task was equally low as triple-task (M = -3.6 %), M = -0.5 %, $t(41)$ = -1.11, p = .274, 95% CI [-1.3 % 0.4 %].

While the response times increased significantly from the single-tasks to the triple-tasks, this trend was not observed for the error rates.

We also calculated the costs in the subtasks within the three dual-tasks. Error rate costs decreased uniformly across stimuli from dual-tasks to the triple-task (comparable to the uniform increase in response time costs). Only the location + pitch dual-task showed a greater reduction in cost for the pitch stimulus ($M_{Location}$= -4.4 %) than for the location stimulus ($M_{Location}$= 0.5 %), M = 4.9 %, $t(41)$ = 4.87, p < .001, 95% CI [2.9 %, 6.9 %].

3.3 Discussion

In Experiment 2, in addition to the three single-tasks and the triple-task from Experiment 1, three additional dual-tasks were performed. These tasks occurred in a between-subjects design either in the stimulus-response pairing (S-R pairing) location + hand, color + foot, and voice + pitch or location + foot, color + hand, and voice + pitch. However, the analyses of the response times did not show any difference in the S-R pairings, therefore these were not considered

Table 4: Triple-task costs, dual-task costs, and standard deviation of error rates in comparison with single-tasks and triple-task costs and standard deviation of error rates in comparison with dual-tasks. Triple-tasks, dual-tasks, and single-tasks were always compared with the same stimulus (e.g. the color task in the triple-task with the color task in the single-task).

Compared Stimulus	**Color**		**Location**		**Pitch**	
	Triple-task costs					
	M	*SD*	*M*	*SD*	*M*	*SD*
Difference to	Triple-task					
Single-task	-1.6	4.6	-3.6	7.7	1.2	2.6
Location + color dual-task	-2.6	5.6	-2.1	4.5	-	-
Location + pitch dual-task	-	-	0.5	2.7	-4.4	6.3
Color + pitch dual-task	-2.9	6.0	-	-	-3.8	5.1
	Location + color dual-task costs					
Difference to	Location + color dual-task					
Single-task	1.0	6.2	-1.4	7.8	-	-
	Location + pitch dual-task costs					
Difference to	Location + pitch dual-task					
Single-task	-	-	-4.0	6.8	5.7	6.5
	Color + pitch dual-task costs					
Difference to	Color + pitch dual-task					
Single-task	1.3	6.1	-	-	5.1	5.7

further in the calculation of the dual-task and triple-task costs. Thus, the determining factors were not the response modalities but the stimuli. The response times were fastest in the single-tasks, followed by the dual-tasks and with the slowest response times in the triple-task. In contrast to the response times, the error rates decreased from single- to dual- to triple-tasks. Initially, a strong increase in errors was expected when more tasks were presented at the same time. However, the very low error rates in the triple-tasks can possibly be attributed to a higher level of attention and concentration. Furthermore, if all effectors are always prepared in mixed blocks, then in the triple-task, none of the effectors had to be suppressed. It can be assumed that all three subtasks were always prepared before each task and when less than three tasks occurred (triple-task) the others had to be suppressed (cf. Hirsch et al., 2021; Schumacher & Hazeltine, 2016).

Comparing single-, dual-, and triple-tasks directly, we observed in the response times as well as in the costs that both increased more from single-tasks to dual-tasks than from dual-tasks to triple-tasks. Consequently, we could not observe a linear increase between the three tasks since this would have implied that the increase would always have been the same. If we assume that the increase from single-tasks to dual-tasks was 100%, we could only observe an increase of 43% in the response times from the dual-tasks to the triple-tasks. Furthermore, the dual-task in comparison to the single-tasks costs showed that the costs in both subtasks were the same, only in the dual-task color-pitch the costs in the pitch and color task increased differently.

4 General Discussion

This study aimed to examine the additional complexity of another simple task added to a classical dual-task paradigm, allowing us to quantify the progression of response times and costs. In Experiment 1 (E1) participants performed single-tasks and triple-tasks which were complemented by dual-tasks in Experiment 2 (E2).

