Acta Psychologica 230 (2022) 103766

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Modality-specific effects of mental fatigue in multitasking

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ARTICLE INFO

Keywords:
Dual task
Modality compatibility
Crosstalk
Executive control
Practice

ABSTRACT

The mechanisms underlying increased dual-task costs in the comparison of modality compatible stimulus-response mappings (e.g., visual-manual, auditory-vocal) and modality incompatible mappings (e.g., visual-vocal, auditory-manual) remain elusive. To investigate whether additional control mechanisms are at work in simultaneously processing two modality incompatible mappings, we applied a transfer logic between both types of dual-task mappings in the context of a mental fatigue induction. We expected an increase in dual-task costs for both modality mappings after a fatigue induction with modality compatible tasks. In contrast, we expected an additional, selective increase in modality incompatible dual-task costs after a fatigue induction with modality incompatible tasks. We tested a group of 45young individuals (19–30 years) in an online pre-post design, in which participants were assigned to one of three groups. The two fatigue groups completed a 90-min time-on-task intervention with a dual task comprising either compatible or incompatible modality mappings. The third group paused for 90 min as a passive control group. Pre and post-session contained single and dual tasks in both modality mappings for all participants. In addition to behavioral performance measurements, seven subjective items (effort, focus, subjective fatigue, motivation, frustration, mental and physical capacity) were analyzed. Mean dual-task performance during and after the intervention indicated a practice effect instead of the presumed fatigue effect for all three groups. The modality incompatible intervention group showed a selective performance improvement for the modality incompatible mapping but no transfer to the modality compatible dual task. In contrast, the compatible intervention group showed moderately improved performance in both modality mappings. Still, participants reported increased subjective fatigue and reduced motivation after the fatigue intervention. This dynamic interplay of training and fatigue effects suggests that high control demands were involved in the prolonged performance of a modality incompatible dual task, which are separable from modality compatible dual-task demands.

1. Introduction

Trying to buy a ticket at the subway ticket machine while answering questions on the mobile phone may result in either missing the train or the inability to answer questions, or both. According to previous research on the role of modality pairings in multitasking situations (Brahms et al., 2021; Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006, 2017), this performance decrement would increase even more when speaking to the ticket machine while concurrently writing a message on the mobile phone. In a more formal description, the risk of missing the train or delaying the answer on the phone reflects the costs when doing two tasks concurrently (i.e., dual-task costs) compared to performing two tasks in isolation as single tasks (Koch et al., 2018). The pairing of specific stimulus modalities with specific response modalities has been shown to substantially affect the magnitude of dual-task costs (Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006). For example, Hazeltine et al., 2006 compared different stimulus-response modality pairings in the context of a cognitive training study. They showed increased dual-task costs for a group performing modality incompatible mappings (see below in Fig. 1), with vocal responses being mapped to visual stimuli and manual responses to auditory stimuli (Hazeltine et al. (2006) referred to as 'non-standard group'). Even after

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https://doi.org/10.1016/j.actpsy.2022.103766
Received 9 June 2022; Received in revised form 23 September 2022; Accepted 6 October 2022
Available online 12 October 2022

extended practice, these costs remained robust and were significantly higher than in the group performing modality compatible mappings with visual-manual and auditory-vocal tasks ('standard group'). Modality compatibility was introduced as a term relating to the difference underlying these robust behavioral differences between certain modality mappings, which has previously been shown in various studies employing dual tasks (e.g., Brahms et al., 2021; Göthe et al., 2016; Stelzel et al., 2006, 2017) as well as task-switching paradigms (e.g., Fintor et al., 2018; Friedgen et al., 2021; Stephan & Koch, 2010, 2011).

Based on ideomotor theory, (Greenwald, 1970; Hommel et al., 2001; James, 1890; Prinz, 1990) modality compatibility refers to the overlap between the stimulus modality and the modality of the perceptual effect of the required response (i.e., action effects). Recently, Schacherer and Hazeltine (2020) provided direct evidence for the role of the modality of action effects on the emergence of modality-based crosstalk and associated dual-task costs. Crosstalk, in general, can occur if there is overlap in any features of two task sets processed with temporal overlap. This overlap is assumed to form the basis for an interaction of one task with the processing of another, otherwise independent task (Navon & Miller, 1987). By manipulating the overlap in modality between stimuli and action effects, Schacherer and colleague showed that dual-task costs were consistently higher if the stimulus modality of one task was the same as the modality of the action effect of the other task (Schacherer & Hazeltine, 2020), thus indicating modality-based crosstalk.

In Fig. 1A, the assumed modality-based crosstalk between two modality incompatible tasks is depicted in the context of the dual-task paradigm applied in the present study. Black arrows indicate the overlap of stimulus modality and the modality of the action effect between the two tasks. Thus, the modality-based overlap between tasks may lead to higher crosstalk for the modality incompatible versus compatible mapping and could therefore explain the consistently reported higher reaction times (i.e., higher costs) for modality incompatible dual tasks, which are not present when the tasks are performed as single tasks (compare Fig. 1B).

The existence of crosstalk between modality incompatible tasks raises the question of how the cognitive system deals with this additional source of interference. Some models assume the necessity of executive control processes that prioritize and coordinate tasks as general dual-task-related mechanisms (Logan & Gordon, 2001; Meyer & Kieras, 1997). Logan and Gordon (2001) explained category-level crosstalk phenomena in the executive control theory of visual attention (ECTVA model) with a confusion of sources regarding stimulus properties. They hypothesized that the categorization of each stimulus could not be performed in isolation. In contrast, the processing of each individual task depends on the respective other task in the dual-task situation. Modality-based crosstalk is not readily explained in these models. Regarding executive control, the cognitive system may allocate a higher amount of the general dual-task-related executive control processes to resolve modality-based crosstalk, thus reflecting a quantitative difference between modality compatible and modality incompatible dual-task situations.

Alternatively, more specific executive control processes may be involved in modality incompatible tasks related to the selective inhibition of overlapping representational features between tasks. The idea of overlapping representational features between tasks is reinforced by an argument of Greenwald (1970), who postulated that every response has a "dominant feedback modality", auditory for vocal responses, and visual for written (manual) responses. He argued that these dominant couplings result from lifelong learning experiences (e.g., constantly hearing the auditory feedback of your voice). Thus, this dominant feedback modality is automatically activated, which is unproblematic for modality compatible mappings but leads to the necessity to inhibit the feedback modality if two temporarily overlapping tasks show an overlap between task representations, as it is the case for the modality incompatible mapping. Whether or not processing modality-based crosstalk in modality incompatible dual tasks involves such a qualitative difference in terms of additional executive control processes remains elusive.

