Additional cognitive load decreases performance but not adaptation to a visuomotor transformation

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ABSTRACT

Dual-task paradigms are procedures for investigating interference with two tasks performed simultaneously. Studies that previously addressed dual-task paradigms within a visuomotor reaching task yielded mixed results. While some of the studies found evidence of cognitive interference, called dual-task costs, other studies did not. We assume that dual-task costs only manifest themselves within the explicit component of adaptation, as it involves cognitive resources for processing. We suspect the divergent findings to be due to the lack of differentiation between the explicit and implicit component. In this study, we aimed to investigate how a cognitive secondary task affects visuomotor adaptation overall and its different components, both during and after adaptation. In a series of posttests, we examined the explicit and implicit components separately. Eighty participants performed a center-outward reaching movement with a 30° cursor perturbation. Participants were either assigned to a single task group (ST) or a dual-task group (DT) with an additional auditory 1-back task. To further enhance our predicted effect of dual-task interference on the explicit component, we added a visual feedback delay condition to both groups (ST/DT$_{DEL}$). In the other condition, participants received visual feedback immediately after movement termination (ST/DT$_{NoDEL}$).

While there were clear dual-task costs during the practice phase, there were no dual-task effects on any of the posttest measures. On one hand, our findings suggest that dual-task costs in visuomotor adaptation tasks can occur with sufficient cognitive demand, and on the other hand, that cognitive constraints may affect motor performance but not necessarily motor adaptation.

1. Introduction

Catching a fish below the water surface with a spear, drifting through the curve in a game of Mario Kart or guiding an endoscope to perform an incision during microsurgery; these three tasks seem to be completely different in their characteristics, but they all comprise operating a tool that requires mastery of a more or less complex sensorimotor transformation.

A mirrored screen, a broken joystick or strong waves can misguide the targeted movements considerably. In such scenarios, humans need to adapt to a new situation by adjusting the mapping between sensory inflow and motor outflow, thus adapting their sensorimotor transformation. The human ability to adjust to new sensorimotor transformations has been a topic of interest for more than 150 years (Stratton, 1896; von Helmholtz, 1867; Welch, 1978). One of the most popular paradigms to study this ability in the laboratory is adaptation to visuomotor rotations (Bond & Taylor, 2017; Cunningham, 1989; Hegele & Heuer, 2010; Heuer & Hegele, 2008; Mazzoni & Krakauer, 2006; Schween & Hegele, 2017; Shabbott & Sainburg, 2010; Taylor, Ivry, 2011b; Taylor & Ivry, 2012; Taylor & Ivry, 2014). In this paradigm, participants control the movements of a computer cursor on a screen by hand movements. The relationship between hand and cursor motion is then changed in a way that the movement direction of the cursor is rotated relative to the hand movement. In analogy to the tools outlined

above, this allows investigating the adaptation to novel or altered sensorimotor transformations. Despite considerable methodological differences, these studies consistently show that humans are able to adapt their hand movements after having practiced reaching a target with the novel visuomotor transformation present.

The apparent simplicity of the change in the visuomotor mapping by rotating cursor motion belies the subtlety of the underlying adaptation, which is not a unitary phenomenon, but requires the interplay of several components. Based on previous studies, a major distinction can be drawn between explicit and implicit components (Hegele & Heuer, 2010; Heuer & Hegele, 2015; Mazzoni & Krakauer, 2006; McDougle et al., 2015; Schween et al., 2018; Schween & Hegele, 2017; Taylor & Ivry, 2014).

The implicit component is thought to reflect the adjustment of an internal model of the respective sensorimotor transformation. Its development is thought to be mainly driven by sensory prediction errors originating from (future) state estimation in the cerebellum (Held, 1965; Wolpert et al., 2011). The effect of these prediction errors and their influence on the development of an internal model has been shown to depend on sensory feedback about the consequence of the performed action (Izawa & Shadmehr, 2011; Wolpert & Miall, 1996). More specifically, previous studies have shown a distinct attenuation of the implicit component, when outcome feedback was delayed (Brudner et al., 2016; Schween & Hegele, 2017). A very important and interesting aspect of the implicit component from the point of view of behavioral experiments is, that it has been suggested that its processing does not engage cognitive resources in general (Seidler & Carson, 2017) and should therefore be more likely to remain unaffected in dual-task paradigms.

The explicit component, on the other hand, is thought to be driven primarily by target (outcome) errors (Taylor, Ivry, 2011a; Wolpert et al., 2011). This explicit component refers to explicit knowledge of the transformation that develops within a conscious focus on the unexpectedly erroneous movement under the new transformation (Frensch et al., 2003). Through this focus, hypotheses are generated about the underlying visuomotor transformation, which are evaluated and refined over the course of practicing the novel transformation. This facilitates the implementation of compensatory strategies of otherwise spontaneously executed movements towards the respective target. One could, for example, point to the side of a visual target knowing that the resulting feedback of the controlled cursor on the computer screen is shifted relative to the hand movement. In contrast to the observed attenuation of implicit adaptation with delayed outcome feedback, explicit adjustments have been shown to either remain unaffected (Brudner et al., 2016) or being facilitated by additional temporal delays in the availability of outcome feedback (Schween & Hegele, 2017). It is argued to be processed in working memory demanding cognitive resources (Anguera et al., 2010; Benson et al., 2011; Seidler et al., 2012), which should make it susceptible to cognitive interference in dual-task paradigms.

