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Tennis expertise reduces costs in cognition but not in motor skills in a cognitive-motor dual-task condition

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ABSTRACT

Dual-process theories predict performance reductions under dual-task situations (= situations where two tasks have to be processed and executed simultaneously), because limited cognitive resources have to be shared between concurrent tasks. Increases in expertise should reduce the attentional resources needed to perform a motor task, leading to reduced dual-task costs. The current studies investigated whether expert tennis players (performance ratings of 1 to 14 in the German system) show smaller costs compared to intermediate players (performance ratings of 15 to 23). Two studies assessed single- and dual-task performance in a within-subject design in the same tennis task, returning balls into a target field. Two different cognitive tasks were used, a 3-back working memory task in study 1, and a vocabulary-learning task (episodic memory) in study 2. As predicted, performance in both cognitive tasks was reduced during dual-tasking, while the accuracy of tennis returns remained stable under cognitive challenge. These findings indicate that skilled tennis players show a task-prioritization strategy in favor of the tennis task in a dual-task situation. In study 1, intermediate players showed higher overall dual-task costs than experts, but the group differences in dual-task costs did not reach significance in study 2. This may have been due to less pronounced expertise-differences between the groups in study 2. The findings replicate and extend previous expertise studies in sports to the domain of tennis. We argue that an athlete's ability to keep up cognitive and motor performances in challenging dual-task situations may be a valid indicator of skill level.

1. Introduction

1.1. Dual-tasking in sports

In everyday life, people are confronted with situations in which motor and cognitive tasks have to be executed simultaneously (dual-task situations). The phenomenon of cognitive-motor dual-tasking has broadly been investigated in the past decades using walking, balancing, and various cognitive tasks (Abernethy, 1988a; Li et al., 2005; Lindenberger et al., 2000; Schaefer et al., 2008; Schaefer, Jagenow, et al., 2015; Schaefer, Schellenbach, et al., 2015). Usually, performances decrease under dual- compared to single-task conditions (= dual-task costs). Dual-task situations are also common in sports games. A football player has to permanently make decisions, recall strategies and adapt to the strategies of the opponent while being aware of the position of other players. These highly demanding situations do not only occur in team sports, but also in individual sports like tennis. For example, an athlete has to anticipate where and with what spin the next ball will be returned by the opponent while running to the position with the best option to reach the ball. These exemplary situations depict that various cognitive skills like anticipation (Loffing & Cañal-Bruland, 2017; Müller & Abernethy, 2012; Williams & Jackson, 2019), attention (Abernethy, 2001; Nougier et al., 1991; Schneider & Shiffrin, 1977), working memory (Buszard et al., 2017; Furley & Memmert, 2010; Furley & Wood, 2016), and episodic memory (Beilock, Carr, et al., 2002) are needed during sport specific situations.

1.2. Theories of motor learning and dual-processes

The ability to overcome cognitive-motor challenges depends on the experience of the athlete. More experienced athletes can keep their motor performance stable or show less performance deterioration while working on a cognitive task, while less experienced athletes show larger performance decrements (Amico & Schaefer, 2020; Schaefer & Scornaienchi, 2020; Beilock et al., 2004; Smith & Chamberlin, 1992). This phenomenon can be explained by various theories on motor skill

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learning (Adams, 1971; Fitts & Posner, 1967; Gentile, 1972) which describe that highly automatized skills require less cognitive resources than skills that are still in an early learning stage. More recent summaries of the motor learning literature (Krakauer et al., 2019; Wolpert et al., 2011) additionally emphasize that distinct neural regions (e.g., the motor cortex and the cerebellum) are involved in motor learning, and that their relative contribution changes with increasing practice. For example, the declarative memory system seems to share resources with motor learning processes that happen within a short time (e.g. adaptions of motor control due to muscle fatigue or muscle damage), while slow motor learning processes (e.g. learning of motor skills as a gradual process) seem to be independent of the declarative memory system (Wolpert et al., 2011). Therefore, fast but not slow learning processes are hampered by concurrent tasks that involve declarative memory (Wolpert et al., 2011).

Performing a well-learned motor task requires less attention (Amico & Schaefer, 2020; Schaefer & Scornaienchi, 2020). Early theories on attention have proposed that signals are filtered and can only be processed through one single channel, leading to a reduction in task performance when multiple signals have to be processed (Broadbent, 1958; Welford, 1967). Later, attention was explained as a resource emerging from a general resource pool (Kahneman, 1973) or from multiple pools (Wickens, 2002), that has to be split up between multiple concurrent tasks. This can lead to performance costs, triggered by exceeding one's capacity, which is affected by task difficulty and by the underlying structures that process the tasks. Wickens ́ multiple resource model (2002) proposes that task interferences will be larger if both tasks require the same cognitive structures compared to tasks that are processed by independent parts of the system. In this context, task interference describes the deterioration in task performance due to the interference caused by other concurrently performed tasks.

Various dual-process theories argue that tasks can be divided into two separate categories based on their dependence on working memory (Evans & Stanovich, 2013; Kahneman, 2012). Tasks categorized as type 1 can be resolved without active control, while type 2 tasks depend on attention and draw on working memory capacity (Evans & Stanovich, 2013). Furley et al. (2015) integrated this view of the dual system theory into the field of sport. They argue that type 1 processes are active on default, whereas type 2 processes are only activated when no solution can be found or when additional information indicates that the overlearned action (a skill that is automatized through extensive training) needs to be changed (e.g., when the initially planned action has to be changed because an opponent anticipated the intended action). Training and high expertise decrease the cognitive demands of skill execution and lead to type 1 task representations, which can be processed automatically (Furley & Wood, 2016). Less skilled athletes therefore need to devote attention to the control processes during planning and execution of the motor task.

1.3. Methodological challenges in dual-task research investigating expertise

Expert athletes need fewer resources to perform a trained motor task compared to athletes with less expertise, and should therefore have more free resources to invest into a secondary cognitive task. Therefore, experts are less likely to exceed their capacity of cognitive resources in cognitive-motor dual-task situations. They are predicted to keep the cognitive task performance on a rather high level and to show no costs in the trained sports skill, while novices are predicted to show performance reductions in the cognitive task. This superiority of experts has been investigated in multiple sport-specific tasks (Abernethy, 1988b; Schaefer & Scornaienchi, 2020; Beilock et al., 2004; Beilock, Carr, et al., 2002; Beilock, Wierenga, et al., 2002; Gabbett & Abernethy, 2013; Leavitt, 1979; Shank & Lajoie, 2013) from various domains (e.g., golf putting, curling, and rugby).

Cognitive tasks, mostly considered as the secondary task, vary a lot between the studies (e.g. counting tasks, n-back, visual and auditory attention tasks, word recognition). We argue that studies need to take differences between the cognitive tasks further into account when comparing the results of dual-task effects. Different demands of the cognitive tasks on the components of working memory, like the visuo-spatial sketch-pad, the episodic buffer, and the phonological loop, can affect dual-task effects (Baddeley, 2010; Baddeley, 2012). According to Wickens (2002), a visual search task will interfere much more with a motor task than an auditory attention task, because both, the motor and the visual search task, require to perceive and process spatial information while the auditory attention task can be processed by a different brain structure with its own pool of resources.