One approach to show the overlap between task processes in different tasks involves investigating "near transfer" between tasks. Several cognitive training studies have demonstrated that dual-task training with one specific dual-task paradigm can be transferred to

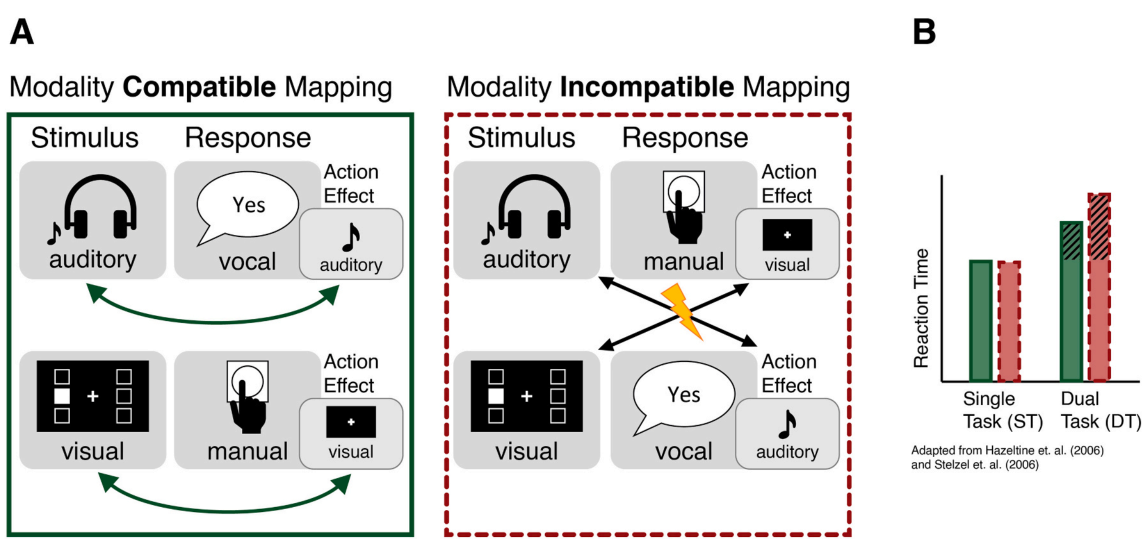

Fig. 1. Modality compatible and modality incompatible mapping with corresponding action effects and typical pattern of reaction times.
Note: **A**: The left part of the figure shows the stimulus-response pairings for the modality compatible mapping (green frame, solid line), first for the auditory stimulus with the vocal response and below the visual stimulus combined with the manual response. For each response, the corresponding action effect is depicted as well. Arrows underline the match between the stimulus modality and the modality of the action effect within each task. Note that the action effect of the manual response is not exclusively visual but also somatosensory. The same setup is depicted in the dashed red frame on the right side for the modality incompatible mapping. The auditory stimulus is paired with a manual response and the visual stimulus with a vocal response. In this condition, the match between action effect and stimulus modality is now between tasks, potentially causing interference. **B**: The classic reaction time pattern for each modality mapping and the single and dual tasks are presented. Studies usually found no difference between the single tasks in the two modality mappings but robust differences for the dual tasks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

similar dual-task paradigms under certain experimental conditions (Liepelt et al., 2011; Schubert et al., 2017; Strobach et al., 2012, 2014). Likewise, there is evidence from mental fatigue studies in which the effects of a fatigue intervention were transferred to another structurally similar task (Borragán et al., 2016; Guo et al., 2018; van der Linden, Frese, & Meijman, 2003; van der Linden, Frese, & Sonnentag, 2003). This transfer is assumed to be related to joint task requirements between the training/fatigue task and the transfer task. After prolonged task performance in one task, cognitive changes are transferred to the other task and may lead to similar behavioral changes.

We applied a mental fatigue approach to investigate near transfer between modality-specific dual-task mappings in the present study. Mental fatigue has been defined as a cognitive condition that occurs after prolonged cognitive activity (Boksem et al., 2005) and is associated with feelings of fatigue/tiredness, boredom, reluctance to continue the task, higher distractibility, and lower focus (Agrawal et al., 2021; Boksem et al., 2005; Borragán et al., 2017; Hopstaken et al., 2015; Takács et al., 2019). Subjective reports of increased fatigue are accompanied by behavioral findings of elevated error rates and reaction times in the fatigued task but also in similar transfer tasks (Boksem et al., 2005; Borragán et al., 2017; Hopstaken et al., 2015; Lorist et al., 2000). For example, van der Linden, Frese, and Sonnentag (2003) showed that performing a fatiguing complex planning task results in an insufficient level of executive control available for other executive tasks like the Wisconsin Card Sorting Task or the Tower of London test (see also Holtzer et al., 2011), which implies transferability of fatigue to tasks with similar executive control demands.

Here, we aim to elucidate whether prolonged processing of modality-related crosstalk in a modality incompatible dual task affects specific mechanisms, such as inhibition of overlapping task features, in addition to general (amodal) dual-task-related mechanisms. Fatigue effects related to processing modality-based crosstalk in modality incompatible tasks are assumed not to be transferred to an otherwise identical dual task (same stimuli, same responses), which does not involve modality-based crosstalk due to non-overlapping modality compatibility mappings. Therefore, we used a between-subject design with modality compatible and modality incompatible dual tasks as mental fatigue interventions and a passive control group to test for transfer effects on both modality mappings afterwards.

We hypothesized that the underlying processes between the two modality mappings would differ because the modality incompatible mapping demands additional processes (i.e., inhibition) due to the modality-specific crosstalk and general dual-task control processes. More specifically, we expected the fatigue intervention with the modality incompatible dual task to weaken the ability to inhibit modality-related task features, resulting in an overadditive increase in dual-task costs for the modality incompatible mapping. More specifically, while fatigue of general dual-task-related executive control was expected to transfer to the modality compatible dual task, crosstalk-specific mechanisms are not relevant in the modality compatible task, thus leading to greater decrements in the post-fatigue session for the modality incompatible dual tasks (i.e., the interaction of modality mapping and time). In contrast, the fatigue intervention using the modality compatible dual task should reduce the level of general dual-task-related executive control involved in both modality mappings. This again may increase dual-task costs for both modality mappings (i.e., an additive effect of mapping and time). For the passive control group, we hypothesized to find a retest effect equal in size for both modality mappings when tested before and after the paused time, i.e., practice-related decrease in dual-task costs for both modality mappings. In addition to performance measures, we assessed participants' states, focusing on levels of subjective fatigue and motivation, which served as a manipulation check for the fatigue intervention.

2. Methods

2.1. Participants

The final sample of this online study consisted of 45 healthy participants. The number of participants per group ($N = 15$) is similar to previous research that also investigated the modality compatibility effect using an n-back task (Brahms et al., 2021; Stelzel et al., 2017). Stelzel et al. (2017) showed a significant interaction between the modality compatibility mappings and task type (single and dual-task) even for ten participants with an effect size of $\eta_p^2 = .575$, indicating that effects at baseline can be expected for the group size of $N = 15$. The prediction of the fatigue effect was difficult because there were no comparable data in the context of modality compatibility. Twenty-three additional participants were enrolled in the experiment but had to be excluded for different reasons: five individuals did not complete the experiment, twelve participants experienced technical issues or problems with the internet connection, which resulted in data loss, and six participants did not meet the performance criteria (see section 2.5). Each participant was pseudo-randomly assigned to one of three groups under the restriction of equal group size and gender distribution: one group (compatible intervention group) continuously completed a modality compatible dual one-back task. The second group (incompatible intervention group) continuously completed a modality incompatible dual one-back task. The third group rested for the time it took the other two groups to complete the tasks, i.e., 90 min. Participants in the passive control group were instructed to avoid cognitively demanding tasks during their break but were otherwise free to choose their activity. Table 1 shows the mean age and the gender proportion per intervention group. We recruited participants through mailing lists at the International Psychoanalytic University Berlin and Freie Universität Berlin and announcements in Facebook groups for psychology students. All participants had normal or corrected to normal vision and hearing. The ethics committee of the Charité Universitätsmedizin Berlin approved the study based on a collaborative project following the Declaration of Helsinki. Participants provided their written informed consent prior to the start of the study. All participants had the chance to choose between 30 Euro or course credit for reimbursement.

2.2. Materials

All materials and code files are available on the OSF project page: https://osf.io/72pr8/. This document was written in RMarkdown using papaja (Aust & Barth, 2020). The experiment was programmed using the jsPsych library (version 6.1.0), an open-source javascript-based tool (de Leeuw, 2015). A customized plug-in was built to simultaneously present auditory and visual stimuli and record vocal and manual responses according to single trials. Study participation was only possible on laptops or stationary computers with a stereo headset. The experiment was hosted on the online platform jatos (version 3.5.4) (Lange et al., 2015), and all participants completed the experiment in the chrome browser. Before the main experiment started, the screen size was controlled with the credit card test, where participants held a credit card on their screen and compared it with a square of the size 9.44 × 5.94 cm (width x

Table 1
Participants age with number of female, male and diverse persons per intervention group.