4.1 Response order in Single-Tasks, Dual-Tasks, and the Triple-Task

In single-tasks, the average response times for the stimuli could be ordered as follows: in E1: location < pitch < color (manual/pedal < vocal < pedal/manual) and in E2: location < color < pitch (manual = pedal < vocal). Hence, both of our assumptions about the response order were wrong, which underlines the usefulness of testing these assumptions as we have done. Modality-compatible tasks (in the present study the location task with response modalities hand or foot and the pitch task with the response modality voice) were expected to be faster than tasks with ideomotor incompatibility (color task with response modality hand or foot) (Göthe et al., 2016; Hazeltine et al., 2006; Koch, 2009; Stephan et al., 2021; Stephan & Koch, 2010). However, the difference in response order could be due to the fact that participants in E1 had to complete both S-R pairings and thus strategic responding played a less prominent role (compared to triple-tasks). In E2, due to the triple-tasks, the focus was assumably more on the hand and foot response modalities, which was also evident in the single-tasks.

In triple-tasks, the pattern of response times was similar in both experiments. The location and color stimuli were responded with equal priority and the response time for the pitch stimulus was the slowest. We originally expected clear sequential processing of the stimuli to avoid a bottleneck, specifically not only to avoid crosstalk between the two visual tasks (Hommel, 2019; Koch, 2009) but also to reduce the coordinative complexity (Logan & Gordon, 2001). Based on similar observations for the two response modalities hand and foot, it seems like that coordination of these two response modalities took place first, similar to studies of bimanual coordination (Franz et al., 2001; Miller & Ulrich, 2008; Ruthruff et al., 2001). Similarly, studies with piano players showed that participants were able to perform better (fewer errors) when both hands acted in concert (e.g., when the hands produce a common rhythm and not two separate rhythms). An indication of the changed response order or rather grouping of visual tasks could be also found in studies on coordination skills. Liepelt et al. (2011) and Strobach et al. (2015) compared training with simultaneous dual-tasks and training with single-tasks and both found a superior effect from training the dual-tasks in a mixed block as opposed to training the two single-tasks separately in a uniform block. The benefit from dual-task training in mixed blocks may be due to the necessity that the combination of two tasks to a dual-task affords extra coordination to treat the two tasks as one task. If this assumption is true, it may also hold for the triple-task with the difference that three single-tasks have now to be treated as one task. This affords more coordination in comparison to dual-tasks and participants must optimize coordination (similar to bimanual coordination). One strategy is to pack effector procedures together into one procedure that is paired with the same type of stimulus. In the case of the triple-task, this is the pairing of the visual stimuli with those motor effectors that are intended to change the state of an object like the button and the pedal. In their review, Strobach and Schubert (2017a) discussed similar mechanisms in the training of dual-tasks, supporting this assumption. If few resources are available and the participants are given the freedom to decide which task should be prioritized, they can train their attention allocation and task coordination. As a result, a high level of efficiency is achieved in the retrieval of task rules and coordination. Further post hoc analyses support this assumption. It was found that only two participants[1] did not group the hand and foot subtask in the triple-task ($RT_{hand} - RT_{foot} <= 100$ ms). However, on average across all participants, in 84% (*SD* = 20%) of all triple-tasks, both subtasks were grouped. Another argument in favor of a strategic response to the tasks is the fact that the cost from location + color dual-task to the triple-task (triple-task cost) was less than 80 ms. These were still significant costs, but compared to the increase in costs from the single-tasks (location and color) to the location + color dual-task with more than 360 ms, this was only a very small increase and almost met Kieras et al.' criterion (2000) of simultaneous processing (costs < 50 ms). Adapted from inhibition in task-switching paradigms (see Koch et al., 2010, e.g.), one could argue that in the mixed blocks all three

1 In the triple-task, the two participants responded with the hand response modality (*M* = 808 ms) the fastest, followed by the foot response modality (*M* = 1231 ms) and with a response time almost twice as high voice response modality (*M* = 2118 ms).

responses (manual, pedal and voice) had to be prepared on every trial and in dual-tasks, the non-demanded task had to be suppressed, so it was similar to a triple-task requiring two responses and one suppression (e.g. in a location + color dual-task, participants had to respond with their hand and foot while the voice response had to be actively suppressed).

