Journal of Human Kinetics volume 25 2010, 5-15
Section I – Kinesiology
DOI 10.2478/v10078-010-0026-1

Dual-task Practice of Temporally Structured Movement Sequences Augments Integrated Task Processing, but not Automatization

by

Klaus Blischke[1], Florian Wagner[1], Barbara Zehren[1], Sebastian Brueckner[2]

After initial learning, a one-finger key stroke sequence, defined by a specific relative timing pattern (temporal structure) and absolute total movement time (temporal parameter), was practiced (with KR provided) either under dual-task conditions (experimental group), or under single-task conditions (control group). During dual-task practice, the key stroke sequence (i.e., the primary-task) was always executed in parallel to one of two cognitively demanding secondary tasks (subtracting numbers, or sorting marbles). Secondary tasks were alternated every 20 practice trials. Before (Pre-test) and after practice (Post-test), performance in each group was assessed under single-task and under dual-task conditions (no KR during tests). From Pre- to Post-test, primary-task performance in both groups significantly increased (relative timing in particular). Also, after practice dual-task costs found during Pre-test in both groups were still prevalent in the control group, but completely vanished in the experimental group with respect to those task combinations that were practiced before. However, when a new secondary task (repeating letters) was introduced, dual-task costs fully reappeared in the experimental group with respect to relative timing of the key stroke sequence. These results contradict the notion of readily acquiring automatic control in the course of dual-task practice by "Structural Displacement" (Blischke & Reiter, 2002), but they are well in line with the concept of developing cognitive strategies for "Integrated Task Processing" (Manzey, 1993). Thus, impact of dual-task practice on motor sequence production may be different from that on motor parameter control. In this context, implications of recent findings from neuropsychology on cortical systems engaged in the pursuit of concurrent behavioural goals (cf. Charron & Koechlin, 2010) are discussed.

Key words: sequence learning; multitasking behaviors; cognitive vs. automatic control

Introduction

Even though different phase models of motor skill learning exist, they all agree on the fact that with sufficient practice, movements initially under cognitive control will eventually become automatized (Müller & Blischke, 2009). Examples from everyday life include gear shifting and simultaneously operating the clutch while driving a car, complex finger-movement sequences in playing musical instruments, specific swimming techniques, or a tennis-serve. Planning and execution of such originally "voluntary" movements, although still dependent on the general intention to act, eventually happens mostly on an unconscious level and almost without any effort. Automatized skills in particular do not require detailed attention any more, and thus, reduce processing demands on working memory considerably. In addition, they cannot be easily disturbed, which is also expressed by the absence of performance decrements usually observed in dual-task situations. Therefore, in experimental research, reduction or elimination of dual-task costs is generally considered as evidence of an increase in automaticity.

[1] - *Saarland University, Institute of Sport Science, P.O. Box 15-11-50, 66041 Saarbruecken, Germany*
[2] - *Olympic Training Center Rheinland-Pfalz/Saarland, Hermann Neuberger Sportschule 2, 66123 Saarbruecken, Germany*

Authors submitted their contribution of the article to the editorial board.
Accepted for pinting in Journal of Human Kinetics vol. 25/2010 on July 2010.

Movement automatization by single-task practice

Depending on the nature of the task and the practice conditions involved, different theoretical models of how movement automatization occurs are presently discussed (cf. Blischke, 2000; Müller & Blischke, 2009). For example, Blischke (2001) was able to find evidence for automatization of a certain movement *parameter* in a gross motor skill (bipedal counter movement jump, CMJ). In this ballistic task, precise and reliable reproduction of a sub-maximal force impulse was required. Dual-task costs initially observable when the CMJ was performed in parallel with auditory-manual choice reaction time probes (CRT) required at randomly selected instances shortly before and during movement execution, completely disappeared after extensive practise under single-task conditions (STC). Moreover, dual-task costs did *not* reappear even when a *new* secondary-task was introduced in the dual-task condition (DTC). This new task was associated with a high cognitive workload, and was not encountered by the subjects in this study before (i.e., subtracting numbers visually presented, and vocally reporting the respective results; SUBTR). The same held true when all three tasks (i.e., CMJ, CRT, and SUBTR) were performed simultaneously.