One way to assess the need for cognitive resources is to measure differences in adaptation between single task conditions (ST), in which only the adaptation task had to be performed, and dual-task conditions (DT), in which an additional secondary task has to be performed simultaneously to the primary adaptation task. The resulting interference between the two tasks is commonly called *dual-task cost* (Eversheim & Bock, 2001; Galea et al., 2010; Taylor & Thoroughman, 2007; Taylor & Thoroughman, 2008). In cognitive psychology, such dual-task interference is frequently used as a tool to examine the contribution of what are assumed to be capacity-limited cognitive resources and processes (Navon & Miller, 1987; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2002).

In visuomotor adaptation experiments, adding a secondary task has yielded inconsistent results: whereas some studies did report dual-task costs (Eversheim & Bock, 2001; Galea et al., 2010; Hesse et al., 2012; Taylor & Thoroughman, 2007), others did not find any indication for impaired adaptation in the presence of a secondary task (Im et al., 2016;

Song & Bédard, 2015). For example, Eversheim and Bock (2001) asked participants to track a moving target with up-down reversed visual feedback on a computer screen. They observed decrements in tracking accuracy when participants had to simultaneously engage in a manual reaction-time task and concluded that attentional resources used for a secondary task attenuate performance especially in early stages of adaptation, during which attention-demanding processes are needed to adjust the spatial relationship between sensory inflow and motor outflow. Similar performance effects of a secondary task on visuomotor adaptation have been reported by Galea et al. (2010). Using a more cognitive secondary task (participants had to vocally shadow an auditory stimulus), they found reduced adaptation rates in response to both a gradually introduced visuomotor rotation of 30° as well as a step-wise rotation of 30° adaptation.

In stark contrast to the two aforementioned studies, Song and Bédard (2015) and Im et al. (2016) conducted a series of dual-task studies, in which they did not find any evidence for dual-task costs on visuomotor memory. In their experiments, participants performed a secondary rapid serial visual presentation task, while adapting to a 45° visually rotated cursor. Contrary to the authors' original hypothesis, they found no attenuation of adapted performance during practice.

Here, we provide and test the tentative hypothesis that these diverging findings might be explained by the differential involvement of explicit and implicit components of visuomotor adaptation across studies. Specifically, we assume that explicit adaptation requires the use of cognitive resources to develop explicit knowledge about the visuomotor rotation (Mazzoni & Krakauer, 2006; Taylor et al., 2014). Hence, a cognitively engaging secondary task should impair explicit adaptation. In contrast to this, feedback corrections based on the same sensory prediction errors that drive implicit adaptation have been found immune to cognitive interference (Taylor & Thoroughman, 2007). We therefore assume that implicit adaptation should be unimpaired by a cognitively engaging secondary task. Assuming that explicit and implicit components of adaptation are approximately additive in producing overall adaptation, variations in task designs across studies that affect the contribution of explicit and implicit components could therefore explain the differential impairment of overall adaptation by secondary tasks. Notably, there might be doubt about our above reasoning based on the fact that implicit learning of motor sequences was attenuated when a secondary cognitive task was performed simultaneously (Frensch et al., 1998; Hsiao & Reber, 2001; Stadler, 1995; Stadler, 1997). We believe that this does not invalidate our assumption that implicit adaptation is immune to interference from a cognitive secondary task. According to recent models of motor control and adaptation (Diedrichsen & Kornysheva, 2015; Ikegami et al., 2021; Wong et al., 2015) the selection of sequential actions is distinct from the adaptation of individual action components to the current spatial and dynamic requirements. Following this reasoning, implicit, prediction error-based adaptation is situated at a lower level of a motor hierarchy (Schween et al., 2019) and thus likely remote from cognitive interference that affects implicit sequences learning.

To summarize, previous studies have shown different results in relation to dual-task costs on visuomotor adaptation. However, these studies did not consider explicit and implicit components of adaptation, separately. Hypothesizing that the two components respond differently to a secondary cognitive task, we will monitor the influence of a cognitive secondary task on practicing a novel visuomotor transformation and quantify the resulting adaptive behavioral changes with respect to its explicit and implicit components. More specifically, we use a series of posttests (adaptive shifts = overall adaptation, aftereffects = implicit adaptation, explicit shifts = explicit adaptation) that (a) dissociate explicit and implicit adaptive components and (b) assess adaptation under single-task conditions to elucidate whether the presence/absence of a secondary task during practice had modulated adaptation. We predict that adaptation is attenuated after practicing with a secondary task whenever the explicit component is able to contribute to

visuomotor adaptation. For our test of aftereffects that is thought to exclusively measure implicit adaptation (see methods for a more thorough description of the design and reasoning behind this set of post-tests), we do not expect any difference between groups that had practiced with or without a secondary task. Furthermore, as both, explicit and implicit components contribute to performance during practice, we also predict dual-task costs to appear during practice of the visuomotor rotation. As a secondary task, we use an auditory 1-back task, which has been shown to be loading working memory and cognitively demanding. To increase the involvement of the explicit component and thus make the design even more sensitive to dual-task interference, we additionally incorporate groups who practiced the visuomotor rotation with delayed outcome feedback as this has shown to attenuate implicit, but facilitate explicit adaptation (Schween & Hegele, 2017).