	Compatible intervention	Incompatible intervention	Passive control
Age	22.93 (3.10)	23.20 (2.81)	23.33 (2.72)
Female:Male: Diverse	7:7:1	10:5:0	8:7:0
N	15	15	15

Note. Showing means (standard deviation) for age and number of participants.

height). Screen parameters were adapted if necessary. In addition, access to the microphone and headset compatibility were verified.

2.3. Stimuli

Participants worked on spatial single and dual one-back tasks (see Fig. 1A). The task commonly used in modality compatibility research (task switching and dual tasking) is the classic choice-reaction task (Fintor et al., 2018; Friedgen et al., 2021; Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006; Stephan et al., 2022; Stephan & Koch, 2010, 2011). But recent studies also showed robust modality compatibility effects for the one-back task (Brahms et al., 2021; Stelzel et al., 2017), a widely used task in fatigue research (Blain et al., 2016; Borragán et al., 2017; Hopstaken et al., 2015; Ren et al., 2019). Thus, participants had to decide whether a stimulus was the same as in the trial before (one-back). Stimuli were presented for 500 ms in a pseudo-random order with a maximum of three consecutive targets and a maximum of two identical positions (see below). The stimuli were followed by an inter-stimulus interval of 1400 ms. The stimulus modality in each component task was either visual or auditory. The response modality was either manual or vocal, resulting in either a modality compatible or a modality incompatible mapping. Participants worked on the following different task combinations, which were instructed at the beginning of each block.

2.3.1. Single one-back task

2.3.1.1. Modality compatible visual-manual condition. A white square (pixel size 56.8 × 56.8) was displayed on a black background at six different positions (top, center, bottom), three on each side of a white fixation cross (pixel size 41.1 × 41.1, thickness 9.9 pixels). Participants responded to the one-back target stimuli (square is at the same position as the previous one) by pressing the space key correctly and as fast as possible. No response was given for non-target trials.

2.3.1.2. Modality compatible auditory-vocal condition. Tones in three different frequencies at 200, 450, and 900 Hz were presented via headphones on either the left or right ear. The black background with the white fixation cross remained on the screen. Participants responded to the one-back target stimulus (same tone at the same ear as the previous one) by saying "Yes" (German "Ja") correctly and as fast as possible.

2.3.1.3. Modality incompatible visual-vocal condition. The stimulus presentation was identical to the visual-manual condition. Participants responded to the one-back target stimulus (square is at the same position as the previous one) by saying "Yes" (German "Ja") correctly and as fast as possible.

2.3.1.4. Modality incompatible auditory-manual condition. The stimulus presentation was the same as for the auditory-vocal condition. Participants responded to the one-back target stimulus (same tone at the same ear as the previous one) by pressing the space key correctly and as fast as possible.

2.3.2. Dual one-back tasks

A visual one-back task was combined with an auditory one-back task, resulting in two dual one-back conditions: visual-manual with auditory-vocal (modality compatible mapping) and visual-vocal with auditory-manual (modality incompatible mapping). Thus, there was no overlap in either response or stimulus modality within each dual-task condition. Both stimuli were presented simultaneously, and participants were asked to indicate separately whether the stimulus was the same as in the previous trial. Targets never occurred on both modalities of the same trial.

2.4. Procedure

The online experiment took place between 9 am and 1 pm in a Zoom session (https://zoom.us), accompanied by an experimenter to ensure that testing conditions were similar. Testing lasted, on average, 3 h. Before starting the main experiment, all participants completed a 15 min practice phase, including all different task types (16 trials for each single task, 32 trials for the dual task, and in each modality mapping, for a total of 128 trials). The main experiment was divided into three parts: pre-measurement, fatigue intervention, and post-measurement (see Fig. 2). During the pre and post-tests, a block consisted of 16 trials with five targets (two or three in the visual modality and two or three in the auditory modality during dual-task blocks) and 11 non-targets. Four blocks of dual tasks and four blocks of single tasks in the same modality mapping formed a run. Participants were allowed to take a self-determined break between the runs if needed. Pre and post-tests included two runs per compatibility mapping (four in total). Every other run was assigned to the same modality mapping. The order of modality mapping (modality compatible or modality incompatible first) and the order of single one-back tasks (visual or auditory task first) was counterbalanced across participants, where the order of single and dual tasks remained constant (compare Fig. 2). The total number of trials per task type (single or dual task), modality mapping and on each timepoint (pre and post) for each participants was 128. The intervention included eight runs, with every run comprising four dual-task blocks and one block consisting of 64 trials with 16 targets and 48 non-targets. The total number of trials during the fatigue intervention was 2048.

Before and after testing, participants were asked to rate their feelings of subjective fatigue, effort, motivation, frustration, mental capacity, and physical capacity. For this purpose, a visual analog scale was used that ranged from "not at all fatigued" (value 0) to "very fatigued" (value 100) (German: "überhaupt nicht" and "sehr", please find items in German and English in the supplemental material in Table C1). Participants in the two fatigue groups also responded to the items after every run during the fatigue intervention (compare Fig. 2). Participants in the passive control group only responded to the items subjective fatigue, motivation, mental capacity, and physical capacity after their rest (before the post-tests).

2.5. Statistical analyses

Performance was measured as the probability of 'hit' minus the probability of 'false alarm' (p(hit)-p(fa)). Vocal responses were analyzed offline. First, Google Speech Recognition (Google, 2021) automatically identified responses and non-responses. Results were manually validated and corrected if necessary. A self-developed Matlab (MATLAB, 2019) script based on Reisner and Hinrichs (2016) was used to determine reaction time latencies using amplitude peak detection. The reaction time latency was defined as the time point before the maximum peak where the amplitude is smaller than the average time window (2000 ms). We excluded participants with an average hit rate below 30 % or a false alarm rate above 30 % during the fatigue intervention to ensure that all participants completed the intervention thoroughly. Additionally, we excluded participants with more than two out of four blocks per run below or above the 30 % criterion at the pre-measurement to prevent an artificially skewed result. We did not apply any participant exclusion based on the post-measurement to detect the effects of fatigue. Six participants did not meet the performance criteria and were excluded from further analysis. We excluded reaction times faster than 150 ms on the trial level, as task processing (stimulus perception and motor responses) is unlikely to be finished earlier than 150 ms (Luce, 1991; Whelan, 2008). Data for the pre-post comparison were averaged for each half of the run (two single task blocks with two dual-task blocks), time point (pre, post), each modality mapping (modality compatible, modality incompatible), and each task type (single and dual task). We calculated relative dual-task costs in

