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Dual-task interference in action programming and action planning — Evidence from the end-state comfort effect

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A B S T R A C T

In the present study, we examined the extent of interference between a cognitive task (auditory n-back task) and different aspects of motor performance. Specifically, we wanted to find out whether such interference is more pronounced for aspects of planning as compared to programming. Here, motor planning is represented by a phenomenon called the "end-state comfort effect", the fact that we tolerate uncomfortable initial postures in favour of a more comfortable final posture. We asked participants to grasp differently sized cylindrical objects and to place them on target platforms of varying height (grasp-and-place task), So, participants were required to (1) adjust their hand opening to the object width (action programming) and (2) to plan whether to grasp the object higher or lower in order to be able to place it comfortably onto the low or high target platform. We found that participants demonstrated the end-state comfort effect by anticipating the final posture und planning the movement accordingly with a higher object-grasp for low end-target position and lower object-grasp height for high end-target position, respectively. The auditory task was negatively affected by having to perform a visuomotor task in parallel, suggesting that the two tasks share cognitive and attentional resources. No significant impact from the auditory task on the motor tasks was found. Accordingly, it was not possible to determine which of the two motor aspects (programming or planning) contributed more towards the interference observed in the auditory task. To address this question, we carried out a second experiment. For this second experiment we focussed on the interference effects found in the auditory task and contrasted two versions of the grasp-and-place task. In the first version of the task, the height of the target-shelf varied from trial-to-trial but the width of the target object remained the same. We assumed that this version had high planning demands and low programming demands. In the second version the width of the target object varied and the target-shelf height remained constant. Presumably this increased programming demands but reduced planning demands. Significant interference with the auditory task was only found for the first version, supporting the hypothesis that motor planning requires more cognitive resources and thus creates higher multitasking costs.

1. General introduction

1.1. The Perception-Action Model (PAM)

In the early 1990's, Milner and Goodale introduced the PAM (Goodale, Milner, Jakobson, & Carey, 1991a; Milner & Goodale, 1995), postulating a division of labour between the dorsal and the ventral visual streams. The dorsal stream, running from the primary visual cortex into the parietal cortex was assumed to process visual information for action (e.g. the width of a cup when grasping it), while the ventral stream was assumed to extend from the primary visual cortex into the temporal cortex and to process visual input for conscious perception (e.g. for object identification: "I see a blue cup of coffee."). Due to the nature of both streams' differential tasks, each of them was associated with certain properties and characteristics. Two of these properties are crucial for understanding the rationale of the present study: Firstly, the distinction between action programming and action planning and secondly, the assumption of dorsal-stream automaticity.

1.1.1. *Action planning versus action programming*

Each action performed towards an object comprises two different phases. First, the target object is selected and an appropriate action towards that object is planned. This initial phase is called the action planning phase. When it comes to adjusting the movement parameters to the specific object and situation, we have entered the action programming phase. Online adjustments and corrections are also part of the action programming phase (for a review of the distinction between planning and programming within the context for the PAM, see Schenk, 2010).

1.1.1.1. Action planning. Action planning, which includes the selection of a target object and the selection of an appropriate template for action to be performed on this object, is suggested to be accomplished by the ventral stream (Milner & Goodale, 1995). Dijkerman and colleagues cite the end-state comfort effect as an example of action planning (Dijkerman, McIntosh, Schindler, Nijboer, & Milner, 2009). The end-state

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comfort effect was introduced by Rosenbaum and describes the phenomenon that people will tolerate and choose relatively uncomfortable initial postures of a movement in order to achieve a more comfortable final posture (Rosenbaum et al., 1990). An instructive example is the twisted wrist position of a waiter who picks up a wine glass, which is standing upside down, in order to put it onto the table in front of a guest. Here, the initial hand position is uncomfortable — the thumb is oriented downward and the wrist is twisted. However, this initial discomfort is tolerated to achieve a comfortable and untwisted end position after the glass has been rotated. In the end position the thumb is oriented upward and the hand is naturally aligned with the glass standing on the table.

It is a matter of some debate why the end-state comfort effect occurs (for an excellent discussion of this issue, consult Herbort & Kunde, 2019). Current research suggests that movements that obey the end-state comfort principle lead to postures that provide optimal control during the manipulation phase of an action and thereby ensure maximal precision of the movement during the most critical phase of the action (Herbort & Kunde, 2019; Kunzell et al., 2013; Rosenbaum, van Heugten, & Caldwell, 1996).

1.1.1.2. Action programming. Since this process of anticipating and planning is assumed to require conscious perception, it is considered a ventral stream process (Liu, Chua, & Enns, 2008; Milner & Goodale, 1995). In contrast, action programming, the adjustment of kinematic parameters to specific situations and targets, is presumably dissociated from the action planning process and assigned to the dorsal stream (Glover & Dixon, 2002; Liu et al., 2008). In the context of the previous example, action programming would be the adjustment of the waiter's grip aperture, i.e. the opening between his thumb and index finger, to the stem of the wine glass. Action programming is considered to be automatic and can be performed in the absence of conscious processing of visual information (Goodale, 2011, 2014; Striemer, Chapman, & Goodale, 2009, 2018). Sometimes, the terminology of action programming versus action planning is used synonymously with the terminology of online versus offline motor processing (Liu et al., 2008), which is misleading, since the concept of action programming as used in the PAM, also involves an initial (offline) adjustment of movement parameters instead of only online correction processes. The background is that originally, the PAM was based on observations of the famous neuropsychological patient DF who, after damage to ventral stream areas as a consequence of carbon monoxide poisoning, experienced difficulties in perceiving objects (e.g. their size), but was able to use visual (e.g. size) information for calibrating her grip aperture when grasping (Goodale et al., 1991a; Milner & Goodale, 1995). This preserved action-related processing of visual information was evident in visuomotor tasks without online correction (Goodale, Milner, Jakobson, & Carey, 1991b). In fact, the main reason for assuming that action programming is an exclusive function of the dorsal stream stems from observations such as those above which demonstrate that a patient with impaired ventral stream but mostly preserved dorsal stream can still adjust her actions to specific aspects of the object and situation. Thus, it appears that action programming is preserved as long as the dorsal stream seems to be largely intact. However, this same patient failed to produce normal online-corrective behaviour (see Rossit et al., 2018). This more recent report on DF suggests that online-corrective behaviour is not an exclusive function of the dorsal stream. This means that either online-corrections are not part of action programming or that action programming itself is not a purely dorsal function.

1.1.1.3. Planning versus programming in patient DF. Together with another visual agnosic patient (SB), DF was also tested with regard to her action planning performance (Dijkerman et al., 2009). In this study, both patients were presented with blocks oriented in different angles with regard to participants' sagittal axes. Their task was to grasp the objects along their length dimension and the patients' performance was compared with the grasping behaviour of five healthy control participants. For this task, participants are not only required to adjust their grip aperture (i.e. the 3D distance between index and thumb) to the target object's length, but also forced to decide whether to position their thumb to the right or the left of the object. In healthy controls, thumb position was related to object orientation with a sharply defined switch point, i.e., they consistently decided to grasp with their thumb oriented to the right or to the left dependent on the object tilt. The agnosic patients, however, did not show a consistent switching behaviour with regard to their thumb position. The decision of whether to position the thumb to the right or left is dependent on participants' ability to classify object orientations in order to choose the ideal motor template for the grasp — a ventral stream task. The finding that patients with ventral stream damage have difficulties with this task can be interpreted as evidence for action planning being a ventral stream task.