2. Methods, setup & protocol

2.1. Participants & experimental groups

80 neurologically healthy, right-handed participants with normal color vision and normal or corrected-to-normal visual acuity were recruited via the Ludwig-Maximilians-University's email distribution list. Handedness was assessed prior to the experiment (Büsch et al., 2009). All participants were either students from the Ludwig-Maximilians- University or the Technical University of Munich. The study was approved by the local ethics committee and all participants gave written informed consent before testing. Participants received monetary compensation or course credit for their participation.

Participants were randomly assigned to one of four experimental groups - single task condition with added feedback delay (ST_{DEL}), single task condition without added feedback delay (ST_{NoDEL}), dual-task condition with added feedback delay (DT_{DEL}), dual-task condition without added feedback delay (DT_{NoDEL}) – implementing a 2×2 factorial design.

One participant from the DT_{DEL} group was excluded from analysis, as they did not finish the experiment due to scheduling issues, resulting in a total number of 79 participants.

2.2. Apparatus

Participants were seated in a dark room on a height-adjustable chair facing a vertically oriented 22-in., 120 Hz LCD-Screen (Samsung 2233RZ) approximately at head height in 1 m distance. Movements were performed in the horizontal plane on a graphic tablet (WACOM Intuos 4 XL; 62 cm $\times$ 46.5 cm $\times$ 3 cm) using a graphic stylus. The tablet was placed in a custom-made occluder so that participants could not see their hand during the experiment. The tablet tracked the coordinates of the tip of the stylus with a sampling frequency of 130 Hz. Data collection and stimulus presentation were controlled and generated in a custom Matlab script (2015a, 32 Bit) using the Psychophysics toolbox (Brainard & Vision, 1997; Pelli, 1997).

2.3. Task

Instructions for the whole experiment were presented as written text on the screen. The participants were able to read through the instructions at their own pace and scroll back, if necessary, before starting the actual task. This was to ensure that they really understood the task required of them. A schematic representation of the task is shown in Fig. 1.

2.4. Motor task

The primary motor task was a center-out reaching task towards one of two possible target locations ($-22.5°$ or $-67.5°$, with $0°$ corresponding to horizontal rightward movement and a negative sign
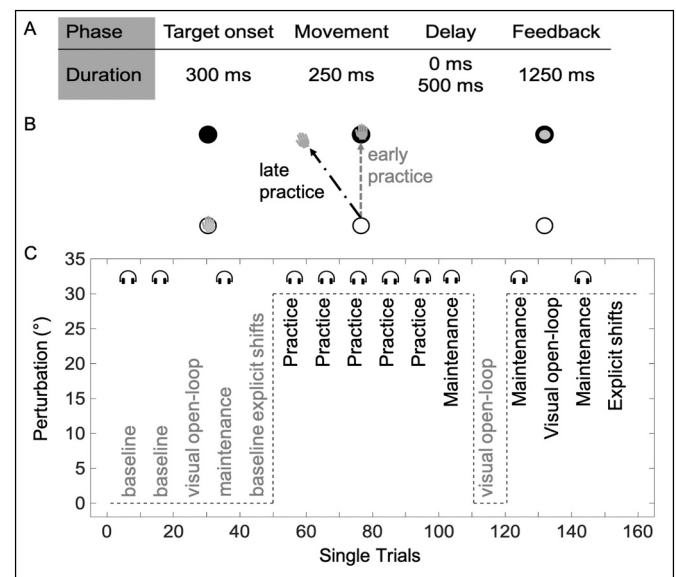

Fig. 1. Schematic representation of the experiment, divided into the temporal sequences (A), visual stimuli and movement subtasks (B) within one trial and across the whole experiment (C). Panel A shows the individual segments of one single trial in their chronological order and their maximum duration. The delay between movement termination and feedback presentation differed between delay groups (NO DEL vs. DEL) and was either 0 ms or 500 ms. Panel B shows the visual feedback presented on the screen with its associated hand movements, each vertically aligned to its respective phase segment from panel A. During target onset (left hand panel), the participant saw the trial target and kept their hand and visible visual cursor within the starting position. During movement (middle pane) participants were required to perform reaching movements to the target in the absence of concurrent visual feedback about their cursor. Arrows represent hand movement. The light grey arrow shows hand movement early during practice, when no compensatory behavior is adapted, while the darker arrow represents hand movement at the end of practice, when participants had developed a compensatory behavior for the cursor manipulation. Panel C shows the perturbation present in the experiment over the individual trials. In addition, the labels of the individual trial phases are inserted in a block-like manner. The shaded phase descriptions represent cursor perturbation (lighter grey for no manipulation, darker grey for a $30°$ manipulation). To illustrate the schedule of the secondary task, headphones are drawn in the blocks with secondary task above the phase label. In the blocks with no headphones above the phase label, participants did not have to complete a secondary task. For a more detailed description of the individual trial types and segments within one trial, see the methods section - experimental protocol.