In dual-tasks, as already mentioned, the response times in all dual-tasks were higher than in comparable studies with similar dual-tasks, but only in the location + color dual-task, both subtasks showed similar response times to the subtasks in the triple-task. In the other two dual-tasks, the response times in at least one subtask were significantly faster (> 300 ms) than in the triple-task. Thus, the results tend to argue for strategic coordination of tasks across all task types and neither suppression nor integration of tasks. This is also supported by the error rates. Participants almost always made the fewest errors in the triple-task.

4.2 Dual-Task and Triple-Task costs

The calculation of dual-task costs is defined in most dual-task studies by the difference between dual- and single-tasks (Hazeltine et al., 2002, e.g.). If this difference is no longer significant, it is often referred to as *perfect time-sharing*, i.e., the task runs equally fast in both conditions (dual-task vs. single-task). However, *perfect time-sharing* in both subtasks can only be achieved by extensively training the dual-tasks and the single-tasks (Schumacher et al., 2001). For triple-task costs, there are several possibilities for computing these costs. Thus, the subtasks of the triple-task can not only be compared with the single-tasks but also with the three possible dual-tasks (see Table A1 in the appendix). In our results, comparing the dual- and the triple-tasks with the single-tasks showed, as expected, very high costs, which were highest with respect to the triple-tasks. However, when comparing the triple- with the dual-tasks, we observed that the costs increased differently depending on the dual-task. When we compared the triple-task to the location (M = 335 ms) + pitch (M = 372 ms) dual-task or location (M = 80 ms) + color (M = 86 ms) dual-task, similar triple-task costs were observed in all subtasks but not for the subtasks in the pitch (M = 217 ms) + color (M = 83 ms) dual-task. Thus, the amount of cost depended on which dual-task the subtask occurred and did not generally increase at the same rate across all tasks. One possible reason for the widely differing costs may be explained as followed: in previous studies, the location + pitch dual-task performed most efficiently in terms of the dual-tasks, i.e. the lowest costs were observed because of modality compatible S-R pairings (Hazeltine et al., 2006). Modality compatible tasks refer to the processing of stimuli and responses working best in their respective combinations (location – hand and pitch – voice). For the location + color and color + pitch dual-task, we also had ideomotor compatibility, but they were probably influenced by strategies. So, both dual-tasks may have been strongly influenced by the strategies already in use, i.e., the coordination of the hand and foot response modalities. This could be seen in the location + color dual-tasks where the two subtasks were grouped which led to the fact that the response times and costs of both subtasks did not greatly increase in the triple-task. Especially since the response time in the location + color dual-task could have been much faster than it ended up being. That the response time in the location and color subtasks could be faster, was seen in the response times in the other two dual-tasks, where both were much faster. Consequently, the strategy of the location + color dual-task might also have affected the color + pitch dual-task. Although the color task was not ideomotor compatible, this subtask was processed first, which led to a strong delay of the ideomotor compatible task with the pitch. The present data indicate that task coordination arguably has a major impact on triple-task processing. In this study, the data were collected in only one session. However, studies on dual-tasks show that training over several sessions changes and ultimately improves task coordination (see review, Strobach & Schubert, 2017a). At this point, it would be interesting to find out to what extent training influences task coordination in triple-tasks.