1.1.1.4. Can we find a criterion to distinguish between planning and programming?. The difficulty is to find a good criterion to distinguish between planning and programming aspects. (Dijkerman et al., 2009) argued that the key distinction is between linear and non-linear visual-to-motor mapping-relationships. A linear mapping is supposed to exist between grip aperture and object width. Accordingly, grip-width adjustment is presumed to be a programming aspect. In contrast a non-linear mapping is assumed between object-rotation and grip-posture in a grasping task directed towards objects that are placed at different orientations relative to the start-posture of the reaching hand. In this case there are only two grip-postures and there is a certain boundary value beyond which further object-rotation will trigger a switch to the alternative grip posture. While it is easy to see how this criterion applies to the experimental paradigm used by Dijkerman et al. (2009), it is not obvious how this criterion can be applied to other motor paradigms. Furthermore, such a criterion presumes that we have correctly identified the relevant visual and motor parameters. In reality this is often a matter of considerable controversy (for discussion of this issue in the case of grasping, see Smeets & Brenner, 1999); in the case of orientation, see Hesse, Bonnesen, Franz, & Schenk, 2021; Hesse, Franz, & Schenk, 2011; in the case of obstacle-avoidance, see Ross, Schenk, & Hesse, 2014; a more general discussion of this thorny issue is provided in Schenk, 2010). To avoid this problem, we chose a task for which the assumption of planning involvement is intuitively much more compelling.

1.1.1.5. Measuring action planning in an end-state comfort task. In 2004, Cohen and Rosenbaum presented participants with a bookshelf with 5 platforms of different heights ranging between 50.8 and 121.9 cm above the floor and a cylindrical grasping object with a rubber base (Cohen & Rosenbaum, 2004; see also Rosenbaum, Halloran, & Cohen, 2006 for a similar approach). In their study, they wanted to find out whether participants would adjust their grip height along the object in accordance with the planned end position of a movement. In order to achieve this goal, the researchers asked their participants to perform a grasp-and-place task, the first step of which was to pick up the object from its home position (which always had the same height) and to place it on one of the platforms of the shelf. Thus, for each trial they had to decide again at which height to grasp the object. This procedure was repeated for all five platforms. The results showed that grasp height was inversely related with target shelf height, i.e. objects with high target shelf positions were grasped more towards the lower end of the cylinder, while the opposite was true for objects with low target shelf positions. By grasping objects destined for higher shelfs at the lower end of the handle participants made it more comfortable for themselves to place the object at the high shelf. Specifically, they reduced the required movement amplitude for this second segment of the action chain. Similarly, by gripping the objects destined for lower shelves at the upper end of the handle, they also made the action more comfortable and reduced the required amplitude of the second movement. Here is how this paradigm relates to the distinction between action programming and action planning. The task consists of an action chain. During the first part of the chain, observers move their hands from the hand's start-position to the object's start-position to pick up the object. During the second part of the chain, this object is then placed onto one of the five different shelves. Interestingly, some aspects of the first part of the action are determined by requirements of the second part of the chain. The grip height at the end of the first movement is determined not by the current position or configuration of the object but is a function of what needs to be achieved at the end of the second movement. This demonstrates that in the control of the first movement the goal of the next movement and the anticipated consequences of current action for further actions are already taken into account. This suggests considerable foresight and it is therefore argued that such effects reflect the operation of a forward planning system.

1.1.1.6. Measuring action programming in an end-state comfort task. In contrast the grip width during the first part of the movement is a simple reflection of the perceived width of the very object that needs to be picked up at the end of the first movement. Grip-width adjustment, or more specifically the adjustment of the maximum grip aperture (MGA) can be seen as a typical example of the modulation of a planned movement in response to the specific stimulus configuration presented to the observer at the time of the action's initiation. Such direct modulation is assumed to happen automatically and is seen as a classic example of action programming (e.g. Ganel & Goodale, 2003, 2014; Göhringer, Löhr-Limpens, Hesse, & Schenk, 2019; Hesse & Franz, 2009b; Löhr-Limpens, Göhringer, Schenk, & Hesse, 2019) and assumed to be the exclusive domain of the dorsal visual stream. MGA reflects the peak 3D distance between index finger and thumb, which typically occurs some time before the participant's finger tips contact the object. The MGA and other measures associated with it (e.g. the standard deviation of the MGA) have been shown to be related to object size in grasping (e.g. Ganel & Goodale, 2014; Schenk, 2012; Utz, Hesse, Aschenneller, & Schenk, 2015), i.e. the larger the object, the larger the grip aperture. One measure, which is used to quantify this relation, is the slope of the linear regression relating MGA to object size (Hesse & Franz, 2009b; Schenk, 2012; Utz et al., 2015). This measure can also be employed to investigate how action programming is affected by irrelevant features or secondary tasks in dual-tasking paradigms (Hesse, Schenk, & Deubel, 2012; Löhr-Limpens et al., 2019).

1.1.2. Dorsal stream automaticity

Dual-tasking costs are defined as the decrement observed when performance for two tasks combined is compared to that obtained when each task is carried out separately (Pashler, 1989, 1994). The underlying concept is that the two tasks compete for the same central attentional and cognitive resources and consequently one or both of the two tasks will not receive the resources required for optimal performance.

1.1.2.1. Dual-tasking and the PAM. According to the PAM, dorsal stream tasks do not rely on central cognitive resources, while the ventral stream does access these capacities in the context of its role in conscious visual information processing. Therefore, dual-tasking can be used as a tool for investigating the validity of the PAM: Dorsal stream tasks should be immune to the influence of a secondary task, while ventral stream tasks should be impacted by a secondary task as a consequence of the capacity limitations (Liu et al., 2008; Singhal, Culham, Chinellato, & Goodale, 2007). A number of studies already examined the interference between motor planning and cognitive performance, for example in the context of a memory task (Logan & Fischman, 2011; Schutz & Schack, 2020; Weigelt, Rosenbaum, Huelshorst, & Schack, 2009). For example, it was found that the recency effect in a memory recall task is reduced when a task involving motor planning is performed shortly after the encoding phase (Logan & Fischman, 2011). However, a comparable reduction of the recency effect was also found when a simpler motor task was used. Currently, it is unclear whether this interference between cognitive and motor processes is more pronounced for motor aspects involving planning as compared to programming. Our study aims to examine this issue.