indicating counterclockwise rotation from $0°$. Participants started with a black screen and the starting position in the center of the screen (outline of a white circle with 3.5 mm radius). The cursor was presented as a white concentric circle, the radius of which depended on the distance of the current hand position to the starting position. As soon as the participants placed the cursor within the starting position (within 3.5 mm of the center of the screen) and kept the stylus still for at least 300 ms, the concentric circle vanished and the cursor turned into a cyan filled cursor (2.4 mm radius) at hand position. At the same time a white, filled circle serving as the trial target (2.8 mm radius) appeared in one of the two locations at a target amplitude of 90 mm. The task goal in every trial was to perform a fast and smooth movement on the tablet, "slicing" the cursor through the target. During maintenance and practice trials, the cursor was present before movement onset, while resting in the starting position. It disappeared upon movement onset and reappeared after movement termination and group specific feedback delay at the intersection of movement trajectory and target amplitude. During visual open-loop trials, the cursor did not reappear at target amplitude but remained completely invisible.

2.5. Cognitive task

The secondary task for dual-task groups was an auditory–verbal 1-Back task. They received written instruction together with the instructions for the motor task to ensure that they understood both tasks before starting the experiment. Over headphones, participants listened to an audio file that reported digits in a mechanical voice in standardized speed and volume while practicing the visuomotor adaptation task. The digits were pseudorandomized for each participant. Participants were required to verbally report whenever they judged a digit to be the same as the preceding one (1-Back) and their responses were collected by the experimenter. Participants did not receive any feedback about correctness of their answer. The secondary task was present during all maintenance and practice trials, independent of the cursor manipulation. In contrast to other studies (Im et al., 2016; Song & Bédard, 2015), our secondary task was not tied to the timing of movement but was applied freely throughout movements and inter-movement intervals. In order to assess explicit and implicit adaptation in the absence of potential performance-attenuating effects of the secondary task, the 1-Back task did not occur in any test sessions, neither in pre- nor posttests. Participants in the single task groups also received auditory input over headphones. They heard two differently pitched sounds. A high-pitched sound signaled the start of the trial and one low pitched sound signaled the end of the trial. The headphones were noise-cancelling headphones (Bose Quiet Comfort 15).

2.6. Procedure

The experiment was divided into five phases: familiarization, baseline, pretest, practice and posttests. The first 72 trials were used to familiarize participants with the procedures. For this, participants performed the center-outward reaching movements of the main task in self-selected directions, with no cursor perturbation and no specific reaching target. Data in this phase was not recorded. For all following phases, trials were segmented into blocks of ten consecutive trials, five movements to each target location. For analysis, values were averaged within one block.

During baseline, visual cursor positions corresponded to the actual stylus positions (i.e., no perturbation). The baseline phase consisted of two blocks of practice trials in which the dual-task groups also had to complete the secondary task. This was then followed by two test blocks in the pretest phase. The pretests were divided into two test types, neither of which was accompanied by a secondary task: visual open-loop trials and explicit shift test trials. In visual open-loop test trials, visual feedback of the cursor was withdrawn. The task itself remained the same as during the baseline practice trials, with participants being required to perform fast center-outward reaching movements, trying to slice the then invisible cursor through the target, without being informed about their movement outcome. For the explicit shift test (Hegele & Heuer, 2010; Heuer & Hegele, 2008), participants were asked to put down the stylus and place their hand on their thigh. A target, and a straight white line (90 mm length) with the origin in the white starting circle appeared on the screen. The experimenter rotated the line clockwise around the starting circle until the participant judged the line to resemble the movement path to that particular target in baseline or maintenance trials in previous phases.

In five blocks of practice trials, the direction of the cursor's path was manipulated so that it was at a 30° angle to the stylus's movement path, which required the participants with the task of adjusting their own movement in a compensatory manner, as they were instructed to make sure, they continued to slice the cursor through the target. Dual-task groups were also continuously asked to perform the secondary task throughout the whole practice phase.

The posttests were similar to the pretests in baseline: It started with two visual open-loop tests, where the cursor remained invisible even after movement termination. For the first visual open-loop test block, the participants were instructed to perform the same movement as in the baseline trials. They were also informed, that the cursor would remain invisible but that it would veridically follow the path of their hand. For the second visual open-loop test, the participants were instructed, that the cursor's path would again be manipulated in the same way, as they experienced during the practice phase. The last test block was the explicit shift test, in which the participants were also informed about the manipulation they would need to consider for their judgement.