At that time, Blischke (2001) explained these results by a change in the mode of control, caused by gradually shifting operations of movement planning and executive control from a cognitive level of processing mechanisms and its underlying central nervous structures towards another, non-cognitive and more basic level (i.e., automatization by "*structural displacement*" (SDP); Heuer, 1984). For a comprehensive paper on recent neuroanatomical findings supporting this notion with respect to the motor skill domain, see Doyon, Bellec, Amsel, Penhune et al. (2009). According to this model (SDP), the cognitive level should be responsible for detecting informational structures and establishing new stimulus-response associations, thus permanently trying to integrate all the different strands of incoming information. The non-cognitive level(s), on the other hand, is/are thought to be organized in a modular fashion, each module dealing with already well-established stimulus-response associations, which are specific for each module with respect to modality and/or processing code (cf. Keele, Ivry, Mayr, Hazeltine & Heuer, 2003; Müller & Blischke, 2009). Because the cognitive system is essentially integrative in nature, two tasks being processed in parallel will easily interfere with each other, while the same two tasks processed by different modules of the non-cognitive system will neither interfere with each other, nor with anything else processed simultaneously by the cognitive system.

Dual-task practice: Integrated task processing or structural displacement?

Using the same criterion-task applied by Blischke (2001), and single reaction time (SRT), as well as choice reaction time probes (CRT) for secondary tasks, in a follow-up study Blischke and Reiter (2002) replicated the above findings. Looking at the results of this important follow-up study, the authors could, at least for this specific motor task, rule out an alternative explanation of dual-task cost reduction in the course of practice. The concept in question, known as "*integrated task processing*" (ITP), has been advocated by Manzey (1988; 1993), and was corroborated by the same author using perceptual-cognitive and motor tasks of several minutes' length. According to the ITP concept, reduction of dual-task costs is inescapably linked to practicing primary- and secondary-tasks simultaneously. As Manzey argues, this allows subjects to functionally uncouple the two tasks to be processed in parallel. At the same time, they are able to circumvent structural conflicts in the central processing stage (e.g., task prioritization with respect to response-selection/initiation; cf. Pashler & Johnston, 1998) by developing appropriate strategies of task-switching and internal grouping of events. However, according to Manzey, automatization of task control in the same sense as defined above, does not take place, because the ITP strategies are always *specific* to the very task combination being practiced simultaneously. Strategies of integrated task processing cannot be "taken along" in case one of the two tasks practiced simultaneously before is transferred to another, new dual-task context. In this case, dual-task costs reduced through dual-task practice before ought to reappear to their full extent.

However, contrary to these predictions arising from Manzey's ITP-concept, results from the study by Blischke and Reiter (2002) showed that dual-task costs still clearly present in the short, ballistic CMJ-task after termination of the first stage of dual-task practice (i.e., CMJ-task plus SRT-task), were completely eliminated, when a new, more difficult secondary task (the CRT-task) was introduced. While this result is well in line with the notion of structural displacement, it contradicts the concept of integrated task processing. At the same time, the amount of practice necessary to eliminate dual-task costs in this experiment by practice under DTC (240 trials), turned out to be considerably smaller than the number of practice trials required under STC (2400 to 3200 trials) in the study by Blischke (2001).

Dual-task practice and automatization of motor sequences

This raises the question, if dual-task practice, *in general,* might be suitable for reducing the typically inordinate numbers of repetitions required to effectively reach automaticity in motor skills. It is, moreover, of particular interest, if dual-task practice is also effective in the automatization of *structural* features of motor skills. The structure or "*pattern*" of a movement may be defined by certain spatio-topological features, by the type and sequence of the different elementary movements forming the skill at hand, and/or by the invariant temporal relations of those elementary movements (i.e., their relative timing). Handwriting, for instance, comprises all of these components. Many skills in sports, in the vocational domain, and in every-day activities are actually determined by invariant sequential patterns, which make them an important field of application for automatization routines. Thus, the purpose of the present study was to examine the generalizability of automatization of movement *sequences* by dual-task practice.

In a first attempt to answer this question, Blischke, Zehren, Utter and Brueckner (in press) had two groups of subjects practice a temporally structured one-finger key-stroke sequence (KSS) under dual-task conditions. One group performed the KSS in parallel with a number calculation task (the SUBTR task), and the other did so simultaneously to sorting marbles with the other hand (the SORT task). After 800 practice trials, dual-task costs initially present in both groups had completely disappeared. However, they re-emerged (especially with respect to the relative timing of the KSS), during a final retention test, when the experimental group was either switched to the other group's secondary task, or when a new secondary task (repeating numbers, the N-Back task) was introduced. While, according to Manzey's ITP-concept, these results can be accounted for by integrated task processing, they clearly speak against any automatization of the KSS on account of structural displacement (SDP).