1.1.2.2. The present study: dual-tasking, action planning vs. action programming, and the PAM. Following this logic, in the present study, we asked the question of whether action programming (dorsal) and action planning (also ventral) are differentially affected by a concurrent auditory task. Proponents of the PAM would predict that action programming is immune to dual-task interference, while action planning will show dual-tasking costs (Liu et al., 2008). However, data from our own lab, as well as from other researchers, suggest the existence of dual-tasking costs for dorsal stream tasks (e.g. Göhringer, Löhr-Limpens, & Schenk, 2018; Hesse et al., 2012; Janczyk & Kunde, 2010; Kunde, Landgraf, Paelecke, & Kiesel, 2007; Löhr-Limpens et al., 2019). Here, as mentioned earlier, we used a paradigm similar to Cohen and Rosenbaum's (2004) study to assess in one task both the action planning and the action programming component: Participants were asked to grasp a cylindrical object, pick it up from its home position and to place it on one of three target shelves (please note that we had one-way home-to-target trials and did not observe the return). In accordance with the end-state comfort effect, we expected participants to choose a higher grip position to place the object on the low target shelf and a lower grip position when planning to place it on the high target shelf. In addition, our grasping objects had three different handle widths, so participants also had to adjust their grip aperture to the specific object. According to the PAM, this component would be part of the action programming and should not depend on central cognitive capacities. This grasp-and-place task was either performed alone or under dual-task conditions, i.e., simultaneously with an auditory tone counting task.

To sum up, with this paradigm, we aimed to address two questions: (1) Do we find dual-tasking costs of a cognitive task on visuomotor performance and vice versa, and (2) Are the dual-task interferences comparable for action programming (grip aperture) and action planning (grip height), or is the interference with the action planning component more pronounced?

2. Experiment 1: methods

2.1. Participants

Participants were 30 healthy students and staff members of the Ludwig-Maximilians-Universität (LMU) Munich (7 males, 23 females). One female had to be excluded due to severe problems performing the experimental tasks. For the remaining sample (N = 29) a mean age of 24 years, at the time of testing, with a standard deviation of 4 years (range: 18–33 years) was computed. Students were reimbursed with course credit or 8€/h. All participants had normal or corrected-to-normal vision, were right-handed by self-report and had no neurological or psychiatric issues. Prior to the experiment, they gave their written informed consent and were debriefed after completion of the experiment. Our experimental procedures were approved by the Ethics Committee of the LMU and conducted in accordance with the Declaration of Helsinki.

2.2. Stimuli and experimental setup

Grasp-and-place stimuli were three plungers (diameter 13.5 cm) with differently sized handles consisting of PVC pipes with a length of 54 cm each. The outer diameters of the handles were 5 cm (small), 6.3 cm (medium) and 7.5 cm (large), so participants had to adapt their grip aperture accordingly when grasping the objects.

In each trial, the relevant object (one of the three different grasp-and-place objects) was placed in the central position of the middle shelf of a storage unit (see Fig. 1, for more information see also section Experimental procedures). The storage unit (H: 72.5 cm × W: 80 cm × D: 36 cm) consisted of three shelf-boards: each board had a thickness of 2 cm. Smaller boards were positioned in the rightmost corner of each shelf-board as well as in the centre of the middle shelf-board. These small pieces of wood, from here onwards called platforms, had a length of 30 cm and one of them was pulled out 15 cm towards the participant before each trial indicating the target location (see section Experimental procedures for more details). The central platform (initial position) was always pulled out. All of those platforms were fixed with heavy bricks (H: 7 cm × W: 9.5 cm × L: 20 cm) to prevent them from keeling over and falling out of the shelf. The experimental setup (shelf and stimuli) was standing on a table with a height of 70 cm (W: 160 cm × D: 80 cm).

The start button (H: 2 cm × W: 6.5 cm × L: 9 cm), was located on a pedestal with a height of 102.5 cm next to the participant in front of the shelf.

The experiment was programmed using Matlab (The MathWorks Inc., Natick, Massachusetts, United States) including the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007). Participants' hand movements were recorded using a 3D IF motion registration system (six Vicon Bonita cameras). Four passive markers reflecting the IF light emitted by the cameras were placed on the participant's right hand: One on the thumb nail, one on the index finger nail, one between index finger and thumb, and one slightly below the wrist. Nexus software was used to construct a hand skeleton, further analyses and recordings were performed using The MotionMonitor software (Innovative Sports Training Inc.).

2.3. Experimental procedures

2.3.1. Grasp-and-place task (primary motor task)

Participants were standing in a dark room (the only source of light was the experimenter's computer screen) wearing LCD shutter goggles (FE-1 Shutter Goggles, Cambridge Research Systems). Participants pressed the start button. As soon as the co-experimenter had prepared the objects and the shelf and the participant was ready, the experimenter manually started the trial. An initial starting beep sounded and the shutter goggles turned transparent. At the same time, the experimental setup, i.e. the storage unit with the object, was illuminated. One of the three objects was standing on the initial position, i.e. on a platform located on the middle shelf and pulled out towards the participant, such that participants were directly facing the initial object position. Please note that this initial position was constant across the whole experiment. On the right of the initial position, each of the three shelf-boards contained a platform, one of which was also pulled out towards the participant on each trial. Participants' task was to first grasp the object and to subsequently place it on the target platform (the one pulled out). After performing these two steps, participants were asked to place their hand on the start button again and keep it depressed. Participants were allowed to move freely and comfortably, but were instructed to avoid extensive stretching or bending when placing the object on the target board.

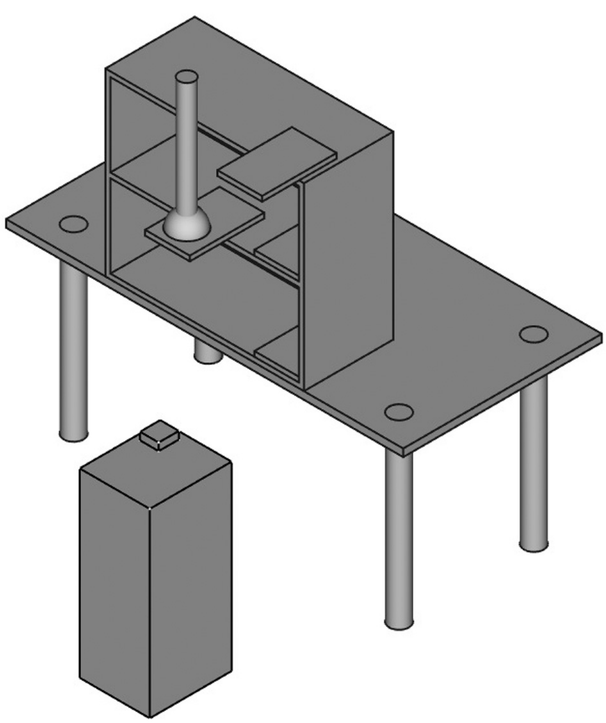

Fig. 1. (Setup). This figure shows the experimental setup (see text for precise measurements) for both experiments. The participant had his hand positioned on a starting block and then had to grasp the object and position it on one of the platforms, which were stabilized with bricks (not shown). There were three possible heights for the platform: top, middle, and bottom (top pulled out is shown). Only one target platform was pulled out during one trial.

2.3.2. Tone counting task (auditory task)

In dual-tasking blocks, participants performed an additional auditory task in parallel with the grasp-and-place task. In auditory-only conditions, participants permanently rested their hand on the start button and exclusively performed the tone counting task. On each tone counting trial, we presented a series of nine tones (single sine wave tones), each of which was categorized as ‘high’ or ‘low’. Tone duration and silent inter-tone-intervals were 200 ms, respectively. Participants were asked to count the high tones and to tell the number to the experimenter at the end of each trial. The auditory task was presented using the computer loudspeaker and began as soon as the shutter goggles turned transparent. The length of each auditory trial exceeded the duration of the grasp-and-place task. The tones were clearly distinguishable from the initial beep sound at the start of each trial and thus any confusion between the go-signal and the auditory task could be avoided.