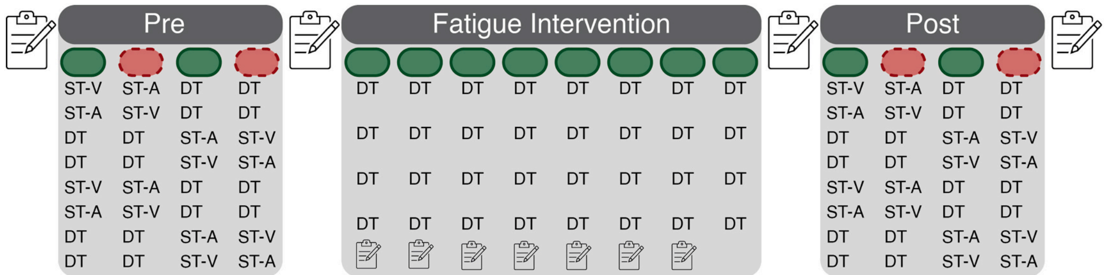

Fig. 2. Exemplatory pre-post design with modality compatible fatigue intervention.
Note: Pre and post-measurement included four runs, each run assigned to the modality compatible mapping is shown in green (solid) and modality incompatible tasks in red (dashed). Each run consisted of eight blocks with two single task blocks with a visual stimulus (ST-V), two single task blocks with an auditory stimulus (ST-A), and four dual-task blocks (DT). Each block at pre and post-measurement included 16 trials. The response modality depended on the assigned modality mapping (compare Fig. 1A). The fatigue intervention consisted of eight runs of the same modality mapping, here, the modality compatible mapping. Each run included four blocks, and each block consisted of 64 trials. Before and after the pre and post-measurement and after each run, participants were asked about their feelings in terms of fatigue, motivation, effort, frustration, focus, mental capacity, and physical capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

percent as $\text{dual} - \text{task costs} = \frac{\text{single task} - \text{dual task}}{\text{single task}}^{*}100$ to account for individual differences in single-task performance, where positive values indicate dual-task costs, negative values indicate dual-task benefits compared to single-task performance. Zero indicates that participants did not exhibit differences between dual and single tasks. Performance values can be found in supplement material in Table A1. Data of a block below and above the mean and two standard deviations for each condition (time point, modality mapping, intervention group) were defined as outliers and excluded (average of 3.55 % per condition). The resulting data, averaged over blocks, were subjected to a $2 \times 2 \times 3$ mixed ANOVA with two within-subject factors (time point, modality mapping) and one between-subject factor intervention group (modality compatible intervention, modality incompatible intervention, and passive control group). Dual-task performance during the fatigue interventions was averaged for each run and subjected to a mixed ANOVA with the within-subject factors run and the between-subject factor intervention group. Performance and reaction time data per run can be found in supplement material in Table B1.

The same procedure was applied for correct target responses' mean reaction times (RT). We will focus the following analyses on the performance parameter because RTs are less reliable as they are based only on 12 to 40 correct responses (M=34.06, SD = 6.44) per participant, time point (pre and post), modality mapping, and task type. A summary of the RT values can be found in the supplement material in Table A2.

Data from the subjective report were averaged for each time point. We subjected the report for each item before and after the fatigue intervention to mixed ANOVA with the within-subject factor time point and the between-subject factor intervention group. P-values were corrected for multiple testing. Two individuals were excluded from the following analysis for the items focus, frustration, and effort, and four participants for subjective fatigue, motivation, mental and physical capacity due to missing data.

3. Results

The reported significance level was at $\alpha = 0.05$, and p-values were corrected for sphericity using the Greenhouse Gaisser method if necessary. For all analysis, pairwise t-tests, corrected with the Benjamini-Hochberg procedure (BH, Benjamini and Hochberg (1995)), were used as post-hoc tests upon significant interactions. All statistical analyses were processed using R (Version 4.0.2, R Core Team, 2020) with RStudio (Version 1.4.1717, RStudio Team, 2019). Effect size is reported as generalized Eta squared ($\widehat{\eta}^2_G$).

3.1. Performance

3.1.1. Group comparison pre measurement

We compared the three intervention groups to ensure that differences in pre-post comparison were not caused by group differences at pre measurement A one-way ANOVA for dual-task costs in the p(hit)-p(fa) parameter revealed a main effect of modality mapping, $F(1,42) = 24.02$, $MSE = 135.55$, $p < .001$, $\widehat{\eta}^2_G = .150$ with higher costs for the modality incompatible mapping ($M = 28.49$ %, $SE = 2.55$) compared to the modality compatible mapping $M = 16.46$ %, SE = 1.81). The main effect of the intervention group and the interaction with modality mapping was not significant, $F< 1.40$. Thus, the performance between the three intervention groups did not differ at the pre measurement.

3.1.2. Comparison pre-post measurement

The ANOVA for the pre-post comparison with intervention group as between subject factor for dual-task costs in p(hit)-p(fa) showed a significant main effect of time point, $F(1,42) = 25.79$, $MSE = 108.11$, $p < .001$, $\widehat{\eta}^2_G = .081$, but contrary to our hypothesis, with higher costs for the pre-measurement ($M = 22.47$ %, $SE = 1.68$) compared to the post test ($M = 14.60$ %, $SE = 1.38$). The effect of modality mapping was significant, $F(1,42) = 32.05$, $MSE = 109.58$, $p < .001$, $\widehat{\eta}^2_G = .101$, with higher dual-task costs being present in the modality incompatible mapping ($M = 22.96$ %, SE = 1.78) compared to the modality compatible mapping ($M = 14.12$ %, $SE = 1.22$). The interaction between time point and modality mapping was also significant, $F(1,42) = 5.27$, $MSE = 87.21$, $p = .027$, $\widehat{\eta}^2_G = .014$, indicating that the decrease from pre to post of dual-task costs was higher for the modality incompatible compared to the modality compatible mapping. In addition, we found a significant three-way interaction for the factors time point, modality mapping, and intervention group, $F(2,42) = 5.44$, $MSE = 87.21$, $p = .008$, $\widehat{\eta}^2_G = .029$. This interaction indicates that the performance changes in the modality mappings from pre to post measurement differed between the intervention groups.

The post-hoc test indicates that the compatible intervention group significantly reduced their dual-task costs for the modality compatible mapping, $t(14) = 2.49$, $p = .026$, (Pre: $M = 22.08$ %, $SE = 3.65$, Post: $M = 14.92$ %, $SE = 2.73$), and the modality incompatible mapping $t(14) = 2.81$, $p = .014$ (Pre: $M = 29.26$ %, $SE = 3.44$, Post: $M = 22.47$ %, $SE = 3.50$). In turn, the modality incompatible intervention group only reduced their dual-task costs for the modality incompatible mapping, $t(14) = 3.76$, $p = .002$, (Pre: $M = 30.93$ %, $SE = 4.68$, Post: $M = 10.76$ %, $SE = 3.77$). The reduction for the passive group shows a tendency in the expected direction, although the difference is not significant (see Fig. 3). Further comparing the difference scores (post-pre) between the three

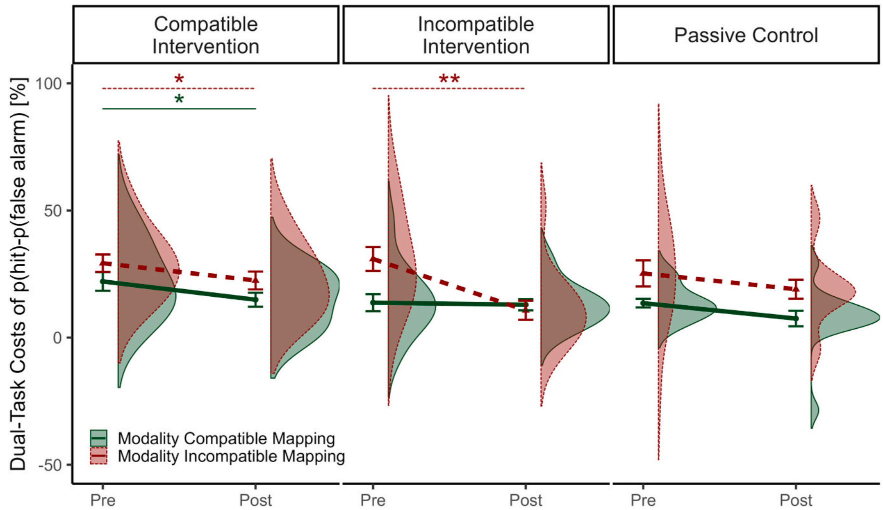

Fig. 3. Dual-task costs per intervention group and modality mapping.
Note: The graph shows distributions of performance. Points indicate means per intervention group and modality mapping. Error bars depict standard errors. Significant codes for corrected pairwise *t*-test: $p < .05$ '*', $p < .01$ '**', $p < .001$ '***'.