4.3 The Triple-Task in the Context of Different Models

One of the most widespread structural models of dual-task processing assumes a response selection bottleneck (RSB) (Pashler 1994, 1990, 1984). The RSB can process only one task per time frame and is presumed to be located in the central system. The model assumes that only at the peripheral stages (perception and motor execution), two tasks could run at the same time. Applied to the triple-task, a clear sequence of responses to the subtasks should now have become apparent as a result of the central bottleneck. But we could not observe this in our experiments, not even for both the visual tasks. The two visual tasks were responded to almost simultaneously. However, this observation is not an argument against the RSB. For performing a dual-task Ruthruff et al. (2001) instructed participants explicitly to respond to both stimuli simultaneously. They could detect massive interference. Participants needed much longer to respond to both tasks than for the single-tasks. They regarded this as clear evidence for the RSB. This would also explain why the response times of the triple-task were so high compared to single-tasks. In order to test this theory in more detail, further experiments would have to be carried out, e.g. with different SOAs.

Resource models also provide explanations for interferences with dual-tasks. The advantage of these models is that they assume the ability to flexibly divide resources (whatever resources are). A single-task can be processed with 100%, but two or more tasks must share the resource. When processing several tasks at the same time, 100% is now divided by the number of tasks (Norman & Bobrow, 1975). On this basis, Tombu and Jolicœur (2003) developed the central capacity-sharing model (CCS). Now, dual-tasks could theoretically run at the same speed as single-tasks. CSS would now explain why the response time for the triple-task increased that much, but it also does not provide clear assumptions about why subtasks are coordinated differentially in dual-, triple- or what seems to be generalizable in multi-tasks.

4.4 Perspectives on triple-tasks

The higher goal of this study is to shrink the gap between laboratory studies and real-world applications (also simulators). Thus, it should be discussed what a task, which can also consist of several subtasks, is. While some assume that driving a car, for example, is a (single-) task, this can also be seen as multiple tasks. Depending on the instruction, even a simple dual-task can be seen as processing two tasks or just one task (see studies on manipulation of instruction). There are now three perspectives on our triple-task.

As discussed in detail before, the triple-task is a task that is coordinated in terms of effectors. This results in a logical sequence of pedal/manual - vocal in the task for the participant. The increased response times thus arose from coordination. This suggests that more complex tasks are combined into one task in order to be able to act more quickly and without errors. The worse performance in the single- and dual-tasks may also be due to the triple-task, which is regarded as one, having to be “disassembled” again, which leads to higher error rates and response times.

Another perspective, especially with regard to the strongly increased response times, can also be found in the high number of S-R pairings to be remembered (cf. Wühr & Biebl, 2011). Duncan et al. (2008) were able to show that in a complex task with multiple components, some were neglected even though participants knew the rules for the neglected task. All facts, rules, and requirements are stored in a task model. However, with increasing complexity, these can compete with each other, which leads to the loss of vulnerable components. In our experiments, all tasks have to be stored in the task model, which can lead to an overload of the working memory due to the number of rules and S-R pairings. In the case of triple-tasks, the consequence is not that a task is necessarily neglected, but that more errors occur when switching between single-, dual-, and triple-tasks. The more rules, i.e. S-R pairings, can be retrieved, the worse the performance (Wühr & Biebl, 2011).

Another view is that tasks are organized hierarchically not on a local but on a global level (Schumacher & Hazeltine, 2016). The activation (task) is stored in a task file, which is similar to the event files in TEC (Hommel, 2019). The information in the task file, between the stimulus and the response, can be bidirectional, i.e. it can flow in both directions. The characteristic is that not a certain mechanism is specified, but a range of processes are deposited, which depend on the task. In the case of the triple-task, the highest priority (and also in the ideal case) would be to respond to it as quickly and error-free as possible. To do this, it is necessary to know the rules (which stimulus to respond to and what the possibilities are), as well as the allowed responses and the presented stimuli. Hirsch et al. (2018, 2021) also see evidence for a hierarchical organization of (dual-)tasks. Specifically, this would mean that even identical tasks achieve different response times, if they are combined and have to be coordinated into a different task model, which we observed in the single-, dual-, and triple-tasks in this study compared to other studies. All task types are thus stored in a single task file and are already activated before each task, which means that all tasks - even “pure” single- and dual-tasks - are only subtasks of the triple-task and therefore lead to longer response times when not needed. (cf. Hirsch et al., 2021).