2.4. Randomisation and counterbalancing

In total, the experiment consisted of six experimental blocks, each of which was preceded by three practice trials in addition to the initial practice phase in the beginning of the experiment. The initial practice phase was introduced in order to familiarize participants with the tasks and always followed the same order: three trials of grasp-and-place single-task, followed by three trials of tone counting single-task and finally three trials of dual-task (grasp-and-place + tone counting). Here, stimuli and positions were pseudorandomized in a way that all three objects and all three positions were used. In the main experiment, each of the six blocks consisted of 18 trials (108 experimental trials in total). Two of the blocks contained only the grasp-and-place task, two contained only the tone counting task and two blocks consisted of dual-task trials with both, grasp-and-place as well as tone counting tasks performed at the same time. The block order was randomized across participants. Thus, for each condition (motor-task only; auditory-task only and motor plus auditory task) 36 trials were performed by each participant.

2.5. Data analysis

Our data were mainly analysed in Matlab (The MathWorks Inc., Natick, Massachusetts, United States) and SPSS (IBM SPSS Statistics for Windows, Armonk, NY: IBM Corp.). Movement data were preprocessed using The MotionMonitor (Innovative Sports Training Inc.).

For the grasping data, MGA was defined as the peak grip aperture prior to object contact. The correct selection of the frame used for MGA computation was also checked manually for each trial. In most trials the automatic selection procedure corresponded to the one suggested by visual inspection. In a few cases, the automatic procedure did not select the correct data point. In this case the correct point was selected manually. This manual selection was based on an inspection of the aperture trajectory and the velocity profile of the movement. With regards to the velocity-criterion we expected the MGA to occur shortly after the velocity of the hand's approach movement had peaked. This is the time-point at which in most grasping studies, MGA occurs. In addition to MGA, we also calculated the slopes of the linear regression relating MGA to object width for each participant and each condition. This measure is commonly used as an indication of how successful participants adjust their hand opening to the object size prior to the actual contact (e.g. Hesse & Franz, 2009a; Löhr-Limpens et al., 2019; Schenk, 2012). Grasp height was measured within the coordinate system (in meters) of our motion tracking system, which was calibrated in a way that the origin was at the same height as the starting position where the participant's hand lay at the beginning of the trial. To make sure that we always used the right grasp height for further analyses, i.e., grasp height at the moment of the first object contact, we carefully checked for each grasping trial that the grasp height at the time point of grip closure was selected. We manually corrected it if necessary (e.g. if our algorithm chose another point due to artifacts or measurement errors in the movement data). For statistical analyses, we mostly used 3 (target shelf: low, middle, high) × 2 (cognitive load: single-task, dual-task) repeated measures ANOVAs. For the analysis of the slope-data and the performance-data in the auditory-task (proportion correct) dependent-samples *t*-tests were used.

3. Experiment 1: results

3.1. Effects of auditory task on motor task

Our first interest was in how the auditory task affected the behaviour in the motor task. There were two relevant aspects. How did the auditory task affect the programming component, reflected in the MGA, and how did the auditory task affect the planning component, reflected in the grasp height.

3.1.1. MGA

Looking at the slope, i.e. the slope of the linear regression relating the object width to the MGA, we found no difference between the single-task condition (M = 0.408, SE = 0.031) and the dual-task condition (M = 0.412, SE = 0.035), $t(28) = -0.156$, $p > 0.05$, Cohen's d = −0.029, 95% CI [−0.393, 0.335]. The data of each cell of the design can be found in Table 1.

3.1.2. Grasp height

With regard to grasp height, we calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*cognitive load*': single-task vs. dual-task) repeated measures ANOVA. The sphericity assumption was violated so all results are Greenhouse-Geisser corrected. We found a significant effect of target position on grasp height. This indicated that participants adapted where they grasped the object dependent on where they were supposed to position the target, $F(1.060,29.673) = 47.250$, $p < 0.001$, $\eta_p^2 = 0.628$, 90% CI [0.421 0.730], with participants grasping higher when the target was in the lower position (M = 405.8 mm, SE = 13.0 mm) than when it was in the middle position (M = 331.3 mm, SE = 8.1 mm) or in the higher position (M = 310.7 mm, SE = 7.4 mm). Bonferroni corrected pairwise comparisons then showed that the difference was significant for all possible comparisons ($p < 0.001$). This is indicative of the grasp height effect, and thus demonstrates that we succeeded in eliciting an end-state comfort effect.

We found no effect of cognitive load, $F(1,28) = 0.167$, $p > 0.05$, $\eta_p^2 = 0.006$, 90% CI [0, 0.115], and no interaction effect, $F(1.174, 32.871) = 1.701$, $p > 0.05$, $\eta_p^2 = 0.057$, 90% CI [0, 0.208]. The data of each cell of the design can be found in Table 2.

3.1.3. Reaction times

Considering the reaction times, we again calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*cognitive load*': single-task vs. dual-task) repeated measures ANOVA. The results are shown in Fig. 2. We found a significant main effect of target position, $F(2,54) = 12.634$, $p < 0.001$, $\eta_p^2 = 0.319$, 90% CI [0.140, 0.444]. Pairwise comparisons showed that reaction times were significantly longer for the bottom target position (M = 853 ms, SE = 50 ms) than for the middle position (M = 768 ms, SE = 37 ms, $p < 0.01$) and for the high position (M = 761 ms, SE = 37 ms, $p < 0.01$). There was no difference between top and middle position ($p > 0.05$). We also found a main effect of cognitive load, $F(1,27) = 6.925$, $p = 0.014$, $\eta_p^2 = 0.204$, 90% CI [0.0247, 0.400]. Participants were significantly slower in the dual-task condition (M = 822 ms, SE = 39 ms) than in the single-task condition (M = 766 ms, SE = 44 ms). We found no interaction effect, $F(2,54) = 1.676$, $p > 0.05$, $\eta_p^2 = 0.058$, 90% CI [0, 0.160]. This indicates that participants are slower when the target was in the bottom position than otherwise and that they were slower in the dual-task condition than in the single-task condition overall. The slower performance in the bottom position might be due to it being the most difficult position to see. The longer reaction times in the dual-task condition are evidence of dual-task interference.

3.1.4. Movement times

In relation to the movement times, we also calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*cognitive load*': single-task vs. dual-task) repeated measures ANOVA. We found a significant main effect of target position, $F(2,54) = 15.579$, $p < 0.001$, $\eta_p^2 = 0.366$, 90% CI [0.183, 0.486]. Pairwise comparisons showed that the movement times were significantly shorter for the top target (M = 873 ms, SE = 30 ms) than for the middle target (M = 900, SE = 31 ms, $p < 0.01$) and bottom target (M = 912 ms, SE = 30 ms, $p < 0.01$). We found no effect of cognitive load, $F(1,27) = 0.808$, $p > 0.05$, $\eta_p^2 = 0.029$, 90% CI [0, 0.183], and no interaction effect, Greenhouse-Geisser corrected: $F(1.659,44.784) = 1.945$, $p = 0.161$, $\eta_p^2 = 0.067$, 90% CI [0, 0.189]. Currently, it is not clear why movements towards objects that were destined for the top shelf were faster than movements in the other conditions.