Between each posttest block, participants performed a block of maintenance trials, that were the same as practice trials with perturbation. The secondary task was present during maintenance trials for dual-task groups (DT_{NoDEL}/DT_{DEL}).

Movement termination was defined as the instance when the stylus had the same coordinates in at least two consecutive frames. Participants in delay groups (ST/DT_{DEL}) received task feedback in form of a static cursor at target amplitude 500 ms after movement termination. Participants in the no delay groups (ST/DT_{NoDEL}) received task feedback immediately after movement termination. If participants performed dynamically irregular movements, like not reaching the desired movement-termination in time, or if they moved too fast (<200 ms) or too slow (>500 ms), they received an error message (in German "Zu schnell!" or "Zu langsam!", respectively) on the screen and the trial was aborted. No messages were displayed when movement criteria were appropriate.

2.7. Data analysis

X and Y position data of the stylus were continuously tracked. In order to filter out high-frequency noise, which for biomechanical reasons could not have originated from the movement, but rather reflected artifacts from the dispersion from the measurement system, a smoothing filter was used. An algorithm that is frequently used for this kind of smoothing is the Butterworth filter. We filtered the data with Matlab's own functions "butter" and "filtfilt" using a 4th order Butterworth filter and a cutoff frequency of 10 Hz. Movement onset was measured as the first frame in which the sensor position reached Euclidean distance to the center of the start larger than 1 mm. Movement end was detected when two exact identical sensor positions occurred in succession. Those had to be at least 45 mm away from the start in order to be detected as movement termination. Movements with extreme durations (<200 ms or > 500 ms) were excluded from analysis. The primary outcome measure was *hand direction* relative to the target. It was calculated as the angular difference between the vector connecting the start position with the hand position at target amplitude and the vector connecting the start position with the actual target position. This procedure was the same in all movement trials. For the *explicit shift* pre-and posttest trials, the angular difference of the orientation of the vector connecting the start position with the target position and presented white line was calculated. The hand directions from the posttest phase were used to determine the change in behavior in the separate adaptation components caused by repeatedly compensating for the cursor perturbation during practice. The outcome variable for the posttest phase was obtained by baseline-correcting hand directions. For this, values from baseline blocks were subtracted from the values of the respective posttest blocks. We thus had three different, continuous, dependent variables, one for *implicit aftereffects,* one for *adaptive shifts* and one for *explicit shifts*. The variable implicit aftereffects measured values from the visual open-loop test without cursor path manipulation, which measure the implicit component of adaptation. The variable adaptive shifts measured values from the visual open-loop test with cursor path manipulation, in which the combined influence of explicit and implicit components was effective. The explicit shift test examined the verbally recallable compensation strategy the participants used to encounter the cursor rotation as a proxy for the explicit component.

For statistical analysis, each of the outcome measures were averaged into trial blocks for each participant, resulting in five average measures

for practice, and one average measure for each posttest. For further analysis, averaged measures were used as dependent variables while delay (DEL and NoDEL) and condition (ST and DT) served as independent between-subject variables, all together resulting in a 2-by-2 factorial design.

Measures were tested for distribution of normality and the assumption of homogeneity of variance using the Shapiro-Wilk test and Levene's test, respectively. Where these assumptions were met, we tested for significant differences using either repeated measure or one way analysis of variance (RM-ANOVA) with between subject factors delay (DEL and NoDEL) and condition (ST and DT) and within subject factor practice block. Where assumptions were violated, we used the ANOVAS nonparametric counterparts. In the case of differences during practice, this was a f2-ld- f1 analysis, which is a non-parametric alternative to a RM-ANOVA (Noguchi et al., 2012). For the posttests, we used the frequentist ANOVA provided by JASP (JASP Team 2021, Version 0.15). All statistical analyses were done in Matlab (2017b), R and JASP (JASP Team 2021, Version 0.15). For dual-task effects on adaptation, the hypothesis predicted the same effect direction in all three posttests: due to dual-task interference during practice, the DT groups should show smaller adaptive adjustments in the posttests than the single task groups. When the frequentist approach revealed non-significant results for one of the group comparisons, for which we hypothesized the occurrence of dual-task effects on adaptation, we additionally computed Bayes Factors (BF_{01}) reflecting the probability of the null model (i.e., no dual-task costs present) conditionally on the observed data. To this end, we computed directed independent sample t-Tests to obtain an estimate of whether the non-significant findings would count against our hypothesis or merely indicate data insensitivity.

For delay effects in the aftereffects, the hypothesis was directed in that we expected lower implicit aftereffects, but larger explicit shifts in the delay groups. No difference was expected for the adaptive shifts, which comprise both explicit and implicit components (Schween & Hegele, 2017).