5 Conclusion

In the present study, we extended the classical dual-task paradigm by a third task. In classical dual-tasks, the first response is indicated similarly fast as compared to single-tasks and only the second response is delayed. In a triple-task setting, all three responses are delayed. Additionally, in the triple-task, modality compatibility and ideomotor compatibility played less of a role as compared to classical dual-task studies which call their general theoretical significance into question. Both visual tasks in the triple-task were responded to equally fast, which is surprising since earlier work hypothesized a clear response order to emerge. Here, we discuss that the effects shown occurred due to differences in task coordination. Overall, our study showed that laboratory-based multitasking research is clearly limited by the restriction to only two tasks and generalization of such results to real-world multitasking should be drawn carefully. Multitasking research would benefit from an extended focus on strategically investigating settings involving more than two tasks.

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References

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: Are there age-related differences in plasticity of attentional control? *Psychology and Aging*, *20*(4), 695–709. https://doi.org/10.1037/0882-7974.20.4.695

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: Further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental Aging Research*, *34*(3), 188–219. https://doi.org/10.1080/03610730802070068

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., Bishop, S., & Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: Competing parts of a complex task. *Journal of Experimental Psychology: General*, *137*(1), 131. https://doi.org/10.1037/0096-3445.137.1.131

Franz, E. A., Zelaznik, H. N., Swinnen, S., & Walter, C. (2001). Spatial Conceptual Influences on the Coordination of Bimanual Actions: When a Dual Task Becomes a Single Task. *Journal of Motor Behavior*, *33*(1), 103–112. https://doi.org/10.1080/00222890109601906

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

Gutzwiller, R. S., Wickens, C. D., & Clegg, B. A. (2019). The role of reward and effort over time in task switching. *Theoretical Issues in Ergonomics Science*, *20*(2), 196–214. https://doi.org/10.1080/1463922X.2018.1522556