Table 1
Means, standard deviations and 95% confidence intervals of the maximum grip aperture relative to the grasp object size and the task condition for Experiment 1 in mm.

Task	Object Size	M	SD	95% CI
Single-task	Small	116.8	9.4	[113.2, 120.4]
Single-task	Medium	122.7	8.1	[119.6, 125.7]
Single-task	Large	127.0	7.2	[124.3, 129.7]
Dual-task	Small	117.0	9.3	[113.4, 120.5]
Dual-task	Medium	122.9	7.9	[119.9, 125.9]
Dual-task	Large	127.3	6.5	[124.8, 129.8]

Note. M = mean, SD = standard deviation, CI = confidence interval.

Table 2
Means, standard deviations and 95% confidence intervals of the grasp height relative to the target position and the task condition in Experiment 1 in mm.

Task	Height	M	SD	95% CI
Single-task	Bottom	409.3	78.1	[379.6, 439.0]
Single-task	Middle	327.9	42.5	[311.7, 344.1]
Single-task	Top	313.6	42.6	[297.3, 329.8]
Dual-task	Bottom	402.3	69.9	[375.7, 428.8]
Dual-task	Middle	334.7	48.8	[316.1, 353.2]
Dual-task	Top	307.9	42.3	[291.8, 324.1]

Note. M = mean, SD = standard deviation, CI = confidence interval.

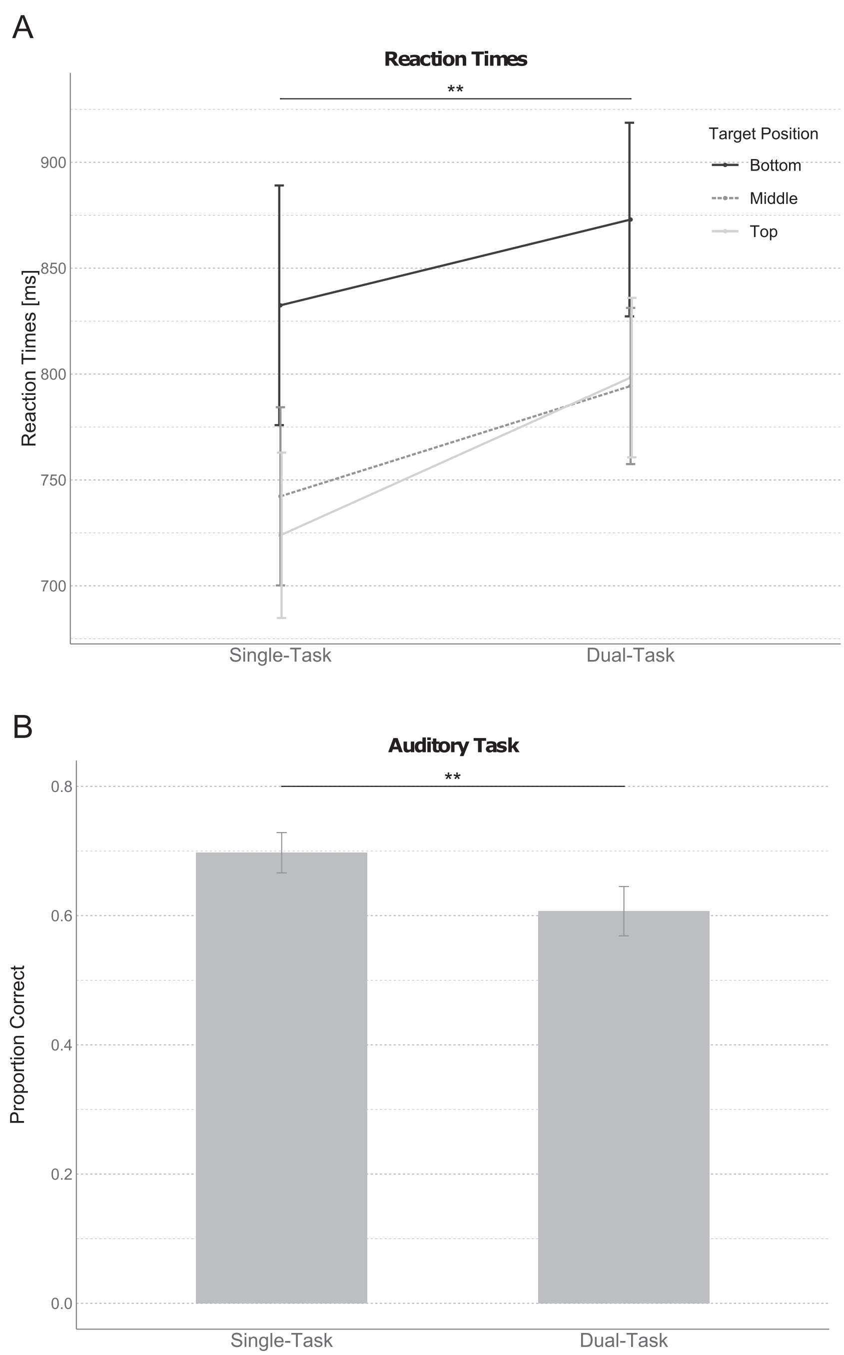

Fig. 2. A (Reaction times). Results of the reaction time analysis in milliseconds of the first experiment. Single-task refers to only the motor task being performed alone, dual-task refers to the motor task being performed concurrently with the auditory task. Target position refers to where the participant has to place the object at the end of the trial. The asterisk shows the main effect of cognitive load.
B (Auditory task). Results of the auditory task of the first experiment. Proportion Correct is the proportion of correct answers given by the participants in the auditory task. Single-task refers to only the auditory task being performed alone, dual-task refers to the auditory task being performed concurrently with the motor task.

3.2. *Effect of motor task on auditory task*

In relation to the effect of the motor task on the performance in the auditory task, as shown in the proportion of correctly answered trials, we calculated a paired-sample *t*-test. The results are shown in Fig. 2B. We found a significant difference with performance in the auditory task dropping when performed concurrently with the motor task instead of alone (dual task: M = 0.61, SE = 0.038; single-task: M = 0.70, SE = 0.031), $t(28) = 3.555$, $p < 0.01$, Cohen's d = 0.66, 95% CI [0.253, 1.058]. This is also indicative of dual-task costs.