groups with a corrected pairwise *t*-test revealed that the modality incompatible intervention group showed a significantly greater reduction for the modality incompatible mapping compared to the other two groups, incompatible intervention group ($M = 20.18$ %, $SE = 5.37$) vs. passive control group ($M = 6.23$ %, $SE = 4.00$), $t(42) = -2.40$, $p = .039$, and incompatible intervention group vs. compatible intervention group ($M = 6.79$ %, $SE = 2.42$), $t(42) = 2.30$, $p = .039$. There was no significant difference between groups for the pre-post changes in the modality compatible mapping. A similar pattern is present for the modality compatibility effect (modality incompatible mapping - modality compatible mapping). Again, only the modality incompatible intervention group showed a significant difference in the modality compatibility effect from pre ($M = 17.19$ %, $SE = 4.93$) to post ($M = -2.18$ %, $SE = 2.72$), $t(14) = 3.30$, $p = .005$, indicating a complete elimination of the modality compatibility effect in this group. The effect was selective to the modality incompatible group and differed at the post measurement significantly compared to the compatible intervention group ($M = 7.55$ %, $SE = 2.88$), $t(42) = -2.41$, $p = .031$, and to the passive control group ($M = 11.54$ %, $SE = 2.97$), $t(42) = 3.40$, $p = .005$. The main effect for the factor intervention group and the two-way interaction of the intervention group with modality mapping or time point were not significant, $F < 1.40$.

3.1.3. *Fatigue intervention*

Average dual-task performance during the eight runs of the fatigue intervention remained surprisingly stable over time (compare Table B1 in the supplement material), as indicated by non-significant main effects for run and modality mapping, as well as the interaction, $F < 1.60$. Fig. 4 shows that in both intervention groups, some participants showed a fatigue effect in terms of a performance decline from the beginning (run 1 & 2) to the end (run 7 & 8) of the 90 min intervention (highlighted in purple, solid lines). However, other participants increased their dual-task performance during the fatigue intervention (highlighted in orange, dashed lines), which is in accordance with the stable pre-post performance improvements reported above. The group's mean performance (dotted line in black) showed no significant changes due to the high interindividual variability.

3.2. *Subjective report*

The assessment of subjective items differed between the two fatigue intervention groups and the passive control group. Thus, we calculated one ANOVA for each item, where items subjective fatigue, motivation, mental and physical capacity only compared the two fatigue groups, while the remaining items were answered by all three groups (compare

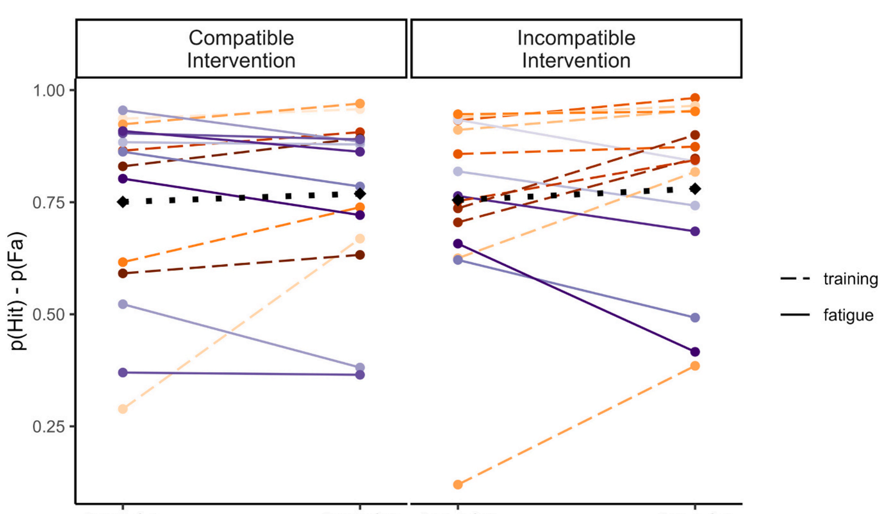

Fig. 4. Individual performance during first and last two runs of the fatigue intervention per intervention group.
Note: Every line shows individual performance and points indicate individual means for the respective runs (mean of run 1&2 and mean of run 7&8). Individuals who increased their performance over the fatigue intervention are colored orange (dashed lines), and individuals who decreased their performance are colored purple (solid lines). The resulting group means is shown in dotted black line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3). The mixed ANOVA for item subjective fatigue revealed a main effect of intervention groups, a main effect of time point and the interaction of both (compare Table 2). The corrected pairwise t-test comparing the difference scores (score after - score before intervention) between the three intervention groups showed a significant difference between the passive control group and the two intervention groups, passive group (M = −9.13, SD = 18.13) vs. compatible group (M = 19.73, SD = 32.79), $t(14) = 2.64$, $p = .029$, passive vs. incompatible group (M = 22.67, SD = 19.92), $t(28) = 4.57$, $p < .001$. There was no significant difference between the two fatigue groups, $t(15) = -0.26$, $p = .795$. The same pattern was found for the item motivation. Both main effects of the intervention group and time point were significant and the interaction. Pairwise *t*-tests revealed again only a difference between the passive group and the two intervention groups, passive group (M = 6.87, SD = 9.98) vs. compatible group (M = −31.46, SD = 34.17), $t(11) = -3.61$, $p = .006$, passive vs. incompatible group (M = −23.33, SD = 26.72),$t(18) = -4.10$, $p = .002$).

The item physical capacity showed only an interaction effect between intervention groups and time points with a similar pattern as the item motivation. The difference scores differ significantly between the passive group and the two fatigue intervention groups, passive group M = 7.80, SD = 16.73) vs. compatible group (M = −11, SD = 12.78), $t(24) = -3.25$, $p = .005$, passive group vs. incompatible group (M = −11.13, SD = 12.67), $t(26) = -3.49$, $p = .005$). This indicates an increase in subjective fatigue and decrease in motivation and physical capacity for the two fatigue intervention groups and the exact opposite pattern for the passive control group, that is a decrease in subjective fatigue and an increase in motivation and physical capacity (compare Table 3 and Fig. 5). The item mental capacity only showed a main effect of time point, indicating reduced mental capacity after completing the intervention compared to before the intervention. The same pattern is found for the item focus. Participants of the two fatigue intervention groups showed a significantly reduced focus after the intervention compared to before (compare means in Table 3). Participants who completed the fatigue intervention reported no significant change in frustration or effort after the intervention.

3.3. Correlation of performance and subjective report

To further analyze the interplay of subjective fatigue reports and individual performance during the course of the intervention, we correlated both measures individually for each participant, resulting in a Pearson-moment correlation for each participant. Those values were then z-transformed and tested against zero with a standard t-test. The reported correlation is the re-transformed value per group after averaging the z-transformed values. We found no significant correlation between the individual fatigue ratings and the performance during the intervention for neither the compatible intervention group, $r = -.02$, 95 % CI [−.36, .32], $t(13) = -0.12$, $p = .903$, nor for the incompatible intervention group, $r = -.05$, 95 % CI [−.40, .29], $t(14) = -0.32$, $p = .752$. This indicates that the fluctuations of the subjective experience of fatigue is not directly related to the intraindividual fluctuations of dual-

Table 2
ANOVA for each subjective item with factor time point and intervention group.