Despite a large number of studies in this research field, differences in methodology make it hard to draw clear conclusions. As already pointed out, most studies treated the motor task as the primary task and instructed participants to focus on it (Abernethy, 1988b, 2001; Leavitt, 1979). This shift of attention to the primary task should ensure that the task performance in the motor task remains stable, while performance in the secondary task reflects the attention demands of the primary task (Abernethy, 2001). Experts performing a well-learned motor task should therefore show smaller performance decrements in the cognitive task than novices that are still in an earlier learning stage (Anderson, 1982; Schmidt, 1975; Schneider & Shiffrin, 1977). The changes in the secondary task during dual-task situations can become difficult to interpret if participants cannot keep up the motor task, as shown in some studies (Abernethy, 1988b; Leavitt, 1979). In these cases, changes in task performance of the secondary task cannot be solely interpreted as the attention demands of the primary task anymore. In addition, it is possible that participants changed their task prioritization (either consciously or without conscious awareness). It may be possible that experts used different strategies in dual-task situations, or that participants did not focus on the main task despite their instructions. Risk of injuries when neglecting the motor domain may influence task prioritization in some tasks (Schaefer, 2014; Schaefer et al., 2008). Furthermore, single-task baselines have often been measured in only one domain, either in motor performance or in cognition (Beilock, Carr, et al., 2002; Beilock et al., 2004; Leavitt, 1979; Vuillerme & Nougier, 2004).

Li et al. (2005) have proposed to measure single-task baselines in both task domains in their ecological approach to dual-task research. This makes it possible to calculate the percentage decrement during dual-tasking by comparing an individual's dual-task performance with his single-task baseline performance (Somberg & Salthouse, 1982). The ecological approach has already been successfully used in age comparative dual-task studies (Lindenberger et al., 2000; Schaefer et al., 2008; see Schaefer, 2014 for a review). In addition, Schaefer and Scornaienchi (2020) has shown that the ecological approach is suitable to compare the motor and cognitive domain in a dual-task situation across expert and novice table tennis players. Single-task baselines for an auditory 3-back task (cognitive domain) and for returning balls into a target field (motor domain) were compared with the respective performance during dual-tasking. Expert table tennis players showed costs of about 10% in both domains, while novice players showed about 30% costs in the motor domain and 40% costs in the cognitive domain. These findings have been replicated and extended by an additional study on expert and novice table tennis players (see Schaefer & Amico, this issue), using tasks that were either timed (3-back, table tennis returns in response to a ball machine), or self-initiated (Counting Backwards, table tennis serves), in a within-subjects design. Again, dual-task costs of experts were significantly lower than costs of novices.

Given the pronounced differences in dual-task costs between experts and novices, we argue that dual-task costs may be used as a valid criterion to distinguish highly-skilled from lesser-skilled athletes in various sports. In soccer, for example, it is currently debated whether better players outperform others not only in physical or “classical” soccer tasks, but also in cognitive abilities, particularly executive control (Beavan, Chin, et al., 2020; Beavan, Spielmann, et al., 2020; Huijgen et al., 2015). Combining motor tasks that are important components of the respective sport (like dribbling or shooting at targets in the case of soccer) with a cognitive task may reveal an athlete's ability to keep up skilled motor performances under cognitive load. This approach can be a useful addition to the assessment of standardized cognitive task-batteries, and also to the pure assessment of competitive sports performances.

1.4. Current research paradigm and research gap

The previous studies on table tennis players have compared expert players with roughly 15 years of experience, who regularly compete in high-level tournaments, to novices. This approach required a careful calibration of table tennis task-difficulties, by choosing an optimal size of target fields, such that ceiling or floor effects could be avoided. Table tennis has the advantage that even players with low skill-levels are often able to somehow return the ball, and to enjoy the game, even if their technique is suboptimal. Many other sports are too complex to be played by novices at all, and require intensive practice. In tennis, for example, placing serves or returns in specific target fields is too difficult for novices, and would lead to floor effects. This may be because the tennis technique is less intuitive and has to be performed with more force than table tennis techniques. In these fields, we propose that our research paradigm should be applied to intermediate-level players and experts.

The studies of this paper investigate the differences in dual-tasking between experts and less-skilled players in a standardized tennis task. Despite the similarities between table tennis and tennis, like the nature of returning the ball with a racket or types of hitting the ball (slice, top spin, etc.), there are also differences that may affect the dual-tasking paradigm. The times between ball returns in tennis are much longer than in table tennis, which may give the tennis player more time gaps to work on a secondary task. Similar to the study by Schaefer and Scornaienchi (2020), participants are instructed to return balls that are served by a ball machine in a fixed inter-stimulus interval (ISI). The motor task is to return the balls into a target field on the opposite side of the net. The performance is measured by counting the hits in each trial. The size of the target field was calibrated to avoid ceiling effects in experts or floor effects in intermediate players. The participants were instructed to use the forehand cross stroke to return the ball, which is a standard skill of a tennis player. However, experts are expected to clearly outperform novices in this task concerning accuracy and stability of performance (Kolman et al., 2019). We also predict that costs in tennis performance of less skilled players during dual-tasking will be larger compared to experts as proposed by theories of motor skill learning (Adams, 1971; Fitts & Posner, 1967; Gentile, 1972). Tennis players who regularly participate in tournaments are ranked according to the classification system of the German Tennis Federation (Deutscher Tennisbund), depending on their wins and losses against opponents in the past. Successful players receive a higher “LK” rank (“Leistungsklasse”). The current studies compare players of LK 1–14 (higher level, experts) to players of LK 15–23 (intermediate level).

In the first experiment, the cognitive task is an auditory updating task, the 3-back task (as used by Schaefer & Scornaienchi, 2020). Participants try to continuously update a stream of numbers and are asked to indicate whenever the currently presented number matches the number presented three positions before. This kind of updating task is often used in cognitive-motor dual-tasking studies (Schaefer, 2018; Schaefer, Jagenow, et al., 2015; Schaefer, Schellenbach, et al., 2015; Schaefer & Scornaienchi, 2020). We predict no differences in single-task baselines between the groups (Chang et al., 2017), but we expect intermediate players to show higher performance costs under the dual-task condition.

Most studies so far have used working memory tasks like n-back (Schaefer, Jagenow, et al., 2015; Schaefer, Schellenbach, et al., 2015), counting (Beauchet et al., 2005; Koedijker et al., 2008; Li et al., 2014), or tasks focusing on visual (Hahn et al., 2011; Leavitt, 1979) or auditory attention (Beilock et al., 2004; Beilock, Carr, et al., 2002; Gabbett & Abernethy, 2013; Gabbett et al., 2011; Sibley & Etnier, 2004), while fewer studies used memory encoding tasks (Beilock, Wierenga, et al., 2002; Lindenberger et al., 2000). Experiment two will use a vocabulary learning task as the cognitive task, to enhance the generalizability of the findings. Participants will hear lists of words, each containing 10 wordpairs, built from a German word and a pseudoword. After the presentation of each list and on the following day, participants are presented the pseudoword and try to recall the corresponding German word. Each correctly recalled word scores one point. A similar word-learning paradigm has been used successfully in a study by Amico and Schaefer (2020) in different age groups. We argue that the differences between intermediate and higher-skilled players should generalize to different cognitive tasks, as long as these tasks require attention and are processed at the same levels of the multiple resource model by Wickens (2002). However, the vocabulary task also draws on episodic memory, because words have to be recalled at the end of the trial, and also one day later. Both cognitive tasks present auditory stimuli, that are processed as verbal codes and require a vocal response of the participant. Concerning these requirements, both tasks should lead to comparable levels of interference when combined with the motor task in a dual-task situation. For the vocabulary task, we predict comparable performances of intermediate players and experts under the single-task condition. Furthermore, we expect that actively encoding the wordpairs will draw on cognitive resources, similar to the 3-back task, leading to more pronounced performance decrements in intermediate as compared to expert tennis players under dual-tasking. This difference is hypothesized to be present in the immediate and the delayed recall. Testing tasks of different cognitive domains will help us understand which cognitive processes are relevant while playing tennis. Although both cognitive tasks occupy working memory capacity, information of the 3-back task has to be stored only for a short time window, while information of the vocabulary-learning task has to be stored longer, and also involves episodic memory.