Hackman, J. R. (1969). Toward understanding the role of tasks in behavioral research. *Acta Psychologica*, *31*, 97–128. https://doi.org/10.1016/0001-6918(69)90073-0
Hazeltine, E., & Ruthruff, E. (2006). Modality pairing effects and the response selection bottleneck. *Psychological Research*, *70*(6), 504–513. https://doi.org/10.1007/s00426-005-0017-3
Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291–345. https://doi.org/10.1016/j.cogpsych.2005.11.001
Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 527–545. https://doi.org/10.1037//0096-1523.28.3.527
Hirsch, P., Nolden, S., Philipp, A. M., & Koch, I. (2018). Hierarchical task organization in dual tasks: Evidence for higher level task representations. *Psychological Research*, *82*(4), 759–770. https://doi.org/10.1007/s00426-017-0851-0
Hirsch, P., Roesch, C., & Koch, I. (2021). Evidence for a multicomponent hierarchical representation of dual tasks. *Memory & Cognition*, *49*(2), 350–363. https://doi.org/10.3758/s13421-020-01097-3
Hirst, W., Spelke, E. S., Reaves, C. C., Caharack, G., & Neisser, U. (1980). Dividing Attention Without Alternation or Automaticity. *Journal of Experimental Psychology: General*, *1*(109), 98–117. https://doi.org/10.1037/0096-3445.109.1.98
Hoffmann, M. A., Pieczykolan, A., Koch, I., & Huestegge, L. (2019). Motor sources of dual-task interference: Evidence for effector-based prioritization in dual-task control. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(10), 1355–1374. https://doi.org/10.1037/xhp0000677
Hommel, B. (1998). Automatic Stimulus-Response Translation in Dual-Task Performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1368–1384. https://doi.org/10.1037/0096-1523.24.5.1368
Hommel, B. (2019). Theory of Event Coding (TEC) V2.0: Representing and controlling perception and action. *Attention, Perception, & Psychophysics*, *81*(7), 2139–2154. https://doi.org/10.3758/s13414-019-01779-4
Hommel, B. (2020). Dual-Task Performance: Theoretical Analysis and an Event-Coding Account. *Journal of Cognition*, *3*(1), 29. https://doi.org/10.5334/joc.114
Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849–878; discussion 878-937. https://doi.org/10.1017/s0140525x01000103
Huestegge, L., & Hazeltine, E. (2011). Crossmodal action: Modality matters. *Psychological Research*, *75*(6), 445–451. https://doi.org/10.1007/s00426-011-0373-0
Huestegge, L., & Koch, I. (2013). Constraints in task-set control: Modality dominance patterns among effector systems. *Journal of Experimental Psychology: General*, *142*(3), 633–637. https://doi.org/10.1037/a0030156
Kahneman, D. (1973). *Attention and effort*. Prentice Hall.
Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern Computational Perspectives on Executive Mental Processes and Cognitive Control: Where to from Here? In S. Monsell & J. Driver (Eds.), *Control of Cognitive Processes. Attention and Performance XV/II: Vol. Attention and Performance XVIII* (pp. 681–712). MIT Press.
Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching–a review. *Psychological Bulletin*, *136*(5), 849–874. https://doi.org/10.1037/a0019842
Koch, I. (2009). The role of crosstalk in dual-task performance: Evidence from manipulating response-code overlap. *Psychological Research*, *73*(3), 417–424. https://doi.org/10.1007/s00426-008-0152-8
Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review*, *17*(1), 1–14. https://doi.org/10.3758/PBR.17.1.1
Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557–583. https://doi.org/10.1037/bul0000144
Koch, I., & Prinz, W. (2002). Process interference and code overlap in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(1), 192–201. https://doi.org/10.1037/0096-1523.28.1.192
Konishi, M., Berberian, B., de Gardelle, V., & Sackur, J. (2021). Multitasking costs on metacognition in a triple-task paradigm. *Psychonomic Bulletin & Review*, *28*(6), 2075–2084. https://doi.org/10.3758/s13423-021-01967-0
Konishi, M., Compain, C., Berberian, B., Sackur, J., & de Gardelle, V. (2020). Resilience of perceptual metacognition in a dual-task paradigm. *Psychonomic Bulletin & Review*, *27*(6), 1259–1268. https://doi.org/10.3758/s13423-020-01779-8
Kramer, A. F., Larish, J. F., & Strayer, D. L. (1995). Training for Attentional Control in Dual Task Settings: A Comparison of Young and Old Adults. *Journal of Experimental Psychology: Applied*, *1*(1), 50–76. https://doi.org/10.1037/1076-898X.1.1.50
Künzell, S., Broeker, L., Dignath, D., Ewolds, H., Raab, M., & Thomaschke, R. (2018). What is a task? An ideomotor perspective. *Psychological Research*, *82*(1), 4–11. https://doi.org/10.1007/s00426-017-0942-y
Laessoe, U., Hoeck, H. C., Simonsen, O., & Voigt, M. (2008). Residual attentional capacity amongst young and elderly during dual and triple task walking. *Human Movement Science*, *27*(3), 496–512. https://doi.org/10.1016/j.humov.2007.12.001
Liepelt, R., Fischer, R., Frensch, P. A., & Schubert, T. (2011). Practice-related reduction of dual-task costs under conditions of a manual-pedal response combination. *Journal of Cognitive Psychology*, *23*(1), 29–44. https://doi.org/10.1080/20445911.2011.448025
Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Quarterly Journal of Experimental Psychology (2006)*, *64*(7), 1251–1272. https://doi.org/10.1080/17470218.2010.543284
Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*(2), 393–434. https://doi.org/10.1037//0033-295X.108.2.393

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

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*(4), 749.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part I. Basic mechanisms. *Psychological Review*, *104*(1), 3.

Miller, J., & Ulrich, R. (2008). Bimanual Response Grouping in Dual-Task Paradigms. *Quarterly Journal of Experimental Psychology*, *61*(7), 999–1019. https://doi.org/10.1080/17470210701434540

Monsell, S. (1996). Unsolved mysteries of the mind. In V. Bruce (Ed.), *Unsoved Mysteries of the Mind* (pp. 93–148). Erblaum (UK) Taylor&Francis.