4. Experiment 1: discussion

In the present study, we aimed to address the questions of (1) whether our visuomotor task is affected by a cognitive task and vice versa, and (2) whether the potential dual-task interferences are different for action programming (grip aperture) and action planning (grip height). In order to answer these questions, we employed a dual-tasking paradigm consisting of a visuomotor grasp-and-place task and an auditory tone counting task. The visuomotor task, inspired by Cohen and Rosenbaum's (2004) paradigm, required participants to pick up a cylindrical object at its home position and to place it onto a target shelf. This task contained two experimental manipulations: First, for investigating the action planning component, the height of the target shelf was varied on a trial-by-trial basis, so participants would have to adjust their grip height in accordance with the end-state comfort effect. Second, in order to measure action programming, the object width also varied from trial to trial, such that participants would have to adjust their pre-contact grip aperture for a successful grasp. The grasp and place task was either performed under single-task conditions or simultaneously with an auditory task, in which participants were asked to count only the high tones of a randomized sequence consisting of sinus tones of two different heights.

4.1. Dual-tasking costs

Our primary interest was to investigate dual-tasking costs from the auditory task on the visuomotor task ("forward" dual-tasking costs, i.e. effects from cognitive task on motor performance) and to differentiate between dual-tasking interferences with action planning vs. action programming. We did not find any significant dual-task effects on our two primary outcome measures (i.e., slope and grasp height) but found a significant dual-task cost for reaction time. We also found clear dual-tasking effects from the visuomotor task on the auditory task ("reverse" dual-tasking costs) in the form of performance being markedly lower when the task was performed together with the grasp-and-place task than when it was performed alone. Together with previous results (e.g. Göhringer et al., 2018; Hesse et al., 2012; Löhr-Limpens et al., 2019), these dual-task interferences between a task requiring central attentional resources (the auditory task) and a visuomotor task speak in favour of dorsal stream tasks also relying on these central resources. As explained earlier, limitations in these central capacities can lead to a competition between both tasks with the result of – in this case – impaired accuracy on the auditory task (Pashler, 1989, 1994). The finding that a secondary task and a visuomotor task can affect each other in dual-task situations (e.g. Göhringer et al., 2018; Hesse et al., 2012; Janczyk & Kunde, 2010; Löhr-Limpens et al., 2019) is at odds with the idea of a strictly isolated and automatized dorsal stream (Goodale & Milner, 1992; Milner & Goodale, 1995).

The effect of the auditory task on reaction time and the effect of the motor task on performance in the auditory task is interesting but does not allow us to determine whether action planning or action programming is more reliant on cognitive resources. It is only in the motor task and in the effect of the cognitive task on specific performance measures, such as slope and grasp height that we could distinguish between the planning and programming aspect. The multitasking cost found in the auditory task and on the reaction time reflect the impact of the motor task in toto and it is not possible to determine which aspect of the motor task was primarily responsible for these costs. It is in fact not entirely surprising that we found no *forward* multitasking effects (e.g. effects of the cognitive task on variables of the motor task) and instead obtained significant *reverse* multitasking effects (e.g. effects of the motor task on the cognitive task). We already saw in a previous study (Löhr-Limpens et al., 2019) that the reverse cost can provide a more sensitive measure of multitasking interference. The reverse cost also has the advantage that it can provide a standardized measure for multitasking costs to be compared across different primary tasks. For example, if you wish to know whether pointing or grasping is more vulnerable to multitasking interference, you can use the same cognitive task as concurrent secondary task and examine which of the two, pointing or grasping, creates the greatest drop in cognitive performance. Trying to do the same with the forward effect is more difficult, since this requires the comparison of effects of the cognitive task on motor performance and these performance measures will be different for different motor tasks (e.g. endpoint-error in the case of pointing versus MGA-variability in the case of grasping) and may also differ with respect to their ability to measure performance drops sensitively.

We therefore decided to carry out a second experiment in order to address the question of whether action programming or planning is more reliant on cognitive resources by exploiting the reverse measure for multitasking costs. This requires that we create two separate motor tasks that differ with respect to their planning and programming demands. Once we have created such tasks we can examine separately which of those two tasks generates the highest reverse costs.

5. Experiment 2: introduction

To create an experiment that would allow us to use the reverse effect in our quest to find out whether planning or programming is more reliant on cognitive resources, we introduced some changes to our original experimental design: only tone counting performance was measured under both, single-task and dual-task conditions, while the grasping task was exclusively performed under dual-task conditions, i.e. simultaneously with the tone counting task. Furthermore, we presented the grasping task in two separate blocks. In the first block, the diameter of the grasping object was the same for all trials within that block but the target platform changed from trial to trial, i.e. the task demanded that participants adjusted their movement in each trial to the current target platform. We, therefore, assumed that the planning system would be more involved in this version of the task. In the second block, the target platform stayed constant, while the object diameter changed from trial to trial. We assumed that this task required more involvement of the processes responsible for motor programming. Our research question was whether tone counting performance (auditory task) would be differentially affected by grasping tasks with more emphasis on action planning vs. action programming. Based on our previous results and evidence from former studies (Göhringer et al., 2018; Löhr-Limpens et al., 2019), we expected to find dual-tasking costs as reflected in a deteriorated performance on the tone counting task under dual- vs. single-task conditions.

6. Experiment 2: methods

6.1. Participants

Participants were 32 healthy young adults with an age range of 19 to 35 years, mean age 25 years with a standard deviation of 4 years. The group of 24 females and 8 males fulfilled the same criteria as the participants from experiment 1. For analyses including the maximum grip aperture (MGA), as well as for analyses including grasp height, 2 female participants had to be excluded due to technical problems with our motion capture system. For the analysis of movement times, we had to exclude the data of 6 participants (4 female, 2 male) because of missing data that would have been crucial for performing the analysis. The analyses of reaction times and performance on the auditory tone counting task contain the data of all 32 participants. They were reimbursed with 10€/h. Prior to the experiment, they gave their written informed consent and were debriefed after completion of the experiment. The experimental procedures were approved by the Ethics Committee of the LMU and conducted in accordance with the Declaration of Helsinki.

6.2. Experimental setup and procedures

The setup and stimuli were the same as used in experiment 1. However, there were some changes with regard to the experimental procedure. The experiment was split up into three blocks with 36 trials each, with the blocks always presented in the same order. The first block was a single-task block, in which participants only performed the auditory tone counting task. This task was also similar to the one in experiment 1. In the second and third blocks, the tone counting task was presented simultaneously with the two variations of the grasping task. In the second block, only target height changed from one trial to the next, while the diameter of the object's handle was constant (diameter constant condition). In more detail, the block was subdivided into 3×12 trials, preceded by 9 practice trials including all possible combinations of diameter and target platform (3 diameters $\times$ 3 target platforms). The diameter was constant for each sub-block of 12 trials, such that one block was performed with the small, one with the medium and one with the large object. Sub-block order was randomized, as well as target height within each sub-block. Furthermore, in order to make participants familiar with the specific object diameter they were required to grasp in the upcoming sub-block, we introduced three additional practice trials (one for each target platform) before each sub-block. The third block was structured in a similar way as the second block, but this time, the object's handle's diameter changed from trial to trial, while the target platform remained constant within each sub-block of 12 trials (height constant condition).

7. Experiment 2: results

It was the main aim of this experiment to study the effect of an auditory task (the reverse multitasking costs) on two different versions of the reach-and-place task. These reverse costs will be presented in Section 7.2. But first we will provide a brief characterization of performance in the two motor tasks by providing information on the motor variables: slope, MGA, grasp height, reaction times and movement times and by analysing the effect of keeping either handle-diameter or target shelf height constant. This information will be provided in Section 7.1.