The current studies investigate differences in cognitive and motor costs between intermediate players and experts. Differences between task domains are revealed by expressing dual-task costs in a percentage metric. In both studies, participants are instructed to work on both tasks equally, which enables us to interpret the tradeoff between the cognitive and the motor task as a type of prioritization of one task over the other, and whether experts differ from novices in this concern. Furthermore, we will not only expand the dual-task literature to a tennis specific task, but also elucidate how cognitive-motor dual-task performance is affected by tasks from different cognitive domains (e.g., working memory in study 1, episodic memory in study 2).

2. Study 1

2.1. Method

2.1.1. Participants

Statistical power is increased by assessing performances repeatedly in each subject (Bellemare et al., 2014; Brysbaert, 2019; Brysbaert & Stevens, 2018; May & Hittner, 2012; Rouder & Haaf, 2018). In the current study, performance in cognition and tennis is measured with multiple responses per trial and with several trials per condition. This enables us to assess task reliabilities for each performance domain (3-back and vocabulary scores, number of hits for returns). Based on the findings by Schaefer and Scornaienchi (2020), who found large differences between novice and expert table tennis players in their dual-task decrements, we expected the differences between experts and intermediate tennis players to be medium sized. To calculate how many participants are recommended to reach a sufficiently large power, we conducted a Power calculation using the G*3 Power software (Faul et al., 2007). The power analysis focused on the interaction effect of expertise group and single- versus dual-task performance decrements. We assumed the correlation among repeated measures to be high (r = 0.85), since task reliabilities for the tasks used in table tennis had been very high in previous work with this paradigm (Schaefer & Scornaienchi, 2020). The analysis indicated that a medium effect size of $f = 0.3$, a significance level of 0.05, and power of 0.95 recommends a total sample size of 14 participants. To make sure that we have enough power, even if the effect between intermediate and expert players is smaller than expected, or if the correlation between repeated measures is not that high in the current study, we decided to test 12 participants per group, leading to a total of 24 participants.

For experiment one, participants were recruited from local tennis clubs. Participants were divided into tennis players with *medium* or *high* expertise in tennis. This selection was based on the classification system for performance of the German Tennis Federation (Deutscher Tennisbund), which ranges from 1 (= very best) to 23 (lowest). In order to be ranked, players need to regularly take part in competitive matches. See Table 1 for descriptive information. All participants had normal or corrected-to-normal vision and hearing and provided informed consent to participate in the study. As background variable, perceptual speed was measured with the Digit-Symbol Substitution task (Wechsler, 1981) to show that the cognitive skills of both groups are comparable. The study was approved by the Ethics committee of Saarland University.

2.1.2. Experimental tasks

2.1.2.1. 3-back task. The 3-back task is a working memory task that requires the updating of a continuously changing sequence of numbers (Dobbs & Rule, 1989). Participants are asked to compare the current number with the number they heard 3 positions before (e.g. targets are indicated with lines: 2 8 3 $\underline{2}$ 5 9 4 $\underline{5}$ …). Each target required a response by saying the word "Tap". The number sequences were presented via loudspeakers with a fixed inter-stimulus interval (ISI) of 3 s. Each trial consisted of 32 numbers, each containing 7 targets. The score of the 3-back task was the number of correct hits minus false alarms.

Table 1
Experiment 1 descriptives, tennis expertise and cognitive background information.

	Medium Expertise	High Expertise	Independent *t*-test
n (males/females)	12 (6/6)	12 (6/6)	
Age (years)			
M	20.2	21.9	t (22) = 1.296, p = .208
SD	2.9	3.6	
Range	16–24	17–26	
German Tennis Level			
M	18.2	3.8	t (22) = 13.852, p < .001
SD	2.5	2.6	
Range	14–20	1–7	
Tennis experience (years)			
M	11.0	15.9	t (22) = 2.747, p = .012
SD	4.8	4.0	
Weekly tennis (minutes)			
M	117.3	145.0	t (21) = 0.438, p = .666
SD	149.1	154.0	
Weekly sport participation (minutes)			
M	190.4	172.5	t (22) = 0.243, p = .810
SD	180.5	180.1	
Digit-Symbol Substitution (correct items)			
M	64.0	65.3	t (22) = 0.317, p = .754
SD	9.6	9.7	

2.1.2.2. Tennis returns. The tennis returns were played on a standard indoor tennis court using the playing field of 1 vs. 1 matches. A tennis robot (Wilson portable 2-Line) was positioned centrally at the opposing side of the field. The machine shot the balls about 50 cm in front of the baseline and 50 cm next to the side line into the field with an ISI of 3 s. The spot could be easily reached by each participant. Participants were instructed to return the ball diagonally into the target field. The target field was a square (size of the field: baseline 140 cm, sideline 350 cm, line to the front 280 cm, diagonal line 377 cm) and was positioned in the top left corner (participants' view) of the field. Fig. 1 shows the setup.

Participants were instructed to return the balls to the target field using a right forehand cross stroke. We did not alternate between different positions (left or right side of the field) and shooting types (forehand or backhand) to reduce physical exertion and control for decision making. Participants were not instructed on how to hit the target (e.g. top-spin, slice, no spin). Each trial consisted of 32 balls and each hitting the target field scored 1 point. The hits were scored by a second experimenter standing next to the target field.

2.1.2.3. Single- and dual-task setting. In the single-task trials, participants performed the 3-back task without any concurrent activity, while standing on the tennis court. During the tennis single-task trials, participants returned the ball from the tennis robot into the target field. In the dual-task trials, participants returned the ball and performed the 3-back task. The ball was always served simultaneously with the auditory presentation of the numbers. For dual-task trials, participants were instructed to work as well as possible on both tasks. This should assure that none of the tasks is consciously prioritized over the other.

2.1.3. Procedure

The testing took place in a local tennis court in Saarland, Germany. Each session lasted between 60 and 90 min. After the assessment of some demographic information (age, profession, sports experience), participants were instructed in the 3-back task, followed by one practice trial, for which they received feedback on their performance (hits minus false alarms). Directly after that, participants were given 5 min tennis warm-up, followed by 2 practice trials of the tennis task with 16 balls each. To control for practice and fatigue effects, single- and dual-task blocks were assessed at multiple time points in an alternating manner: S D S D S (S = single-task, D = dual-task), with 1 trial of each task in the first and the last single-task block, 2 trials of each task in the middle single-task block, 3 trials in the first dual-task block, and 2 trials in the last dual-task block. Participants did not receive feedback on their performance during single- and dual-task blocks. Experimenter 1 scored the 3-back task, while experimenter 2 scored the tennis hits. The Digit-Symbol Substitution Test was assessed after the first dual-task block to counteract boredom or fatigue during the testing session. Table 2 presents an overview of the procedure.