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

Naefgen, C., Caissie, A. F., & Janczyk, M. (2017). Stimulus-response links and the backward crosstalk effect—A comparison of forced- and free-choice tasks. *Acta Psychologica*, *177*, 23–29. https://doi.org/10.1016/j.actpsy.2017.03.010

Nett, T. (2017). *VoiceExperiment: This package allows the analysis of vocal responses to psychological experiments. R package version 1.0.2*.

Nijboer, M., Borst, J. P., van Rijn, H., & Taatgen, N. A. (2016). Driving and Multitasking: The Good, the Bad, and the Dangerous. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.01718

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*(1), 44–64. https://doi.org/10.1016/0010-0285(75)90004-3

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 358–377. https://doi.org/10.1037//0096-1523.10.3.358

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 826–842. https://doi.org/10.1037/0096-1523.16.4.826

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*(2), 220–244. https://doi.org/10.1037//0033-2909.116.2.220

Pashler, H., & Christian, C. L. (1994). *Bottlenecks in planning and producing vocal, manual and foot responses*. 61.

Pashler, H., & Sutherland, S. (1998). *The psychology of attention (Vol. 15)*. Cambridge, MA: MIT press.

Pieczykolan, A., & Huestegge, L. (2014). Oculomotor dominance in multitasking: Mechanisms of conflict resolution in cross-modal action. *Journal of Vision*, *14*(13), 1–17. https://doi.org/10.1167/14.13.18

Pisella, L., Arzi, M., & Rossetti, Y. (1998). The timing of color and location processing in the motor context. *Experimental Brain Research*, *121*(3), 270–276. https://doi.org/10.1007/s002210050460

Rinkenauer, G., Ulrich, R., & Wing, A. M. (2001). Brief bimanual force pulses: Correlations between the hands in force and time. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(6), 1485–1497. https://doi.org/10.1037/0096-1523.27.6.1485

Ruthruff, E., Pashler, H., & Klaassen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review*, *8*(1), 73–80. https://doi.org/10.3758/BF03196141

Salvucci, D. D., & Taatgen, N. A. (2010). *The Multitasking Mind*. Oxford University Press.

Sangals, J., Wilwer, M., & Sommer, W. (2007). Localizing practice effects in dual-task performance. *Quarterly Journal of Experimental Psychology*, *60*(6), 860–876. https://doi.org/10.1080/17470210600822720

Santiago-Espada, Y., Myer, R. R., Latorella, K. A., & Comstock Jr, J. R. (2011). *The multi-attribute task battery ii (matb-ii) software for human performance and workload research: A user's guide*.

Schuhfried, G. (1991). Wiener Determinationsgerät. *Grundprogramm Und Erweitertes Programm. Wiener Testsystem [Vienna Determination Test]. Dr. G. Schuhfried GmbH, Mödling*, 1–48.

Schumacher, E. H., & Hazeltine, E. (2016). Hierarchical Task Representation: Task Files and Response Selection. *Current Directions in Psychological Science*, *25*(6), 449–454. https://doi.org/10.1177/0963721416665085

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually Perfect Time Sharing in Dual-Task Performance: Uncorking the Central Cognitive Bottleneck. *Psychological Science*, *12*(2), 101–108. https://doi.org/10.1111/1467-9280.00318

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

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

Stephan, D. N., Josten, J., Friedgen, E., & Koch, I. (2021). Crossmodal Effects in Task Switching: Modality Compatibility with Vocal and Pedal Responses. *Journal of Cognition*, *4*(1), 9. https://doi.org/10.5334/joc.129

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

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task Switching, Modality Compatibility, and the Supra-Modal Function of Eye Movements. *Experimental Psychology*, *60*(2), 90–99. https://doi.org/10.1027/1618-3169/a000175