However, certain methodological features inherent in this recent experiment may have biased subjects to develop ITP, than to allow for SDP: In the KSS, keeping to a specific relative timing and simultaneously controlling for total movement time may involve less "motor" functions than force production in the CMJ, thus causing the cognitive system to actively supervise the "time-counting" process for each inter-tap interval as long as it possibly could. Considering this, practicing the KSS routinely (i.e., for 800 trials) in one consistent DTC, may provide just the amount of context-regularity necessary for our subjects to gradually work out the appropriate cognitive strategies of ITP. Following this line of reasoning, a drastic increase in the general level of chance and uncertainty in the stream of up-coming events in the DTC, then should disrupt consolidation of any task-switching or grouping strategy specific to a certain task combination, thus effectively preventing subjects from establishing any regular routines of ITP.

The present study: rationale and design

The present study was designed to test exactly this assumption. By alternating two different secondary-tasks every 20 trials in the dual-task practice condition, and thus, increasing context-uncertainty considerably, ITP should be largely suppressed in participants subjected to this experimental condition. If this measure was successful, at the end of dual-task practice, any dual-task costs initially present should either be eliminated and stay absent even when a third, new secondary-task is introduced, or they should still be present even in those dual-task conditions that were practiced before. The first of these two possible outcomes, then, could be taken as proof for SDP. The second alternative, however, would seriously challenge the idea of relative timing in movement production being amenable to automatization at all. In order not to obscure any possible experimental findings following this increase in context-uncertainty by simultaneously changing other experimental variables, all secondary-tasks implemented in the study presented here were identical to those used in the previous experiment. This allowed for direct comparison of the results of both studies. Also, the present study incorporated a single-task practice group, thus providing a baseline-measure of dual-task cost reduction in the KSS under different practice conditions.

Kinesiology

Method

Subjects

Fifteen women and 13 men, aged 19 to 37 years (*M* = 24.6; *SD* = ± 2.6) participated in this study. Of these, three subjects were left-handed. All 28 subjects were naïve with respect to the criterion task. Subjects were randomly assigned to an experimental group (EG; n = 14) and to a control group (CG; n = 14).

Tasks and Apparatus

Primary task: The *primary task* in this experiment was a temporally structured *key stroke sequence* (KSS; visual-manual), performed on the square number-field of a regular computer key board. Starting from a waiting position following a visual "go"-signal, four number keys (2, 4, 8 6) had to be pressed, one after another, with the index finger of the non-dominant hand. Subjects then immediately returned their finger to the waiting position. The number-field was displayed on a computer screen, with the next key to be pressed always highlighted until the action was executed. A trial was completed only after all four number keys were pressed in the correct order. After one trial was finished, the "go"-signal for the subsequent trial always followed three seconds later. There were two learning criteria: the required *Total Movement Time* (TMT) of 2400 ms, and the *Temporal Pattern* (TP) of the sequence, which was defined by the three inter-stroke intervals amounting to 10%, 30%, and 60%, respectively, of the actual over-all duration of the sequence. Dependent measures (DM) were total *Percentage of Deviation* (PD [%]) from the TP-criterion (calculated as the sum of absolute deviations from each interval criterion %-value per trial), and *Absolute Error* (AE [ms]) with respect to the TMT-criterion. Subjects were instructed to give equal priority to both learning criteria throughout the experiment. In feedback conditions, KR was provided visually after every other trial. KR consisted of two horizontal bars, each divided into three differently coloured segments. The information was presented on the screen below the number-field display. The top bar always represented the previous trial with respect to TMT (overall length of bar) and TP (relative length of its three segments), while the bottom bar represented the respective target values. The software for primary task presentation and data acquisition was implemented on a PC 486 equipped with a Windows-98 operating system.

Secondary tasks: Three different *secondary tasks* were incorporated: subtracting numbers (SUBTR; auditory-vocal), sorting marbles (SORT; tactile-manual), and repeating letters (N-Back; auditory-vocal).