2.1.4. Data analysis

Tennis hits and 3-back scores were averaged across the respective condition (single- and dual-task). Cronbach's Alpha was calculated to check for the reliability of the tasks. The performances in both tasks were analyzed with mixed-design analyses of variance (ANOVA) with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor. In addition, dual-task costs were calculated for both task domains, depicting the performance reduction as a percentage of each individual's single-task performance. A mixed-design ANOVA with expertise (2: medium or high) as between-subjects factor and task (2: tennis or 3-back) as within-subjects factor was conducted for the dual-task costs. F values and partial Eta square values for effect sizes are reported. The alpha level used to interpret statistical significance was $p < .05$.

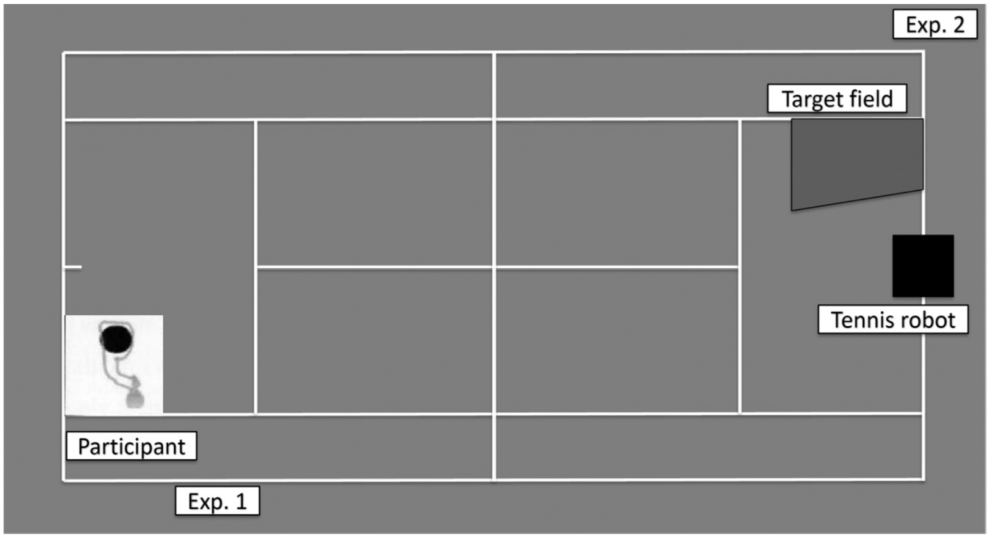

Fig. 1. Experimental setup.

Table 2
Overview of the procedure of study 1.

Condition	Trials
Instruction and Practice	5 min tennis warm-up Instruction and 2 practice trials 3-back
Single-task Block 1	1 trial single-task 3-back 1 trial single-task tennis
Dual-task Block 1	3 trials tennis and 3-back
Background Measure	Digit-Symbol Substitution
Single-task Block 2	2 trials single-task 3-back 2 trials single-task tennis
Dual-task Block 2	2 trials tennis and 3-back
Single-task Block 3	1 trial single-task 3-back 1 trial single-task tennis

2.2. Results

2.2.1. 3-back single- and dual-task performance

Cronbach's Alpha for the 9 trials assessed for the 3-back task was high (α = 0.949). Performance scores were averaged across the trials of the respective condition, resulting in mean scores for the 4 single-task trials and the 5 dual-task trials. The ANOVA with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor showed a significant main effect of single- ($M = 4.67$, $SD = 2.1$) versus dual-tasking ($M = 3.84$, $SD = 2.3$), $F\ (1,22) = 13.27$, $p = .001$, $\eta^2_p = 0.376$. The main effect of expertise did not reach significance, $F\ (1,22) = 1.621$, $p = .216$, $\eta^2_p = 0.069$. Also, there was no significant interaction of expertise and single- versus dual-tasking, $F\ (1,22) = 2.167$, $p = .155$, $\eta^2_p = 0.090$. Fig. 2 presents the pattern of findings.

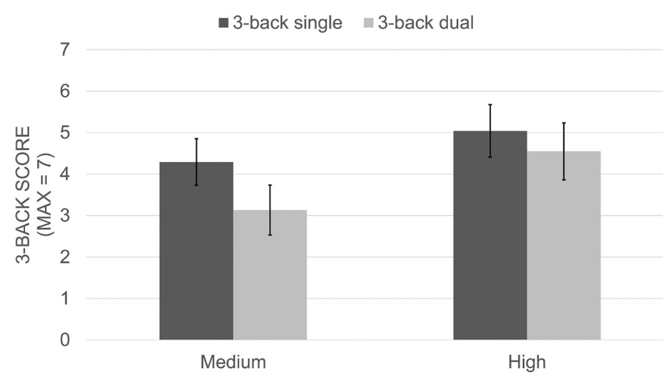

Fig. 2. 3-back single- and dual-task performance for medium and highly skilled players.
Note. Error bars present SE means.

2.2.2. Tennis single- and dual-task performance

Cronbach's Alpha for the 9 trials assessed for the tennis task was high (α = 0.974). Performance scores were averaged across the trials of the respective condition, resulting in mean scores for the 4 single-task trials and the 5 dual-task trials. The ANOVA with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor did not show a significant main effect of single- ($M = 16.64$, $SD = 4.83$) versus dual-tasking ($M = 16.65$, $SD = 5.23$), $F\ (1,22) = 0.003$, $p = .958$, $\eta^2_p < 0.001$. The main effect of expertise did reach significance, showing that experts ($M = 20.42$, $SD = 3.46$) hit the target more often than medium experienced players ($M = 12.87$, $SD = 2.98$), $F\ (1,22) = 32.778$, $p < .001$, $\eta^2_p = 0.598$. The interaction of single- versus dual-tasking and expertise did not reach significance, $F\ (1,22) = 2.265$, $p = .147$, $\eta^2_p = 0.093$. Fig. 3 presents the pattern of findings.

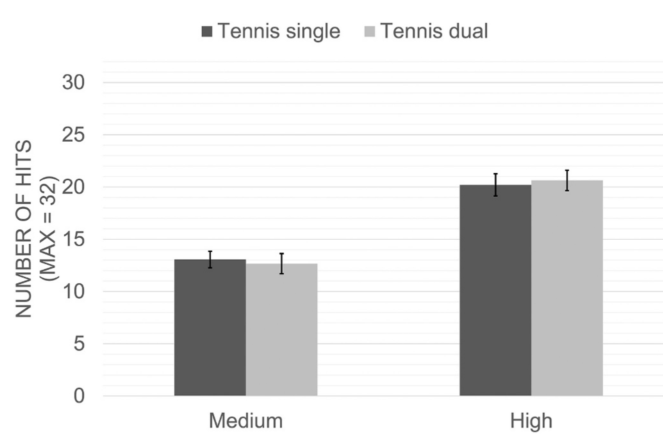

Fig. 3. Tennis single- and dual-task performance for medium and highly skilled players in study 1.
Note. Error bars present SE means.

2.2.3. Dual-task costs

To compare the performance reduction across the motor and the cognitive domain, percentage scores for the dual-task costs have been calculated using the following formula: $\left(\frac{(DT-ST)}{ST}\right)$ x (-100) (see Schaefer, 2014; Somberg & Salthouse, 1982). Fig. 4 depicts the pattern of dual-task costs. Medium level players show rather high variance in costs between both domains (30% to 4%), while experts show less variance (5% to −3%). A mixed-design ANOVA with expertise as between-subjects factor and task (2: tennis or 3-back) as within-subjects factor showed a significant main effect of task domain, $F(1,22) = 7.265$, $p = .013$, $\eta^2_p = 0.248$. In addition, the main effect for expertise was significant, $F(1,22) = 6.840$, $p = .007$, $\eta^2_p = 0.237$. Medium level players showed higher overall dual-task costs ($M = 16.77$, $SD = 16.17$) than experts ($M = 1.08$, $SD = 13.05$). The interaction of task domain and expertise did not reach significance, $F(1,22) = 2.162$, $p = .156$, $\eta^2_p = 0.089$.