Strayer, D. L., & Johnston, W. A. (2001). Driven to Distraction: Dual-Task Studies of Simulated Driving and Conversing on a Cellular Telephone. *Psychological Science*, *12*(6), 462–466. https://doi.org/10.1111/1467-9280.00386

Strobach, T., Frensch, P. A., Soutschek, A., & Schubert, T. (2012). Investigation on the improvement and transfer of dual-task coordination skills. *Psychological Research*, *76*(6), 794–811. https://doi.org/10.1007/s00426-011-0381-0

Strobach, T., Frensch, P., Müller, H., & Schubert, T. (2015). Evidence for the acquisition of dual-task coordination skills in older adults. *Acta Psychologica*, *160*, 104–116. https://doi.org/10.1016/j.actpsy.2015.07.006

Strobach, T., Hendrich, E., Kübler, S., Müller, H., & Schubert, T. (2018). Processing order in dual-task situations: The \textquotedblfirst-come, first-served\textquotedbl principle and the impact of task order instructions. *Attention, Perception & Psychophysics*, *80*(7), 1785–1803. https://doi.org/10.3758/s13414-018-1541-8

Strobach, T., & Schubert, T. (2017a). Mechanisms of Practice-Related Reductions of Dual-Task Interference with Simple Tasks: Data and Theory. *Advances in Cognitive Psychology*, *13*(1), 28–41. https://doi.org/10.5709/acp-0204-7

Strobach, T., & Schubert, T. (2017b). No evidence for task automatization after dual-task training in younger and older adults. *Psychology and Aging*, *32*(1), 28–41. https://doi.org/10.1037/pag0000144

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

Tombu, M., & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology. Human Perception and Performance*, *30*(5), 795–810. https://doi.org/10.1037/0096-1523.30.5.795

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Watson, J. M., & Strayer, D. L. (2010). Supertaskers: Profiles in extraordinary multitasking ability. *Psychonomic Bulletin & Review*, *17*(4), 479–485. https://doi.org/10.3758/PBR.17.4.479

Wechsler, K., Drescher, U., Janouch, C., Haeger, M., Voelcker-Rehage, C., & Bock, O. (2018). Multitasking During Simulated Car Driving: A Comparison of Young and Older Persons. *Frontiers in Psychology*, *9*, 910. https://doi.org/10.3389/fpsyg.2018.00910

Welford, A. T. (1952). The Psychological refractory period and the timing of high-speed performance—A review and a theory. *British Journal of Psychology*, *43*(1), 2.

Wickens, C. D. (1981). *Processing Resources In Attention, Dual Task Performance, and Workload Assessment*. University of Illinois. https://apps.dtic.mil/dtic/tr/fulltext/u2/a102719.pdf

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

Wühr, P., & Biebl, R. (2011). The role of working memory in spatial S-R correspondence effects. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(2), 442–454. https://doi.org/10.1037/a0020563

Appendix

Table A1: *Triple-task costs, dual-task costs and standard deviation in milliseconds in comparison with single-tasks and triple-task costs and standard deviation in milliseconds in comparison with dual-tasks. Triple-tasks, dual-tasks, and single-tasks were always compared with the same stimulus (e.g., the color task in the triple-task with the color task in the single-task).*

Compared Stimulus	**Color**		**Location**		**Pitch**	
	Triple-task costs					
	M	*SD*	*M*	*SD*	*M*	*SD*
Difference to	Triple-Task					
Single-task	452	238	628	238	878	250
Location + color dual-task	86	132	80	132	-	-
Location + pitch dual-task	-	-	335	209	372	207
Color + pitch dual-task	83	176	-	-	217	211
	Location + color dual-task costs					
Difference to	Location + color dual-task					
Single-task	366	215	548	199	-	-
	Location + pitch dual-task costs					
Difference to	Location + pitch dual-task					
Single-task	-	-	293	198	506	180
	Color + pitch dual-task costs					
Difference to	Color + pitch dual-task					
Single-task	396	194	-	-	661	252