3. Results

3.1. Differences during adaptation practice

Fig. 2 shows the whole practice phase. Participants in both delay groups of the respective task condition show a similar level of performance already at the beginning of the practice phase. This is due to the fact that the practice blocks represent the mean value of ten consecutive trials and thus the increase in performance gain from the first couple of trials is not visible in this figure. Furthermore, a differentiation over the course of the practice phase between dual-task and single task is clearly visible, not so much so for the delay groups within the same task condition. At the end of the practice phase, all four groups had achieved a similar level of performance. We used a non-parametric version of a 2 (single- or dual-task) x 2 (delay or no delay) x 5 (time-point) mixed ANOVA with hand position as the dependent variable. We found a significant main effect for practice block (ANOVA Type Statistic = 9.088, df = 3.30, $p < 0.01$). We hypothesized that the dual-task groups would show decreased performance during practice, revealing dual-task costs. In support of this hypothesis, ST groups did indeed show better performance during practice, as indicated by a significant main effect of task condition (ANOVA Type Statistic = 5.977, df =1, $p < 0.01$). There was no significant effect of feedback delay, nor any significant interaction for the practice phase.

3.2. Differences during posttest phase: overview

After the practice phase, participants performed a series of posttests in the absence of the secondary cognitive task. Those tests provided measures for implicit aftereffects, adaptive shifts reflecting overall adaptation and explicit shifts. Results for all three posttests are shown for each group in Fig. 3.

3.2.1. Implicit aftereffects

For implicit aftereffects, we calculated a 2 (single- vs. dual-task) x 2 (delay vs. no delay) between-subjects ANOVA with relative hand movement direction as dependent variable. In line with previous studies (Brudner et al., 2016; Schween & Hegele, 2017), the feedback delay attenuated implicit aftereffects. The ANOVA revealed a significant main effect for delay, $F(1,75) = 17.399$, $p < 0.01$, $\eta p^2 = 0.188$, confirming a reduced contribution of the implicit component of adaptation in the delay groups compared to no delay groups. There was, however, no effect for task condition, $F(1,75) = 0.621$, $p = 0.433$, $\eta p^2 = 0.008$. Even though we had no prior expectation for dual-task effects on implicit aftereffects, we took inspiration from prior studies in cognitive psychology using serial reaction time tasks that showed dual-task costs for implicit sequence learning (Frensch et al., 2003; Hsiao & Reber, 2001) and computed a directed Bayesian independent samples t-Test to further probe the non-significant effect of a concurrent secondary task during practice on the implicit component of adaptation. This analysis yielded a Bayes Factor (BF_{01}) of 6.971 indicating that the data were almost 7 times more likely under the null hypothesis of no dual-task costs in the implicit aftereffects. There was no significant interaction (Fig. 3 left panel).

3.2.2. Adaptive shifts

The adaptive shifts posttest is assumed to comprise both explicit and implicit components of adaptation. The explicit component was predicted to be more susceptible to cognitive interference. Therefore, we expected to find significant differences between single task and dual-
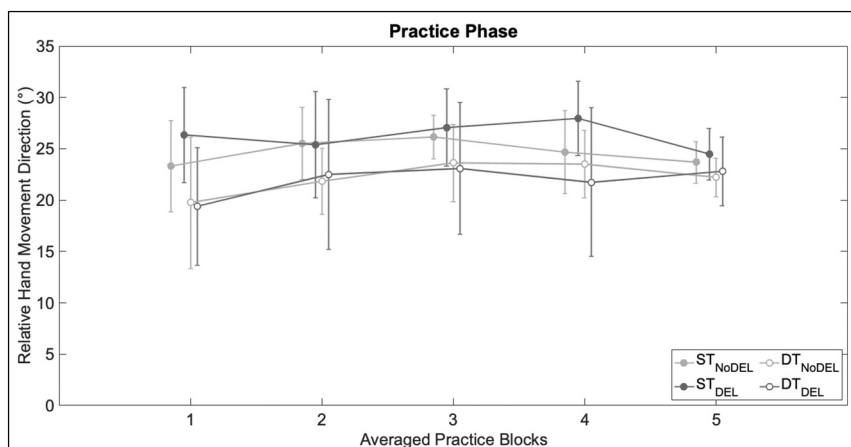