2.3. Discussion study 1

In study one, the performance of tennis experts and medium skilled players was compared in a cognitive-motor dual-task, consisting of a tennis and a working memory task. Baseline single-task performance was measured in both task domains, which allows us to compare single- to dual-task performance for both tasks. In addition, participants were instructed to perform as well as possible in both tasks in dual-task situations, enabling us to interpret performance decrements in one task as a strategy of shifting attention to the other.

Our predictions could only be partially supported. Both groups showed performance declines in the 3-back task, while no performance reduction was shown in the tennis task for both groups. Furthermore, experts outperformed the medium skilled players in tennis, which serves as a manipulation check of the tennis task.

The calculation of dual-task costs allows for the comparison across task domains and groups. In the tennis task, experts' and medium skilled players' performance ranged from small benefits (−3%) to small costs (4%) when concurrently working on the 3-back task. Furthermore, medium skilled players showed costs in 3-back of about 30% under dual-tasking, while experts showed costs of only about 5% (see Fig. 4). The analysis revealed that both groups showed higher costs in cognition, but experts showed overall smaller costs than medium skilled players. However, the interaction of group and task domain did not reach significance, possibly due to the rather small sample size.

In the current field-test we were not able to measure reaction times for the 3-back task. Earlier studies conducted in laboratory settings could show that reaction times (RTs) increase, while accuracy is decreasing during dual-tasking (Fraser et al., 2010; Wolkorte et al., 2014). The authors argue that the effect can be attributed to executive control processes that interfere with the execution of the concurrent task. We suspect that this would also apply to our current study, leading to slower RTs in the cognitive task. Since the motor task was externally timed by the frequency of the balls, we assume that RTs in the motor task do not differ between single- and dual-task situations.

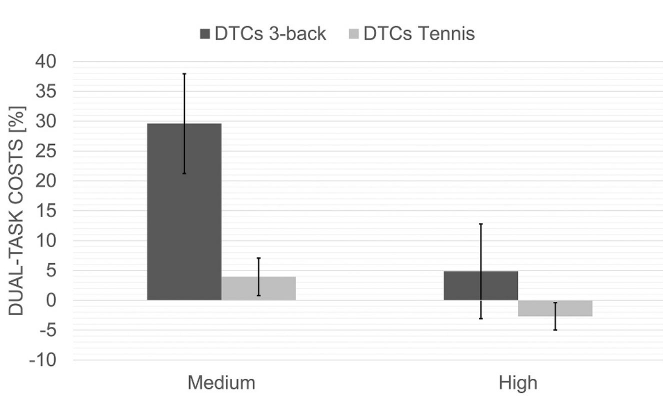

Fig. 4. Dual-task costs in the cognitive and motor domain for medium and highly skilled players.
Note. Error bars present SE means.

Although we expected intermediate players to show performance decrements in both task domains, they only showed performance reductions in cognition, and prioritized the motor domain. Interestingly, experts showed the same type of task prioritization, but were able to keep their cognitive performance almost stable. This finding is in line with theories of motor skill learning which assume that automatized skills don't require cognitive resources, while skills at an earlier learning stage need more attention (Adams, 1971; Fitts & Posner, 1967). Future research may investigate if task-prioritizations are based on explicit decisions. A subjective ranking of perceived task difficulty and invested mental effort could shed light on this question (Paas et al., 1994).

Study 2 investigates whether the findings generalize to a vocabulary task, which also requires attentional resources. We predict that intermediate players will again show higher costs in cognition compared to expert tennis players. The second experiment will use the same tennis task as used in experiment one to increase the comparability between both studies.

3. Study 2

3.1. Method

3.1.1. Participants

We calculated a Power analysis to estimate the required sample size using the G*3 Power software (Faul et al., 2007). The power analysis focused on the interaction effect of expertise group and single- versus dual-task performance decrements, comparable to the analysis of study 1. We assumed the correlation among repeated measures to be high ($r = 0.85$). The analysis indicated that a medium effect size of $f = 0.3$, a significance level of 0.05, and power of 0.95 recommends a total sample size of 14 participants. To take potential differences between the 3-back task and the vocabulary task into account, we tested roughly twice as many participants as estimated by the power calculation.

Study 2 recruited 32 participants from a local tennis sports club. Participants were divided into tennis players with *medium* or *high* expertise in tennis, as described in study 1. See Table 3 for descriptive information. All participants had normal or corrected-to-normal vision and hearing and provided informed consent to participate in the study. As background variable, perceptual speed was measured with the Digit-Symbol Substitution task (Wechsler, 1981) and vocabulary knowledge was measured with the MWT-A (Lehrl et al., 1991) to show that the cognitive skills of both groups are comparable. The study was approved by the Ethics committee of Saarland University.

3.1.2. Experimental tasks

3.1.2.1. Vocabulary learning task. In the Vocabulary learning task participants are asked to encode and repeat word lists containing 10 word-pseudoword pairs each (see also Amico & Schaefer, 2020, for a similar paradigm). In total, 4 different word lists were used in the experiment. The word-pseudoword pairs of a list are presented with an ISI of 9 s via loudspeakers. After perceiving each word-pseudoword pair, participants had to repeat both words aloud to control for memorizing techniques and to make sure that both words were understood acoustically. After all words of a list had been presented, participants performed a retention test of the learned vocabulary. For the retention tests, each pseudoword was presented in a randomized order and the participant had to answer by recalling the corresponding German word. Each correctly recalled word was scored with 1 point. On the following day, all 40 word-

Table 3
Study 2 descriptives, tennis expertise and cognitive background information.

	Medium Expertise	High Expertise	Independent *t*-test
n (males/females)	17 (9/8)	15 (7/8)	
Age (years)			
M	28.5	30	t (30) = 0.662, p = .513
SD	6.9	5.5	
Range	20.8–39.6	21–39.3	
German Tennis Level			
M	20.2	9.4	t (30) = 8.520, p < .001
SD	3.1	4.1	
Range	15–23	1–14	
Tennis experience (years)			
M	13.8	23.1	t (30) = 2.454, p = .02
SD	13.8	5.0	
Weekly tennis (minutes)			
M	143	194	t (30) = 1.549, p = .132
SD	77.6	108.1	
Weekly sport participation (minutes)			
M	278	472	t (30) = 2.921, p = .007
SD	142.5	228.6	
Digit-Symbol Substitution (correct items)			
M	60	66.3	t (30) = 1.397, p = .173
SD	13	12.5	
MWT-A (words)			
M	29.3	30	t (30) = 0.797, p = .432
SD	2.8	2.1	
Experience in foreign languages (years)			
M	14	21	t (30) = 1.656, p = .108
SD	12.4	11.7	

pseudoword pairs were assed via phone call. As before, the experimenter presented the pseudoword and the participant tried to recall the corresponding German word.