Effect	$\widehat{\eta}^2_G$	F	df^{GG}	df^{GG}_{res}	MSE	p	p.adj	
Fatigue								
Groups	0.231	7.67	2	38	809.14	0.002	0.006	**
Timepoint	0.056	8.97	1	38	275.10	0.005	0.011	*
Groups × Timepoint	0.098	8.12	2	38	275.10	0.001	0.006	**
Motivation								
Groups	0.245	9.94	2	38	498.49	<0.001	0.001	**
Timepoint	0.144	16.87	1	38	303.52	<0.001	0.001	**
Groups × Timepoint	0.155	9.21	2	38	303.52	0.001	0.001	**
Physical capacity								
Groups	0.107	2.55	2	38	874.78	0.091	0.213	
Timepoint	0.012	4.46	1	38	102.63	0.041	0.144	
Groups × Timepoint	0.044	8.26	2	38	102.63	0.001	0.007	**
Mental capacity								
Groups	0.053	2.00	2	38	548.84	0.150	0.349	
Timepoint	0.104	9.46	1	38	476.59	0.004	0.027	*
Groups × Timepoint	0.077	3.39	2	38	476.59	0.044	0.155	
Focus								
Groups	0.034	1.52	1	26	644.26	0.229	0.801	
Timepoint	0.137	10.32	1	26	428.68	0.003	0.024	*
Groups × Timepoint	0.000	0.02	1	26	428.68	0.888	1.000	
Effort								
Groups	0.000	0.00	1	26	562.03	0.951	1.000	
Timepoint	0.006	0.39	1	26	341.58	0.538	1.000	
Groups × Timepoint	0.032	2.28	1	26	341.58	0.143	1.000	
Frustration								
Groups	0.002	0.09	1	26	1245.60	0.767	1.000	
Timepoint	0.002	0.12	1	26	742.41	0.737	1.000	
Groups × Timepoint	0.025	1.77	1	26	742.41	0.195	1.000	

Note. Table showing ANOVA results with adjusted p-values for multiple testing (BH method). $\widehat{\eta}^2_G$ generalized Eta squared; MSE Mean-squared errors; significant codes: $p < .05$ '*', $p < .01$ '**', $p < .001$ '***'.

Table 3
Subjective report per intervention group before and after the fatigue intervention.

	Compatible intervention		Incompatible intervention		Passive control	
	Before	After	Before	After	Before	After
Fatigue	46.73 (5.88)	66.45 (5.69)	53.40 (6.63)	76.07 (5.40)	41.20 (6.48)	32.07 (6.79)
Motivation	72.09 (4.94)	40.64 (8.28)	84.73 (3.33)	61.40 (7.20)	80.87 (4.88)	87.73 (3.10)
Physical Capacity	59.64 (6.04)	48.64 (5.83)	61.80 (6.93)	50.67 (6.57)	66.67 (5.08)	74.47 (4.78)
Mental Capacity	63.91 (5.63)	36.82 (7.75)	67.67 (4.83)	47.47 (7.09)	62.33 (5.26)	64.67 (6.02)
Focus	81.14 (3.34)	56.00 (8.71)	88.71 (2.88)	65.14 (7.61)	–	–
Effort	75.64 (3.62)	71.29 (6.57)	83.50 (3.11)	64.21 (7.94)	–	–
Frustration	45.93 (7.78)	42.43 (8.96)	39.07 (8.50)	54.93 (8.44)	–	–

Note. Table showing means (standard error).

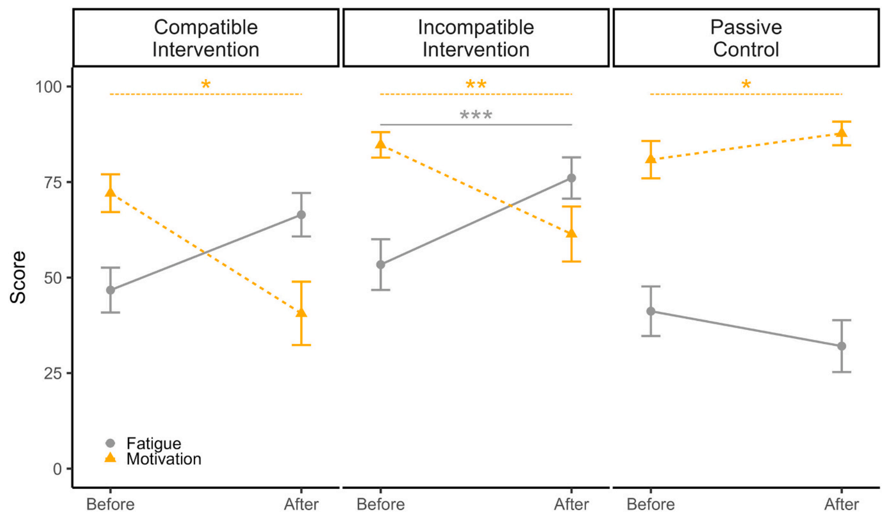

Fig. 5. Subjective motivation and fatigue per intervention group, before and after the fatigue intervention.
Note: Points indicate group means and error bars show standard error. Significant codes for corrected pairwise *t*-test: $p < .05$ '*', $p < .01$ '**', $p < .001$ '***'.

task performance during the intervention.

4. Discussion

This study aimed to elucidate whether processing modality-based crosstalk in dual tasks is based on general dual-task-related control processes or whether the processing of modality incompatible dual tasks requires additional control demands. We investigated this research question using a repeated measure pre-post design with modality-specific fatigue interventions. One group performed 90 min of modality compatible dual tasks, the other modality incompatible dual tasks, while the third group was a passive control and did not perform any specific actions. Pre and post-tests included single and dual tasks with both modality mappings. This study design allows us to investigate near transfer effects between highly similar dual tasks only differing in the specific modality mappings while controlling for retest effects. We hypothesized an overadditive fatigue-related increase in dual-task costs of the modality incompatible mapping compared to the modality compatible mapping from pre to post in the modality incompatible intervention group. For the modality compatible intervention group, we assumed an additive increase of dual-task costs for both modality mappings. In addition to performance, we assessed subjective fatigue as a manipulation check.

4.1. Summary of main findings

We found a significant increase in subjective fatigue ratings and decreased motivation and physical capacity in both fatigue groups but not in the passive control group (compare Fig. 5 and Table 3). As hypothesized, the passive control group reported less subjective fatigue and more motivation after the rest period. In addition to an increase in subjective fatigue, participants in the fatigue groups also reported a significant decrease in focus and mental capacity. We did not find a significant correlation between dual-task performance and the rating of subjective fatigue for neither of the two intervention groups. Potentially due to the high intra- and interindividual variability in the performance during the fatigue intervention (compare Fig. 4). However, the finding of the subjective level indicate that our fatigue manipulation was successful.

In spite of the successful manipulation at the subjective level and contrary to our hypothesis, we observed a significant decrease in dual-task costs over time for all three intervention groups on the performance level, indicating the presence of practice rather than fatigue effects in behavioral performance. More specifically, we had hypothesized an increase in dual-task costs for the two fatigue groups and a retest benefit for the passive control group. However, we found a reduction in dual-task costs in both modality mappings for the modality compatible intervention group and the same trend for the passive control group. Group comparisons of the pre-post difference revealed a significant difference only between the incompatible intervention group and the other two groups. In more detail, the incompatible intervention group showed a significant reduction from pre to post in dual-task costs only for the modality incompatible mapping and no difference for the modality compatible mapping. This selective reduction indicates that there was no complete transfer from performing a specific modality incompatible dual tasks for 90 min to a highly similar dual task but with a modality compatible mapping. When comparing the modality compatibility effect (difference between modality incompatible and modality compatible dual-task costs) after the intervention, we were surprised to find that only the modality incompatible intervention group was able to eliminate the otherwise robust difference in dual-task costs between the modality mappings. The other two groups (passive control group and modality compatible intervention group) did not show a significant change in the modality compatibility effect over time (compare Fig. 3). Although our results are in the opposite direction to our assumptions, the observation that only the modality incompatible group shows this selective decrease for the modality incompatible mapping, and thus differs significantly from the other two groups, is highly interesting on a theoretical basis.