Fig. 2. Results for hand movement direction relative to trial target during practice. Lines with solid markers are single task groups with and without feedback delay. Lines with hollow markers are dual-task groups with and without feedback delay. Lighter grey represents the groups without feedback delay, both in the single and dual-task condition, while darker grey represents both condition groups with feedback delay. Values for final hand movement direction are median averaged for each practice block (10 consecutive trials, 5 to each target). Error bars show median absolute deviation (mad).
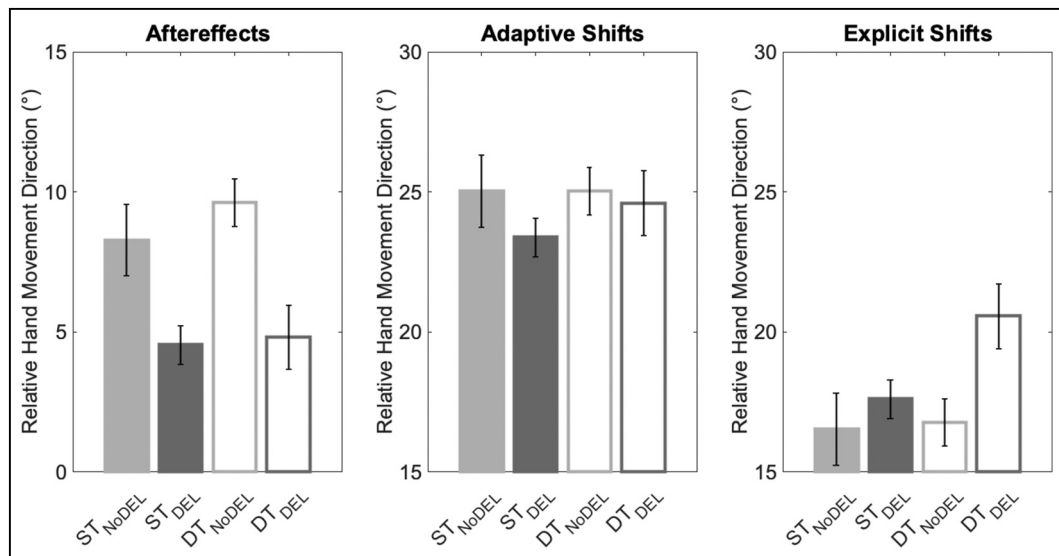
Fig. 3. Change of hand direction relative to target direction from pre to posttest. Error bars represent standard error of the mean (SEM).

task groups within this posttest. We calculated a 2 (single- vs. dual-task) x 2 (delay or vs. delay) between-subjects ANOVA. Even though we did find evidence for dual-task costs during practice, there was no main effect for task condition, $F (1,75) = 0.091$, $p = 0.764$, $\eta p^2 = 0.001$. The absence of dual-task effects on adaptive shifts was further supported by a directed Bayesian independent samples t-Test that yielded moderate evidence against dual-task interference in adaptive shifts ($BF_{01} = 5.309$). Further, there was no significant main effect for delay, $F (1,75) = 0.268$, $p = 0.606$, $\eta p^2 = 0.003$; $BF_{01} = 3.786$ (non-directed) and no significant interaction, $F (1,75) = 0.091$, $p = 0.764$, $\eta p^2 = 0.001$ (Fig. 3 middle panel).

3.2.3. Explicit shifts

A previous study, from which the current experimental design was adapted, postulated the idea of a push and pull relationship between the explicit and the implicit component, meaning that whenever certain manipulation causes the implicit participation to decrease, the explicit process will proportionally increase to compensate for the reduced contribution from implicit processes (Schween & Hegele, 2017). We calculated a 2 (single- vs. dual-task) x 2 (delay vs. no delay) between-subjects ANOVA with perceptual judgments of hand movement directions appropriate to reach a specific target as dependent variable. We used the feedback delay manipulation to promote the explicit component and to further highlight the dual-task effects to be expected in this component. In contrast to our assumption, our results showed that delay had no impact on explicit contributions to visuomotor adaptation ($F (1,75) = 1.464$, $p = 0.230$, $\eta p^2 = 0.019$). Following up on this non-significant result with a directed Bayesian independent samples t-Test yielded a Bayes Factor (BF_{01}) of 1.327 suggesting that the explicit shifts posttest was not sensitive enough to provide empirical evidence for either hypothesis. In addition, and also contrary to our predictions, we did not find any dual-task effects in the explicit shifts' posttests, $F (1,75) = 0.619$, $p = 0.434$, $\eta p^2 = 0.008$. Contrary to the follow-up analysis of the delay factor, however, a Bayes Factor of 6.933 (BF_{01}) obtained from the directed Bayesian independent samples t-Test provided moderate evidence against an effect of dual-task interference on the explicit components of adaptation.

4. Discussion

The aim of this study was to investigate whether a secondary cognitive task would differentially interfere with explicit and implicit components of visuomotor adaptation. This would provide a potential

explanation for inconsistent findings by previous studies, which did not control for the contribution of explicit and implicit processes. We hypothesized that a cognitive secondary task should interfere with the explicit component of adaptation, while the implicit component should remain unaffected. Assuming that the explicit component was susceptible to dual-task interference, we expected to find dual-task effects on adaptation (i.e., less accurate reaching) whenever the explicit component dominated the adaptive adjustments. Accordingly, we expected to see dual-task costs during the practice phase, when potentially both explicit and implicit processes are at work, as well as dual-task effects during the posttests for adaptive shifts and explicit shifts. However, we did not expect to see dual-task effects on the implicit aftereffects.