3.1.2.2. Tennis returns. The tennis returns were played on a standard outdoor tennis clay court using the playing field of 1 vs. 1 matches. Except for the type of tennis court, the experimental setup was identical to study 1 (see Fig. 1). Also the instruction on how to return the ball was the same as in study 1, except that in study 2, each trial consisted of only 27 balls. This change was made to match the timing of the word pair presentation and the balls during the dual-task trials.

3.1.2.3. Single- and dual-task setting. In the single-task trials, participants performed the vocabulary learning task without any concurrent activity, while standing on the tennis court. During the tennis single-task trials, participants returned the balls from the tennis robot into the target field. In the dual-task trials, participants returned the ball and performed the vocabulary learning task. The balls were always served during the encoding interval of the vocabulary learning task (3 balls with an ISI of 3 s in-between two word-pseudoword pairs). For dual-task trials, participants were instructed to work as well as possible on both tasks. Before starting the first trial of each test block, participants were informed about the upcoming task.

3.1.3. Procedure

The testing took place in a local tennis court in Saarland, Germany. Each session lasted between 60 and 90 min. After the assessment of demographic information (see study 1), the Digit-Symbol Substitution Test and the MWT-A, participants were given 5 min tennis warm-up, followed by two practice trials in the tennis task. Then, participants were instructed in the vocabulary learning task, followed by a practice trial to adjust the volume of the speakers. To control for practice and fatigue effects, single- and dual-task blocks were assessed at multiple time points in an alternating manner: S D S (S = single-task, D = dual-task), with 2 trials of each task in each single-task block and 4 trials in the dual-task block. Participants did not receive feedback on their performance during single- and dual-task blocks. Experimenter 1 scored the vocabulary learning task, while experimenter 2 scored the tennis hits. Table 4 presents an overview of the procedure. The order of the used lists was counterbalanced across all participants to control for possible list effects.

3.1.4. Data analysis

Tennis hits and vocabulary scores were averaged across the respective condition (single- and dual-task). Cronbach's Alpha was calculated to check for the reliability of the tasks. The performances in the tennis task, and both vocabulary retention tests were analyzed with mixed-design analyses of variance (ANOVA) with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor. In addition, dual-task costs were calculated for both task domains, depicting the performance cost as a percentage of each individual's single-task performance. A mixed-design ANOVA with expertise (2: medium or high) as between-subjects factor and task (2: tennis or vocabulary) as within-subjects factor was conducted. F values and partial Eta square values for effect sizes are reported. The alpha level used to interpret statistical significance was $p < .05$.

3.2. Results

3.2.1. Vocabulary single- and dual-task performance of day 1

Cronbach's Alpha for the 8 trials assessed for the vocabulary task was high (α = 0.933). Performance scores were averaged across the trials of the respective condition, resulting in mean scores for the 4 single-task trials and the 4 dual-task trials. The ANOVA with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor showed a significant main effect of single- ($M = 5.05$, $SD = 2.18$) versus dual-tasking ($M = 3.74$, $SD = 2.19$), F (1,30) = 18.150, $p < .001$, $\eta^2_p = 0.377$. The main effect of expertise did not reach significance, F (1,30) = 0.533, $p = .803$, $\eta^2_p = 0.002$. Also, there was no significant interaction of expertise and single- versus dual-tasking, F (1,30) = 0.627, $p = .435$, $\eta^2_p = 0.020$. Fig. 5 presents the pattern of findings.

3.2.2. Vocabulary single- and dual-task performance of day 2

The 40 word-pseudoword pairs measured on day 2 were scored depending on whether they had been encoded under single- or dual-task

Table 4
Experiment 2: overview of the procedure of study 2.

Condition	Trials	Counterbalancing order of word lists	
		Order 1	Order 2
Instruction and Practice	Digit Symbol Test and MWT-A 5 min tennis warm-up Instruction of both tasks and 2 practice trials tennis		
Single-task Block 1	2 trials single-task vocabulary task 2 trials single-task tennis	list 1	list 2
Dual-task Block	2 trials tennis and vocabulary task	list 2	list 1
	2 trials tennis and vocabulary task	list 3	list 4
Single-task Block 2	2 trials single-task vocabulary task 2 trials single-task tennis	list 4	list 3

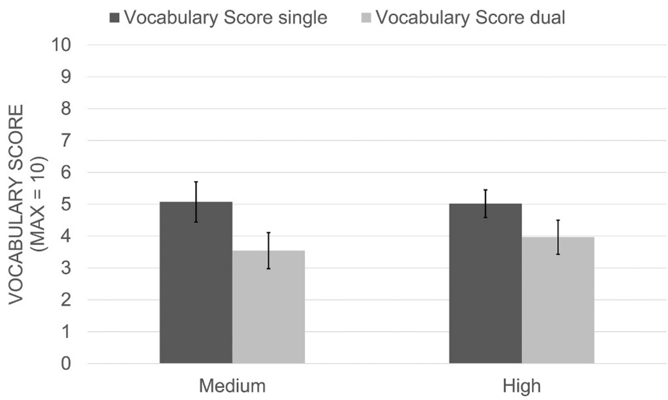

Fig. 5. Vocabulary single- and dual-task performance for medium and highly skilled players.
Note. Error bars present SE means.

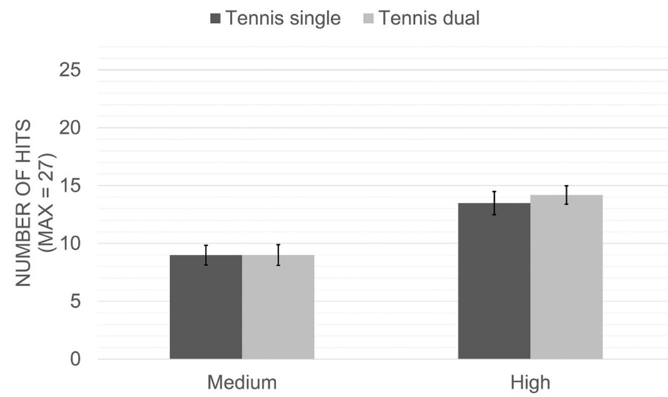

Fig. 7. Tennis single- and dual-task performance for medium and highly skilled players of study 2
Note. Error bars present SE means.

conditions, resulting in a maximum score of 20 for the single- and the dual-task vocabulary performance. The ANOVA with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor showed a significant main effect of single- ($M = 7.41$, $SD = 4.13$) versus dual-tasking ($M = 5.0$, $SD = 4.30$), $F(1,30) = 14.243$, $p = .001$, $\eta^2_p = 0.322$. The main effect of expertise did not reach significance, $F(1,30) = 0.000$, $p = .997$, $\eta^2_p = 0.000$. Also, there was no significant interaction of expertise and single- versus dual-tasking, $F(1,30) = 0.367$, $p = .549$, $\eta^2_p = 0.012$. Fig. 6 presents the pattern of findings.

3.2.3. Tennis single- and dual-task performance

Cronbach's Alpha for the 8 trials assessed for the tennis task was high ($\alpha = 0.950$). Performance scores were averaged across the trials of the respective condition, resulting in mean scores for the 4 single-task trials and the 4 dual-task trials. The ANOVA with expertise (2: medium or high) as between-subjects factor and single- versus dual-tasking (2: single or dual) as within-subjects factor did not show a significant main effect of single- ($M = 11.10$, $SD = 4.29$) versus dual-tasking ($M = 11.43$, $SD = 4.27$), $F(1,30) = 1.041$, $p = .316$, $\eta^2_p = 0.034$. The main effect of expertise did reach significance, showing that experts ($M = 13.83$, $SD = 3.36$) hit the target more often than intermediate players ($M = 8.99$, $SD = 3.46$), $F(1,30) = 15.999$, $p < .001$, $\eta^2_p = 0.348$. The interaction of single- versus dual-tasking and expertise did not reach significance, $F(1,30) = 0.957$, $p = .336$, $\eta^2_p = 0.031$. Fig. 7 presents the pattern of findings.