In summary, these findings suggest two main directions: First, it seems possible to improve task performance despite a subjective feeling of fatigue, which raises the well-discussed question of where practice ends, and fatigue begins (Boksem et al., 2005; Lorist et al., 2000). Second, irrespective of fatigue or practice, the different performance pattern of the modality compatible and the modality incompatible intervention groups suggests the presence of specific mechanisms involved in modality incompatible dual-task performance, which do not transfer to modality compatible task performance. In the following part, we first discuss the different patterns of the modality mappings and subsequently elaborate on the role of practice and fatigue.

4.2. Additional mechanisms for modality incompatible dual-task processing

Beginning with the modality incompatible intervention group, the intervention did not affect the modality compatible mapping, meaning that there was no transfer effect from the modality incompatible mapping to the modality compatible mapping. In turn, the practice effect for the modality incompatible mapping was clearly more prominent than the effects in the other two groups. This indicates that working for 90 min on a modality compatible dual task has different effects on both modality mappings than working for the same time on a modality incompatible dual task. Hence, the present findings support the assumption that the underlying mechanisms of modality compatible and modality incompatible dual tasks are different and more specific for the modality incompatible mapping.

As outlined before, the modality incompatible mapping is the only condition that shows an overlap between stimulus and action-effect modalities between tasks, potentially causing interference in terms of modality-based crosstalk (compare Fig. 1A). Data by Schacherer and Hazeltine (2021) supported the crosstalk theory not specifically for an overlap in modalities but also for a conceptual overlap between two tasks in terms of stimulus and manipulated action effect, emphasizing the importance of the mapping between stimuli and action effects. Thus, specific mechanisms seem to be necessary to resolve crosstalk. The observation that only the modality incompatible group showed the selective pre-post reduction in the modality incompatible mapping supports the assumption that this mechanism was practiced selectively during the 90 min of modality incompatible intervention.

One potential candidate for such a mechanism is the ability to inhibit irrelevant task features. In the case of modality incompatible mapping, the irrelevant feature is the action effect as it no longer facilitates performance as it does on the modality compatible mapping (see Fig. 1A). For the modality incompatible mapping, the feature of the action effect has now an interfering effect due to the overlap with the concurrent task. At the beginning of the experiment, participants may rely on the mapping between stimulus and action effect modality as it is not interfering in the modality compatible mapping, which is assumed to be based on the life-long learning experience. During the intervention, participants then may practice inhibiting the interfering feature, thus significantly reducing their dual-task costs for the modality incompatible mapping. Recently, Stephan et al. (2022) suggested a similar idea in the context of short-term pre-exposure with a task switching paradigm consisting of two-choice discriminations tasks. They proposed that the pre-exposure with modality incompatible single tasks leads to a lower weighting of the anticipated effect code (i.e. action effect), resulting in "overshadowing" or even inhibition of the modality feature of the action effect. Thus, both experiments with different experimental paradigms and task requirements result in convergent theoretical ideas.

Another potential and similar candidate from the task-switching literature is the mechanism of task shielding, which has been assumed to prevent irrelevant information from influencing the task performance (Dreisbach & Haider, 2008). Dreisbach and Wenke (2011) found that shielding is active during task repetitions, presumably protecting the actual performance from interference produced by the other, at that moment irrelevant, task set, and loose during task switches. In the context of dual-task processing, prioritization of task one in a PRP paradigm has been associated with similar mechanisms (Sigman & Dehaene, 2006; Stelzel et al., 2009). Inferring from the initially high dual-task costs for the modality incompatible tasks compared to the modality compatible tasks, participants may not allocate enough effort to shield the relevant task mapping. This effort is assumed to be increased during the modality incompatible intervention resulting in more efficient shielding processes after than before the intervention, visible in the decreased dual-task costs for the modality incompatible mapping. This assumption is supported by the finding of Stelzel et al. (2009), who found that participants with better dual-task performance showed higher functional brain connectivity of the prefrontal cortex with sensory regions related to a prioritized component task, which may reflect shielding of this task against interference.

It is also plausible that the two mechanisms are not mutually exclusive but contribute to the selective decrease in modality incompatible dual-task costs. Inhibition thereby interacts more actively with the distracting or irrelevant features and shielding more actively preserves the task set itself (Egner & Hirsch, 2005). The assumption about an additional mechanism raises the question of why we did not find a transfer effect from the modality incompatible intervention to the modality compatible mapping.

There are different possible explanations for this finding.

One possibility is that practiced inhibition from the modality incompatible intervention is transferred to the modality compatible mapping, but here it hinders the usually facilitating action effect. Evidence for the facilitating property of action effects is provided by Schacherer and Hazeltine (2020) (Exp.1), who showed that a compatible action effect is beneficial for dual-task performance compared to an unmanipulated condition (no action effects). Inhibition is only crucial in situations with interference such as crosstalk, which is not the case for the modality compatible dual task. As a result, the robustly found modality compatibility effect vanished in the modality incompatible group after the intervention. This elimination of the modality compatibility effect after only 90 min of task practice may be surprising, considering the robust finding in the dual-task literature and the task-switching field. However, we compared the design and the data from Hazeltine et al. (2006) experiment 2a with our design and results. The eliminated modality compatibility effect is entirely in line with their findings.

Another possibility for the lack of transfer from the modality incompatible mapping to the modality compatible mapping is that participants do not practice a specific mechanism but practice a specific task set by binding stimulus, responses, and action effects which is per definition specific for the modality mapping. According to several authors, practicing a specific stimulus-response mapping increases the strength of this specific binding (Hazeltine et al., 2002; Hommel, 1998; Hommel et al., 2001; Schumacher et al., 2001; Strobach et al., 2014). Since the participants in the modality incompatible intervention group repeated the modality incompatible mapping over 2000 times in a relatively short period, increased binding strengths within this specific task set could explain the reduced dual-task costs after practice. Stephan et al. (2022) showed that even short pre-exposure to modality incompatible single tasks is sufficient to reduce task-switching costs for the modality incompatible mapping. They concluded that it seems possible to override the life-long learning association for the modality compatible mapping with the modality incompatible mapping. It seems likely that the same overriding happened with our study's high number of repetitions. In a more theoretical and broader frame, the binding process of stimulus, response, and action effects forms, together with, for example, the task goal and the task context, a specific task representation (Musslick & Cohen, 2021). Garner and Dux (2015) provided neurophysiological evidence that only multitasking training (consisting of single and dual task trials) led to changes in the task representations of the single tasks. Using the machine learning approach by Garner and Dux (2015) in combination with modality-specific effects, future studies could disentangle whether the significant reduction of modality incompatible dual-task costs after the intervention is either due to changes in task representations or whether an additional mechanism such as inhibition is improved or whether both changes contribute jointly.

A third possibility for the lack of transfer is that there are potentially two diverging processes overlapping in our design, one related to practice and one to fatigue. It might be possible that the reduction in the dual-task costs due to practice is equal to the increase in dual-task cost due to fatigue so that both processes cancel each other out and no difference between pre and post-performance is visible (see Section 4.3). Theoretically, it is also possible that neither of the two processes contributed to the resulting pattern. Though given the large body of evidence about time-on-task (Boksem et al., 2005; Borragán et al., 2017; Hockey & Earle, 2006; Holtzer et al., 2011; Hopstaken et al., 2015; Langner et al., 2010; Lorist et al., 2000) and practice effects within a task in general (Dux et al., 2009; Garner & Dux, 2015; Strobach et al., 2012), and specifically within the modality compatible mapping (Göthe et al., 2016; Hazeltine et al., 2006; Schumacher et al., 2001), this is highly unlikely.