7.1. Characterization of performance in the motor tasks

7.1.1. MGA

We found no significant difference in the slope of the linear regression relating maximum grip aperture (MGA) to object size between the diameter constant (M = 0.429, SE = 0.040) and height constant condition (M = 0.369, SE = 0.042), $t(29) = 1.474$, $p = 0.151$, Cohen's d = 0.269, 95% CI [−0.098, 0.631].

We therefore also looked at the MGA data without the slope analysis. We calculated a 3 (factor '*object size*': small, middle, large) × 2 (factor '*block-condition*': diameter is constant or height is constant) repeated measures ANOVA. The sphericity assumption was violated for the factor '*object size*', therefore those results are Greenhouse-Geisser corrected. We found a main effect of object size, $F(1.246,36.125) = 108.957$, $p < 0.01$, $\eta_p^2 = 0.790$, 90% CI [0.669, 0.843]. We also found an interaction effect between object size and block condition, $F(2,58) = 11.051$, $p < 0.01$, $\eta_p^2 = 0.276$, 90% CI [0.110, 0.401]. Bonferroni adjusted pairwise comparisons showed that only for the large object was there a small difference between whether the diameter (M = 143.1 mm, SE = 1.9 mm) or the height was constant (M = 140.1 mm, SE = 1.8 mm, $p < 0.01$). Irrespective of the block-condition (height-constant or diameter-constant) all comparisons between object sizes were significant ($p < 0.01$). There was no effect of the factor '*block-condition*', $F(1,29) = 3.105$, $p = 0.089$, $\eta_p^2 = 0.97$, 90% CI [0, 0.276]. These effects show that participants adapted their MGA to the size of the objects with the adaptation being weaker for the large object in the height constant condition. The data of each cell of the design can be found in Table 3.

7.1.2. Grasp height

Looking at the results for grasp height, we calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*block-condition*': diameter is constant or height is constant) repeated measures ANOVA. The sphericity assumption was violated so all results are Greenhouse-Geisser corrected. There was a main effect of target position, $F(1.108,32.142) = 84.718$, $p < 0.01$, $\eta_p^2 = 0.745$, 90% CI [0.593, 0.813]. There also was a significant interaction effect between target position and block-condition, $F(1.535,44.502) = 48.513$, $p < 0.01$, $\eta_p^2 = 0.626$, 90% CI [0.443, 0.694].

Bonferroni adjusted pairwise comparisons showed that in the case of the bottom target the grasp was lower for the diameter constant condition (M = 405.0 mm, SE = 13 mm) than for the height constant condition (M = 463.7 mm, SE = 16 mm, $p < 0.01$). In the case of the middle target, the grasp was higher in the diameter constant condition (M = 314.8 mm, SE = 6 mm) than in the height constant condition (M = 300.4 mm, SE = 7 mm, $p < 0.05$). Lastly, in the case of the top target condition, the grasp was also higher in the diameter constant condition (M = 283.1 mm, SE = 8 mm) than in the height constant condition (M = 261.2 mm, SE = 6 mm, $p < 0.01$). Taken together, these findings show that participants' adjustment of grasp-height to intended target-shelf position was better and more pronounced when shelf-position remained constant within blocks (varying only between blocks) than in a condition where shelf-position varied from trial to trial.

There was no main effect of the factor '*block-condition*', $F(1,29) = 2.051$, $p > 0.05$, $\eta_p^2 = 0.066$, 90% CI [0, 0.236]. The data of each cell of the design can be found in Table 4.

7.1.3. Reaction times

For the reaction times in the second experiment, we calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*block-condition*': diameter is constant or height is constant) repeated measures ANOVA. We found a significant main effect of block condition, $F(1,31) = 57.511$, $p < 0.01$, $\eta_p^2 = 0.65$, 90% CI [0.456, 0.745], with participants reacting faster (M = 615 ms, SE = 24 ms) when the height was constant than when the diameter was constant (M = 777 ms, SE = 30 ms). We found no effect for target position, $F(2,62) = 1.217$, $p > 0.05$, $\eta_p^2 = 0.038$, 90% CI [0, 0.120]. We also found no interaction effect, $F(2,62) = 1.597$, $p > 0.05$, $\eta_p^2 = 0.49$, 90% CI [0, 0.139]. The significantly longer reaction times in the diameter-constant condition suggests that increasing planning demands of a task increase movement-preparation times more significantly than increasing programming requirements.

7.1.4. Movement times

For the movement times, we again calculated a 3 (factor '*target position*': lower, middle, upper) × 2 (factor '*block condition*': diameter is constant or height is constant) repeated measures ANOVA. We found a significant main effect of block condition, $F(1,25) = 13.746$, $p < 0.01$, $\eta_p^2 = 0.355$, 90% CI [0.109, 0.531]. We found no effect of target position, Greenhouse-Geisser corrected: $F(1.373,34.318) = 2.475$, $p = 0.115$, $\eta_p^2 = 0.090$, 90% CI [0, 0.244]. We also found a significant interaction effect, $F(2,50) = 3.668$, $p = 0.33$, $\eta_p^2 = 0.128$, 90% CI [0.005, 0.254]. Bonferroni adjusted pairwise comparisons were significant for the difference between diameter and height constant for all target positions (bottom target and diameter constant: M = 1084 ms, SE = 69 ms, bottom target and height constant: M = 925 ms, SE = 42 ms, $p < 0.01$; middle target and diameter constant: M = 986 ms, SE = 43 ms, middle target and height constant: M = 905 ms, SE = 35 ms, $p < 0.05$; top target and diameter constant: M = 1025 ms,. SE = 57 ms, top target and height constant: M = 897 ms, SE = 47 ms, $p < 0.01$). This shows that participants took longer for movements towards objects when the diameter of

Table 3
Means, standard deviations and 95% confidence intervals of the maximum grip aperture relative to the grasp object size and the block-condition for Experiment 2 in mm.

Block-condition	Object size	M	SD	95% CI
Diameter constant	Small	131.4	10.9	[127.3, 135.5]
Diameter constant	Medium	137.8	10.6	[133.8, 141.8]
Diameter constant	Large	143.1	10.5	[139.1, 147,0]
Height constant	Small	131.8	11.9	[127.4, 136.3]
Height constant	Medium	136.5	10.8	[132.4, 140.5]
Height constant	Large	140.1	10.1	[136.4, 143.9]

Note. M = mean, SD = standard deviation, CI = confidence interval.

Table 4
Means, standard deviations and 95% confidence intervals of the grasp height relative to the target position and the block condition for Experiment 2 in mm.

Block-condition	Height	M	SD	95% CI
Diameter constant	Bottom	405.0	69.5	[379.0, 430.9]
Diameter constant	Middle	314.8	35.6	[301.5, 328.1]
Diameter constant	Top	283.1	45.7	[266.1, 300.2]
Height constant	Bottom	463.7	86.0	[431.5, 495.8]
Height constant	Middle	300.4	37.3	[286.5, 314.3]
Height constant	Top	261.2	33.9	[248.5, 273.8]

Note. M = mean, SD = standard deviation, CI = confidence interval.

the handle remained constant within a given block but the target shelf position varied from trial to trial. Put differently, it seems that adding planning demands to a task slows down movements more than adding programming requirements.