3.2.4. Dual-task costs

To compare the performance reduction across the motor and the cognitive domain, percentage scores for the dual-task costs have been calculated (see study 1 for details). Fig. 8 depicts the pattern of dual-task costs. High and medium level players both show higher costs in cognition (23% to 29%) and small benefits in the motor domain (−9.4% to −3.6). A mixed-design ANOVA with expertise as between-subjects factor and task (2: tennis or vocabulary) as within-subjects factor showed a significant main effect of task domain, $F(1,30) = 34.793$, $p < .001$, $\eta^2_p = 0.537$. Costs in cognition ($M = 26.14$, $SD = 27.71$) were higher than costs in tennis ($M = -6.35$, $SD = 24.15$). However, the main effect for expertise, $F(1,33) = 0.618$, $p = .438$, $\eta^2_p = 0.020$ and the interaction of task domain and expertise did not reach significance, $F(1,30) = 0.138$, $p = .987$, $\eta^2_p < 0.001$.

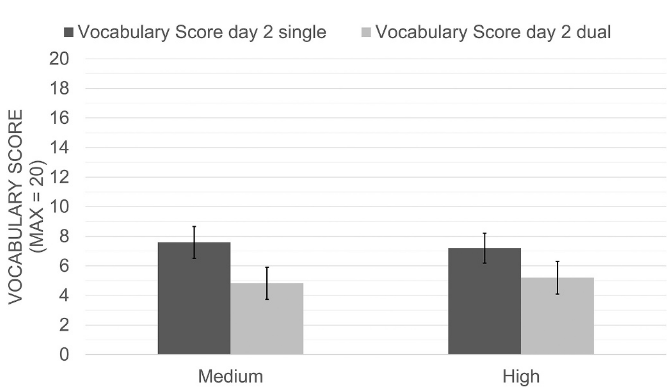

Fig. 6. Vocabulary single- and dual-task performance of day 2 for medium and highly skilled players.
Note. Error bars present SE means.

3.3. Discussion study 2

In study two, tennis experts and medium skilled players were tested in a cognitive-motor dual-task, using a tennis task and a vocabulary encoding task. Baseline single-task performance was measured in both task domains like in study one. Participants were instructed to perform as well as possible in both tasks in the dual-task situations.

Both groups remembered fewer words on the immediate memory recall and on the following day when vocabulary had been encoded during dual-tasking. On the other hand, both groups were able to keep their motor performance stable during dual-tasking. As hypothesized, experts showed higher performance in the tennis task compared to novices, while both groups performed equally in the vocabulary-learning task.

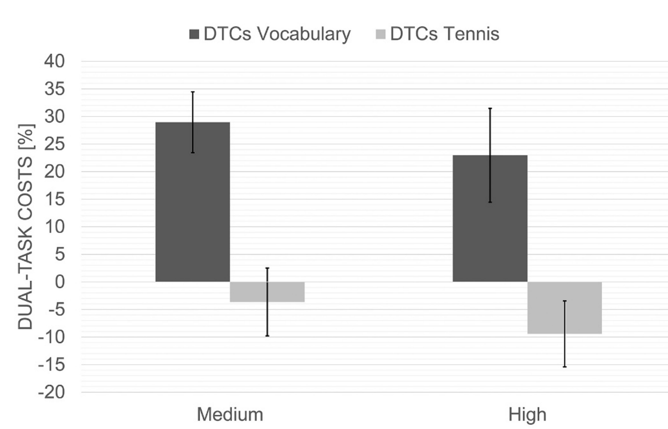

Fig. 8. Dual-task costs in the cognitive and motor domain for medium and highly skilled players of study 2.
Note. Error bars present SE means.

Performance decrements have also been expressed as a percentage score. Both groups showed higher costs in cognition (23% to 29%) and small benefits in the motor domain (−9.4% to −3.6%). We predicted that medium skilled players would show costs in the motor and the cognitive domain, while expert players would be able to keep their performance stable. However, dual-task costs of experts and medium skilled players were comparable. In addition, both groups showed small benefits in the motor domain. It is possible that concentrating on a cognitive task helped to avoid "overthinking" while performing the forehand cross stroke. Studies could show that online monitoring of already well-learned skills can harm the performance (Beilock et al., 2004; Beilock, Wierenga, et al., 2002). Interestingly, even the intermediate skilled tennis players showed small increases in motor performance while dual-tasking. One reason for this may be that the forehand cross stroke is an essential technique and is taught at the very first stages of learning.

The pattern of results is similar for both expertise groups, although experts outperformed medium skilled players in the tennis task. Performance decrements were only observed in the cognitive task. Apparently, returning tennis balls while encoding word pairs harms subsequent memory performances even in highly skilled tennis players.

4. General discussion

In two studies, expert and medium skilled tennis players were confronted with a cognitive-motor dual-task situation. Participants had to return balls into a target field, while concurrently working on a 3-back task (study 1) or while encoding wordpairs (study 2). In both studies, experts outperformed the less skilled players in the tennis task, while both groups performed equally well in the cognitive tasks. In addition, experts and medium skilled players showed higher performance decrements in the cognitive domain and prioritized the motor task, although they had been instructed to perform as well as possible in both tasks in the dual-task situation. Medium skilled players showed higher overall dual-task costs in study one, while both groups showed comparable costs in study two (see the analysis of the main effects of expertise in the dual-task costs ANOVAs).

Differences between the cognitive processes primarily involved in 3-back and vocabulary learning may have contributed to the pattern of findings. Three-back requires constant updating operations (Dobbs & Rule, 1989), and responses are given during the trial. If participants "lose track" of the current numbers during a trial, they can re-start encoding the upcoming stimuli, but such a lapse of attention will most likely result in several missed targets. Apparently, such problems occurred more often in intermediate players, resulting in relatively high cognitive dual-task costs, while experts could keep up their 3-back performance when returning balls from the ball machine. For vocabulary learning, participants most likely silently rehearse the word-pseudoword pairs during the trial, but their recognition performance is only measured afterwards (see also Amico & Schaefer, 2020). Lapses of attention during the encoding phase are more likely to result in only one missed word, but the relatively high cognitive costs for both groups in study 2 indicate that rehearsal and encoding processes suffer from concurrent tennis playing even in highly skilled players. According to Baddeley (2000), 3-back and vocabulary learning both involve the central executive and the phonological loop, but information of 3-back has to be stored only for a short time (about 12 s with an ISI of 3 s), while vocabulary learning is an ongoing process throughout the trial. The phonological loop and the episodic buffer are needed for memory encoding, and they are also needed to access and integrate information in long-term memory (Baddeley, 2000). To successfully encode the word list during dual-tasking, the participant has the option to switch his/her attention between the currently presented wordpair, the previously encoded wordpairs, and the motor task, which could affect strategies of attention allocation (Kahneman, 1973; see also a review about the interactions of attention and memory by Chun & Turk-Browne, 2007).