The potential interplay of practice and fatigue processes may also contribute to the pattern of outcomes in the modality compatible intervention group. We did not observe any difference between the passive control group and the modality compatible group for either of the two modality mappings. As hypothesized, we found an additive effect of the modality compatible intervention on the two modality mappings, regardless of whether the source was practice, fatigue, or the interplay of both.

Explaining the non-existing fatigue transfer in this group, the argument from Lorist and Faber (2011) regarding the interplay of motivation and task difficulty seems plausible. The modality incompatible mapping is generally more complex than the modality compatible mapping and thus might motivate participants more and is, therefore, less susceptible to fatigue. Alternatively, by interpreting the feeling of fatigue as a sign to stop or switch the task (Agrawal et al., 2021; Boksem et al., 2005, 2006; Boksem & Tops, 2008; Dora et al., 2022; Hockey, 2011), participants may be more motivated to complete the modality incompatible mapping after the long run of the modality compatible intervention because it is simply a change of tasks and more challenging. Consequently, our findings emphasize the role of practice and fatigue mechanisms.

4.3. Fatigue or practice

Without knowledge of the content of the intervention in this study, the pre-post performance result might indicate a pure practice effect without a sign of fatigue. Similarly, computational models of learning could also not differentiate between practice and fatigue (Agrawal et al., 2021). Only the number of trials at the end of an intervention is relevant for those models. This raises the question of the exact differences between practice and fatigue for participants. One important factor seems to be time or duration (Helton & Russell, 2015; Ross et al., 2014) between the sessions to allow offline processing mechanisms in the brain (Tambini et al., 2010; Wamsley, 2019). Thus, practice interventions usually extend over several weeks (Dux et al., 2009; Hazeltine et al., 2006; Strobach et al., 2014), while fatigue interventions are typically completed in one day, with almost no rest occurring between sessions (Hopstaken et al., 2015; van der Linden, Frese, & Sonnentag, 2003). Additionally, some studies suggested that it is crucial to eliminate any motivation and engagement such as feedback, sense of time, and reward, to establish the state of fatigue (Hopstaken et al., 2015; Katzir et al., 2020; Nakagawa et al., 2013). The exact opposite is true for practice-related studies, in which feedback and performance-related bonuses are provided to motivate the participants (Liepelt et al., 2011; Schubert et al., 2017; Strobach et al., 2012).

Despite the contextual factors in a fatigue study, the literature indicates that the task characteristics and its complexity in particular, play an essential role.

On the one hand, for example, Lorist and Faber (2011) argued that a lower task load would lead to a higher state of fatigue than a high task load because the higher task load might motivate people to remain at their level of performance. In contrast, a low task load requires additional motivation to continue the task.

On the other hand, Blain et al. (2016) only found an effect of fatigue on impulsivity (choosing between two reward options, one immediate or a higher one in the future) in the group performing for 6 h a task with high load (3-back), compared to a group performing a task with lower load (1-back). Agrawal et al. (2021) explained this finding by interpreting fatigue as a sign of taking a break to let offline processing happen (Dora et al., 2022; Shenhav et al., 2013). However, this offline processing is only necessary if the task cannot be executed automatically, that is, only for complex tasks where a learning curve is expected. Hopstaken et al. (2015) did not find an effect of fatigue on a 3-back task but on the easier 1- and 2-back tasks, which is contrary to Blain et al. (2016) but in line with Lorist and Faber (2011).

Interestingly, the 3-back task even showed an effect of learning, which they explained by the lower performance at the beginning of the experiment indicating a higher level of complexity and leaving a greater possibility to improve performance. The argument from Hopstaken et al. (2015) could explain why we did not find a fatigue effect for the modality incompatible mapping, in which performance starts at a very low level compared to single-task performance (i.e., high dual-task costs). It is possible that for our tasks, not the task load itself (one-back for all task conditions) contributes to the low-performance level, but the additional interference of the modality incompatible mapping. However, this is not the case for our modality compatible mapping. Here, dual-task performance is lower than single-task performance but higher than the modality incompatible dual-task, leaving the possibility to increase and decrease performance with a low task load (one-back).

In sum, the results in the fatigue literature show a mixed picture regarding the influence of task complexity on the fatigue effect. It makes it difficult to pinpoint one specific reason why the self-reported state of fatigue is not related to participants' performance even though we implemented central recommendations to create a state of fatigue. It is plausible that the reasons are manifold rather than singular.

Possible explanations could be the task complexity and the task type, including the amount of executive control needed for the demanding tasks as opposed to traditional vigilance tasks. In addition, the less controllable online environment, in which participants could easily ignore instructions about taking breaks or paying attention to the current time, might be an essential factor. However, van der Linden, Frese, and Sonnentag (2003) reported that participants showed deficits in maintaining an adequate level of executive control after a fatigue intervention. This suggests a tendency for action selection to be driven more by automatic regulatory processes than by task goals. According to this rationale, we should have found a more prominent effect of fatigue in our modality incompatible mapping, assuming that the interference between the two tasks requires a higher level of executive control than the modality compatible mapping (compare the previous paragraph). Contrary to our intervention, van der Linden, Frese, and Sonnentag (2003) used a 2 h scheduling task and compared the performance in the Wisconson-Card Sorting Test (WCST) and the Tower-of-London (TOL) only between the fatigue and control group. This difference could potentially explain why they found an effect of fatigue on executive control requirements. However, Our finding that the modality compatible intervention group showed a performance increase for the modality compatible mapping is in line with the rationale from van der Linden, Frese, and Sonnentag (2003). Assuming that the modality compatible mapping has a dominant coupling between stimulus and response due to the non-overlapping action effects and the lifelong learning experience (Greenwald, 1970; Stephan & Koch, 2011), it is reasonable that it benefits from a shift towards more automaticity.

The observation that the modality incompatible mapping also benefits from the compatible intervention underlines that both mappings need more general dual-task-related processes, which are improved with the modality compatible intervention and a task repetition after a break (passive control group). The reviewed literature on mental fatigue and training could only partially explain our pattern of results. Thus, it is reasonable to suggest that a complex interaction of practice and fatigue effects led to our observations. One way to address this further would be to apply a fatigue intervention to participants after practicing the specific tasks up to a certain criterion.

One open question that our design cannot answer is how long-lasting those effects of the compatible and especially incompatible intervention are. Smith et al. (2019) added a 60 min recovery time, at which end Psychomotor Vigilance Task performance was again similar to the initial level. Further research is necessary to clarify whether the observed pattern of results is only short-term, as found by Smith et al. (2019), or persists for a longer duration. In addition, the contribution of practice and fatigue to the effect should be disentangled and the exact mechanism required for the modality incompatible mapping should be investigated further.

5. Conclusion

This study emphasizes the dynamic interplay between practice and fatigue in a dual-task setting using modality compatible and modality incompatible mappings. Prolonged performance of modality mappings in a dual-task context was utilized to provide evidence that the underlying mechanisms for modality compatible and modality incompatible mappings are different. A selective practice effect in the modality incompatible intervention group, which did not transfer into the modality compatible condition, supported this assumption. Further research is needed to disentangle whether the specific task representation for the modality incompatible mapping changed over time or whether the involvement of additional mechanisms such as inhibition or shielding contributed to the selective decrease in modality incompatible dual-task costs.

Declaration of competing interest

The authors have no competing interests to disclose.

Data availability

Link to the data and all analysis on OSF is provided in the methods section of the manuscript.

Acknowledgements

The authors would like to thank Phileas Heim, Dominik Schulze and Maria Zwissler for their support in collecting the data.

The work was supported by the German Research Foundation, Priority Program SPP 1772 [grant numbers: STE 2226/4-2; GR 3997/4-2; HE 7464/1-2; RA 1047/4-2].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2022.103766.

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