7.2. Effect of motor task on auditory task

To examine the effect of the motor task on the auditory task, we performed a repeated measures ANOVA with factor '*block condition*' comparing the proportion of correct trials in the auditory single-task condition with the diameter constant and height constant dual-task conditions. The results are shown in Fig. 3. We found a significant main effect ($F(2,62) = 15.724$, $p < 0.01$, $\eta_p^2 = 0.337$, 90% CI [0.169, 0.454]). Bonferroni adjusted pairwise comparisons showed that participants were significantly worse in the diameter constant condition (M = 0.677, SE = 0.041) than in the height constant (M = 0.751, SE = 0.043, $p < 0.01$) and auditory only condition (M = 0.788, SE = 0.036, $p < 0.01$). There was no significant difference between the auditory only and the height constant condition. This shows that the planning process as represented in the varying target shelfs interferes more strongly with the auditory task than the programming process as represented in the varying diameters.

8. Experiment 2: discussion

The aim of this follow-up experiment was to investigate whether a task with a higher effort with respect to action planning and a task putting more emphasis on the action programming component would differentially interfere with an auditory task. Since auditory tone counting performance turned out to be a promising measure for reflecting these potential interferences, we chose it as the main dependent variable in this experiment. To sum up, we presented participants either with the auditory tone counting task alone or in combination with two variations of a grasp-and-place task, one of which involved a trial-wise change in object diameter (i.e. more effort with respect to action programming), while the other variation involved trial-wise changes in target platform height (i.e. more effort with respect to action planning). We expected the latter variation of the grasp-and-place task to interfere to a larger extent with the cognitive task than the variation with more emphasis on action programming, which is assumed to be an automatized aspect of motor control (Liu et al., 2008; Milner & Goodale, 1995, 2008).

Indeed, we found tone counting performance to be significantly deteriorated when combined with the task involving more action planning as compared to when performed under single-task conditions, while there was no significant difference between single-task performance and dual-task performance when object diameter was varied (action programming). This finding is compatible with the predictions made by the Perception-Action Model (PAM). However, the absence of a significant effect regarding dual-tasking costs in the action programming condition does not lead to the conclusion that action programming is so automatized as not to interfere with another cognitive task. Given evidence from previous studies (Göhringer et al., 2018; Hesse et al., 2012; Janczyk, Franz, & Kunde, 2010; Janczyk & Kunde, 2010; Löhr-Limpens et al., 2019), suggesting that action programming and cognitive tasks can interfere (but see also Liu et al., 2008 for a different opinion), it is likely that our measures in this study were not sensitive enough to reveal such subtle effects and that the null-result for this comparison may be a type-II-error.

Our present data suggest that the planning process (at least in the operationalization used here, namely as process that anticipates the consequences of a current action on future actions) relies more heavily on cognitive resources than the aspect of motor programming. Previous studies already suggested that motor planning tasks interfere with cognitive performance (specifically with aspect of memory recall, see (Logan & Fischman, 2011; Schutz & Schack, 2020; Weigelt et al., 2009), In addition, our study shows that the cognitive costs are more pronounced for motor planning than for motor programming.

9. General discussion and conclusions

In the present report, we asked two questions: (1) Do we find dual-tasking costs between our visuomotor task and an auditory task? And (2) do potential dual-tasking costs differ for the action planning vs. the action programming phase of the visuomotor task? Concerning the first question, we detected dual-tasking costs as reflected in a deteriorated accuracy in the auditory task as well as in the form of prolonged reaction times in the single- as compared to the dual-task condition in experiment 1. However, in experiment 1, we did not find dual-tasking costs on the motor measures that would have allowed us to distinguish between

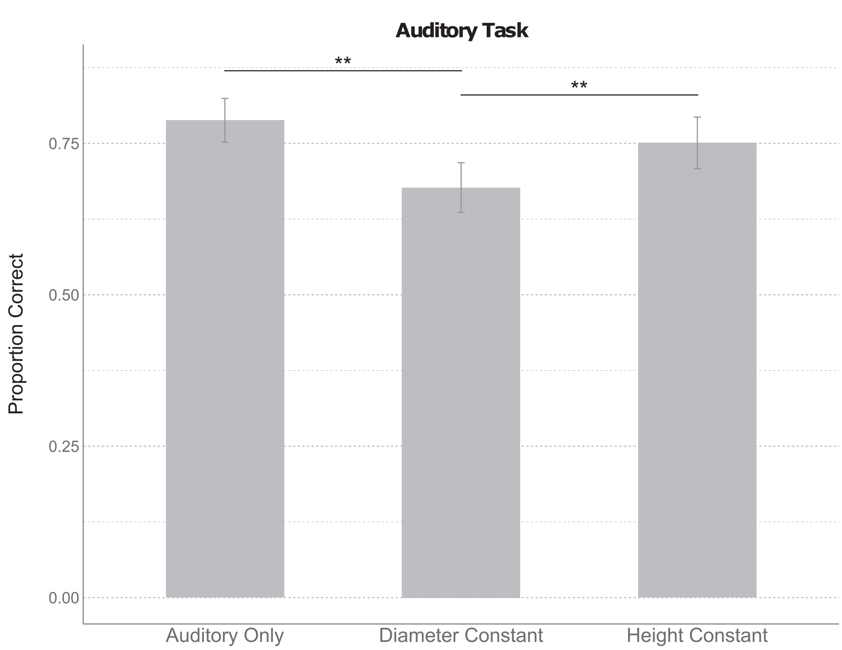

Fig. 3. (Auditory task). Results of the auditory task of the second experiment. Proportion Correct is the proportion of correct answers given by the participants in the auditory task. Single-task refers to only the auditory task being performed alone, dual-task refers to the auditory task being performed concurrently with the motor task. Diameter constant refers to when the diameter of the object has been held constant and the height where the object was to be placed varied. Height constant refers to when the height where the object was to be placed was held constant and only the diameter of the object varied. Auditory only refers to the auditory single task condition with no concurrent motor task.

planning and programming aspects. Therefore, in order to address question 3, we conducted a second experiment. This second experiment allowed us to compare two tasks – one with higher planning demands and one with higher programming demands – and to examine which of the task interfered more substantially with a concurrent cognitive task. We found that the task emphasizing the planning aspect affected concurrent cognitive performance significantly more than the task with emphasis on action programming. This observation provides support for the distinction between action planning and action programming and furthermore suggests that the higher reliance on cognitive resources may be one distinguishing feature of the planning component. However, it should be noted that this conclusion is currently based on just one task and one specific definition of a planning process (i.e. a process that anticipates the demands of a later action on the control of a preceding action component). It should be noted that while the finding of more cognitive interference in the case of the planning component is compatible with corresponding predictions of the PAM (Liu et al., 2008; Milner & Goodale, 1995, 2008), it is also compatible with any other model that recognizes a distinction between planning and programming and shares the assumption that planning is more cognitively involved than programming. Put simply, our findings are consistent with PAM but do not require the assumption of separate visual streams to obtain a plausible account.

Declaration of competing interest

None.

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