While the present results clearly show dual-tasks costs in the performance of a novel visuomotor transformation, our posttests failed to provide any evidence of dual-task effects on visuomotor adaptation. Bayesian analyses of the posttest data with respect to the main effect of presence/absence of a secondary task during practice yielded moderate evidence for the null hypothesis suggesting that the absence of dual-task effects in all of the posttests was not primarily due to the data just being insensitive, but rather reflects the absence of dual-task interference with respect to implicit, and surprisingly also explicit adaptation. Analyzing performance during practice, however, revealed clearly observable dual-task costs, which disappeared once the secondary task was removed in the posttest phase.

While it is admittedly hard to argue for evidence of absence based on the absence of evidence, we believe this particular study to be informative as we obtained some evidence in support of the absence of evidence (see above) and also designed our study to maximize the chances of detecting dual-task effects, if there were any, specifically in the explicit component of visuomotor adaptation.

Firstly, we not only compared single- and dual-task practice of a visuomotor rotation. In order to increase the experiment's sensitivity for observing potential dual-task effects on the explicit component, we included feedback delay as an additional between-participants factor. Delaying outcome feedback has been previously shown to shift adaptation towards using explicit strategies (Schween & Hegele, 2017). We thus expected higher chances to detect dual-task effects on the explicit component as we hypothesized that performance in the delayed condition would be more susceptible to dual-task interference. But even with delayed feedback, we did not observe any dual-task effects on adaptation as measured in our posttests after practice. Note however, that while the present study successfully replicated the previously observed attenuation of implicit adaptation under conditions of delayed outcome

feedback, indicating that this is a rather robust empirical finding probably associated with the temporal discounting of error information or the temporal decay of prediction errors in the implicit adaptation system, we could not replicate the delay effect on the accumulation of explicit knowledge of the transformation, probably due to insufficient sensitivity of our data.

Another measure to assess dual-task interference in visuomotor adaptation was that we examined a larger sample of participants ($N =$ 79), compared to previous studies on this topic (Eversheim & Bock, 2001; Im et al., 2016; Song & Bédard, 2015; Taylor & Thoroughman, 2008). This led to an increase in statistical power allowing us to identify dual-task costs on performance during the practice phase.

Furthermore, we sought to maximize the potential effects of a concurrent secondary task on visuomotor adaptation by employing the secondary task throughout the entire practice phase, not limiting it to trial on- and offset. This ensured that participants in the dual-task groups had to attend to both the primary motor task and the secondary cognitive task throughout the entire practice phase. Thus, there was no opportunity for them to focus only on the motor task during the intertrial interval. As we found clear evidence for dual-task interference during practice, we consider the secondary task chosen in this paradigm to be effective in engaging cognitive resources. Having a cognitive demanding secondary task present throughout the whole practice phase might be critical as it has been shown that a few seconds of pause are sufficient to allow for consolidation of the acquired motor task (Bönstrup et al., 2020; Reis et al., 2008). Having only a cognitive secondary task during the execution of the motor task, but not within the inter trial interval might also explain why Im et al. (2016), and Song and Bédard (2015), found no dual-task costs in their studies.

Thus, the design features of the experiment were informed choices to reinforce and differentiate the dual-task effects on the explicit component of adaptation. Therefore, we consider the null results of this study to be meaningful. Given the results of the follow-up Bayesian analysis of the non-significant group differences with respect to dual-task cost, which provided moderate evidence in favour of accepting the null hypotheses, this indicates that visuomotor adaptation, at least under certain conditions, does not necessarily depend on cognitive resources. However, if future research develops studies that are even more specifically adjusted for finding dual-task interference, we expect that these effects will be extremely small, if they exist at all. However, it is not entirely out of the question that other factors may have led to us not finding dual-task effects on adaptation in the posttests, which are discussed below.

Firstly, the posttest phase in our study was preceded by an instruction phase of about two to five minutes giving participants enough time between the last trial of the motor task with cognitive interference and the first posttest trial to let offline gains occur. This would imply that humans can keep relevant feedback information from practice of the visuomotor rotation in memory and use it for learning once cognitive resources become available. From theoretical reasoning, we would expect such offline gains only to affect the explicit component, since the implicit component already decays with a 500 ms feedback delay (Brudner et al., 2016; Schween & Hegele, 2017) and is therefore unlikely to be consolidated offline.

A second explanation for the absence of dual-task effects on adaptation in our posttests is the length of the practice phase. Because there were only two targets, it is possible that participants quickly reached a ceiling effect in the motor task. Since we did find dual-task costs during the practice phase, it is possible that those costs reflect participants in the dual-task groups taking longer to reach the same level of adaptation as the participants in the single task groups, but the practice phase was sufficiently long for participants in the dual-task group to eventually overcome those differences.

It is also worth noting that our results contrast previous studies that claimed that performance in visuomotor tasks does not suffer from cognitive dual-task interference (Liu et al., 2008; Singhal et al., 2007).

The findings from our study contradict this claim and add a further paradigm (the visuomotor rotation task) to the growing list of visuomotor tasks for which dual-task interference has been demonstrated (Göhringer et al., 2018; Hesse et al., 2012; Hesse & Deubel, 2011; Janczyk & Kunde, 2010; Kunde et al., 2007; Löhr-Limpens et al., 2020).

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