In general, tasks differ in the range in which performances can change from single- to dual-tasking. Future studies using cognitive-motor dual-tasks should take such differences into account (see also the study by Schaefer and Amico, this issue). In addition, a more detailed assessments of the cognitive task, for example by including measures of reaction time for the 3-back task, can further increase measurement precision in future research. Expert and novice tennis athletes differ in their reaction time and anticipatory skill in a tennis specific task (Singer et al., 1996). The measures of motor performance could also be improved by using targets of different difficulty levels or by including motor tracking systems to reveal differences in the quality of tennis play. Not only hitting accuracy, but also the speed and trajectory of the ball play a substantial role for success in tennis (Kolman et al., 2019). Modern camera systems could measure the variability of hits within the target field and would allow a qualitative analysis of the movement during skill execution, which will increase the chances to find further performance differences between expertise groups in future research.

Both cognitive and tennis tasks elicited results that were far from ceiling or floor effects in single- and dual-tasking. This indicates that task-difficulty level had been adjusted successfully to the current samples. In addition, all tasks could be measured with very high reliabilities, pointing to stable between-person differences in performance levels.

Although there were clear differences between intermediate and expert tennis players concerning their "LK" as well as their tennis performance in both studies, the experts' skill level in study one ($M = 3.8$, $SD = 2.6$) was higher compared to the experts' level in study two ($M = 9.4$, $SD = 4.1$), $t(25) = 4.073$, $p < .001$. This may have contributed to the main effect of expertise in dual-task costs of study 1, which could not be replicated in study 2. It would have been advantageous to use exactly the same participants for both studies, but this was not possible for organizational reasons and due to constraints caused by the Corona pandemic. Previous table tennis studies using the same paradigm (Schaefer & Amico, this issue; Schaefer & Scornaienchi, 2020) compared highly skilled players to novices. Future research should include more than two expertise levels, to reveal the extent to which expertise/experience explains variance in cognitive-motor dual-task performance in different sport settings.

Experts and medium skilled players showed higher performance decrements in the cognitive domain, while they kept their performance in the motor domain stable. We interpret this result as a prioritization strategy towards the motor task. Future studies should investigate how task prioritization is affected by the difficulty levels of the tasks. Participants usually invest more mental effort when task difficulty is increased (Norman & Bobrow, 1975). However, it appears plausible that participants invest more attention to tasks of high difficulty only as long as they subjectively asses the task to be solvable, but they may switch their attention to the other task when one task is perceived as too difficult. Performance decrements due to task difficulty can be divided into two categories: *resource limitation* refers to decrements due to insufficient invested mental effort (e.g. low motivation or interference with concurrent tasks), while *data limitation* is bound to the testing material and cannot be compensated for by additional effort (Navon & Gopher, 1979; Norman & Bobrow, 1975). To assess mental effort, physiological markers of invested effort like heart rate variability, electrodermal activity (EDA), electroencephalography (EEG), and electrooculography (EOG) (Paas et al., 2003; Vanneste et al., 2021; Veltman & Gaillard, 1998) may be added to future study designs.

Another possible explanation for the prioritization of the motor task in the current study could be that the affordance to react to ball that is flying towards somebody is higher than the affordance to verbally reply to an acoustic signal. The Gibsonian view on affordances would suggest that perceiving a ball flying towards you would activate a strong impulse to use the racket to interact with the ball, independently from previous intentions to act (Borghi & Riggio, 2015; Gibson, 1979). Thus, it may even be a challenging cognitive task to refrain from hitting the ball, whereas missing the auditory information in the 3-back task or the vocabulary-learning task may just be the result of the relatively lower affordance of the cognitive task. This view could also explain results of other studies where participants failed to voluntarily prioritize the cognitive over the motor task (Schaefer, 2014; Schaefer et al., 2008).

Future studies should also include differential-emphasis instructions, by asking participants to focus more on one task than the other under dual-task conditions (Li et al., 2005). It is possible that experts are better in switching their attention between both task domains. Based on models of motor skill learning (Adams, 1971; Fitts & Posner, 1967; Furley et al., 2015; Gentile, 1972), the motor performance of novices should profit from focusing their attention on the motor task. For experts, however, focusing on an already automatized motor skill has been shown to impair motor performance, while focusing on a secondary task can lead to performance increases (see Beilock et al., 2004; Beilock, Wierenga, et al., 2002). The ability to focus and to resist harmful distractions like noise, anxiety, or a stadium full of spectators can make the difference between winning and losing (see Furley & Wood, 2016, for a review).

Furthermore, future studies should use training regimes that include single- and dual-task trials of both task domains across the learning process. Based on various theories of motor skill learning (Adams, 1971; Fitts & Posner, 1967; Gentile, 1972), we would expect dual-task costs to be progressively reduced with increasing motor skill level. In this context, a study by Singer et al. (1994) could show that the anticipatory skills of intermediate tennis players could be trained within a 3-week training regime. Additionally, Rowe and McKenna (2001) demonstrated that expert tennis players show reduced dual-task costs compared to novices in a tennis related anticipatory task. Future studies should investigate how task specific cognitive skills develop alongside the motor skills and if these components consume cognitive resources to varying degrees.

Tennis performance is a complex construct that involves motor skills, but also cognitive skills like anticipation and decision making. In the current study, the tennis task used was to return balls into a fixed target field while always using a forehand cross stroke, which reduced cognitive components of the tennis performance. In a real tennis match, athletes have to permanently switch between different techniques and have to decide between plenty of options. However, experts do outperform novices not only in the quality of the motor skill, but also in sports specific cognitive components (Kolman et al., 2019; Rowe & McKenna, 2001). Therefore, experts should show smaller increases in costs when tennis specific cognitive components are increased (e.g. flexibly decide between forehand and backhand or between slice and topspin) compared to when non-tennis specific cognitive components are increased (e.g. difficulty of the secondary cognitive task). Instead, novices should show equal increases in costs, regardless of whether the difficulty of the tennis specific or non-specific task is increased. It would be interesting to use cognitive tasks that are more closely related to cognitive processes going on during a tennis match, like e.g. visual choice reaction time tasks. In a real tennis match, the player always has to monitor his own and his opponents' position to anticipate the best option to return the ball. Therefore, we would expect higher dual-task costs for a concurrent visual choice reaction time task.

Dual-task training paradigms could be a well-suited addition to existing training regimes in early tennis education. Especially cognitive aspects of tennis play could profit from cognitive-motor dual-task training, as studies could show improvements in various executive functions like task switching, inhibition, and updating following systematic training in early childhood (Li et al., 2020; Schmidt et al., 2020; Veldman et al., 2020).

In conclusion, the current study could replicate the findings of recent cognitive-motor dual-tasking studies, showing that less skilled players show higher dual-task costs than experts (study 1). In addition, we could show that the effects can be generalized to the tennis sport by using a new tennis specific motor task. Both groups showed higher costs in cognition, while keeping their motor performance stable. Another aim of the current study was to compare two different cognitive tasks regarding their effect on tennis-specific dual-task situations. The results showed that performance in both cognitive tasks is reduced during dual tasking. We argue that an athlete's ability to keep up motor and cognitive performances in dual-task situations in sporting contexts may be a valuable indicator of their overall performance level, over and above "pure" performances of motor or cognitive tasks under single-task conditions.

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Data availability statement

Data to this article will be shared upon request to the corresponding author.

Author contributions

SS developed the study design. GA and SS contributed equally to the literature overview. GA analyzed and interpreted the data with contribution from SS. GA led the writing and draft of the manuscript with support from SS.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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