- In the SUBTR task, subjects were acoustically presented with pairs of two-digit numbers in a random order. Numbers in each pair were announced one second apart, each pair of numbers followed by a three second pause. Numbers ranged from 10 to 99, the first in a pair always being the larger one. However, numbers in each pair were never spaced more than nine figures apart. Subjects had to quietly subtract the numbers in each pair, and call out either "Ja" ("yes") when the difference was ≥ 5, or "Nein" ("no") when it was < 5. A (wrong) answer could be corrected within the three-second interval. As DM, frequency [h] of incorrect decisions plus omissions was registered.
- In the SORT task, marbles of different size and material (small/glass; medium/rubber; large/wood) were selected at random by the experimenter and placed into a bowl, one by one, every three seconds. Subjects then picked up each marble with their dominant hand and placed it into one of three assigned target-bowls according to its characteristics. All bowls were precluded form subjects' sight by a dividing screen. As a DM, the number [h] of marbles placed in the wrong bowl was registered for each subject.
- The N-Back task is a continuously delayed response task (CDRT): From a continuous stream of letters presented auditorily, subjects were to vocally repeat always the second last letter, as soon as they heard a new letter being announced ("1-back-task"). Following a vocal start signal, letters were presented every three seconds by a computer. The 26 letters of the German alphabet were arranged into random samplings ("lists"). Whenever one list was completed, or a wrong letter was called out, a new list was presented. Again, frequency of errors plus omissions [h] was registered as DM.

Both the SUBTR and the N-Back secondary tasks differed from the KSS task (i.e., the primary task) in all dimensions relevant to information processing (i.e., stimulus modality: auditory vs. visual; processing code: verbal vs. (spatio)-temporal; response modality: vocal vs. manual). Therefore, any dual-task interferences observed for the above mentioned task pairings may be attributed to conflicts arising in the domain of generic central processing stages (namely response selection and response initiation), if and as long as both primary and secondary tasks are under cognitive control (Wickens, 2008). However, the SORT secondary task and the KSS task share the same manual response modality, which allows for additional, effector-specific conflicts ("response code overlap"; cf. Koch, 2009). This kind of structural interference is assumed to be peripheral rather than central in nature, and may possibly not be eliminated, even by extensive practice (Heuer, 1995).

Design and Procedure

On day 1, after having been familiarized with task-specific requirements, procedures and the apparatus, subjects performed one block of ten trials for the KSS task (TP: 10%, 30%, 60%; TMT: 2400 ms) in a single-task condition (STC) with KR provided on every second trial ("initial learning"). Then, after a ten-minute pause, subjects underwent a *Pre-test*. This consisted of one block of 20 trials of the KSS task in STC (no KR), followed by two blocks of 20 trials each in dual-task condition (DTC; no KR), one comprised of the KSS and SUBTR tasks (DTC_{SUBTR}), the other comprised of the KSS and SORT tasks (DTC_{SORT}), respectively. The sequence of DTC-blocks was counterbalanced across subjects in each group with respect to type of secondary task. The Pre-test was finished by two more blocks of 20 trials each of the SUBTR-task and the SORT-task, now under STC (no KR). Every two trial-blocks were separated by a five minute break.

After ten more minutes subjects started practicing the KSS in four consecutive blocks of 100 trials each (KR provided; ten-minute break between block two and three). While the CG practiced the criterion task under STC, the EG was subjected to dual-task practice, with secondary-tasks (SUBTR and SORT) changing every 20 trials. On the next day (day 2), both groups practiced the KSS for another 400 trials following the same procedure. 24 hrs later, on day 3, subjects underwent the *Post-test*. Here, subjects first performed two blocks of 20 trials each (no KR) in the DTC_{SUBTR} and the DTC_{SORT} (order counterbalanced again across subjects in either group), followed by another block of 20 trials (no KR) that consisted of the KSS and the N-Back task in a new dual-task context (DTC_{NB}). Finally, four STC-blocks of 20 trials each (no KR) were executed in the KSS, the SUBTR, the SORT, and the N-Back task. For all DTCs subjects were urged to give equal emphasis to both the primary and the secondary task.

Statistics

For inferential statistics, One-way, Two-way, and Three-way ANOVAs were run. Whenever repeated measures factors were incorporated, in case of violation of the sphericity assumption, *df*-correction according to Huynh-Feldt was applied. There were neither missing values in our data, nor any necessity to correct for outliers. A significance level of $p < .05$ was used for all inferential statistics. All calculations were conducted with SPSS-PC, version 15.0.

Results

Primary task: temporal pattern (TP)

Initial situation: As for the TP (i.e., the structural component of the primary task), initial learning (KR provided) yielded similar results in both groups (EG: *M* = 27.70, *SD* = 11.98; CG: *M* = 26.18, *SD* = 6.55). With respect to Pre-test data (no KR; see Table 1), a repeated measures 2 x 3 ANOVA ("between"-subjects factor "Group"[EG; CG], "within"-subjects factor "Test condition" [STC; DTCSUBTR; DTCSORT]) was calculated. Here, only the main effect "Test condition" reached level of significance ($F_{[\text{"Test cond"}]}(2, 52) = 23.057$, $p < .0005$, $\eta^2_p = .470$), while both EG and CG did not differ in any respect ($F_{[\text{"Group"}]}(1, 26) = .227$, $p = .637$; $F_{[\text{"Group" x "Test cond"}]}(2, 52) = .126$, $p = .882$). As can be inferred from within-subjects comparisons, both dual-task conditions yielded significant dual-task costs during Pre-test, however at a different order of magnitude ($F_{STC:DTCSUBTR\ [\text{"Test cond"}]}(1, 26) = 15.570$, $p = .001$, $\eta^2_p = .375$; $F_{STC:DTCSORT\ [\text{"Test cond"}]}(1, 26) = 69.533$, $p < .0005$, $\eta^2_p = .728$).

Changes in performance: Under No-KR conditions, performance in each group improved significantly from Pre- to Post-test, as results of a repeated measures 2 x 3 ANOVA ("within"-subjects factors "Test" [PRE-T; POST-T], and "Test condition" [STC; DTCSUBTR; DTCSORT]), calculated for each group separately indicated ($F_{EG\ [\text{"Test"}]}(1, 13) = 26.892$, $p < .0005$, $\eta^2_p = .674$; $F_{CG\ [\text{"Test"}]}(1, 13) = 129.788$, $p < .0005$, $\eta^2_p = .909$). In the EG, relative changes in performance were greater in each DTC than in the STC ($F_{EG\ [\text{"Test" x "Test cond"}]}(2, 26) = 8.571$, $p = .001$, $\eta^2_p = .397$). In the CG, this effect was observed

Kinesiology

Table 1

Primary task performance measures: PD from criterion-TP of key-stroke sequence [%]

Practice condition (KR provided)	Test condition (No KR)	Pre-test *M*	Pre-test *SD*	Post-test *M*	Post-test *SD*
EG	STC	23.44	(12.27)	11.00	(4.00)
Dual-task practice with alternating	DTCsubtr	30.21	(15.91)	11.59	(4.22)
secondary tasks:	DTCsort	32.47	(12.99)	11.35	(4.52)
Subtracting numbers; Sorting marbles	DTCnb	---		13.96	(5.56)
	STC	21.52	(6.25)	8.26	(3.82)
CG	DTCsubtr	27.75	(7.25)	13.31	(7.41)
Single-task practice	DTCsort	31.42	(7.31)	13.21	(7.09)
	DTCnb	---		14.81	(6.88)

Annotations: Reported are group means and standard deviations (in parentheses) of the dependent measure TP ("Temporal pattern") in the key-stroke sequence (KSS) for each test series. EG: Experimental group [n = 14; practice of criterion task under dual-task condition with two different secondary tasks ("Subtracting numbers"; "Sorting marbles") alternating every 20 trials]. CG: Control group [n = 14; practice of criterion task under single-task condition]. STC: Single-task condition. DTCsubtr: Dual-task condition, secondary task "Subtracting numbers". DTCsort: Dual-task condition, secondary task "Sorting marbles". DTCnb: Dual-task condition, secondary task "N-Back" = Repeating letters. PD: Percentage of deviation from the TP-criterion, calculated as the sum of absolute deviations from each inter-tap interval criterion value [%] per trial. Pre-test and Post-test: 20 trials per subject in each test condition.

only for DTCsort, but not for DTCsubtr; thus, the interaction in this group did not reach significance ($F_{CG\ [\text{"Test"} \times \text{"Test cond"}]}$ (2, 16.65) = 3.273, p = .080, η^2_p = .201). As shown by an additional 2 x 2 ANOVA ("between"-subjects factor "Group" [EG; CG], "within"-subjects factor "Test" [PRE-T; POST-T]) calculated for the "STC"-data only, "pure" learning (i.e., improvement under No-KR STC) was statistically relevant and equal in size in both groups, although treatment conditions differed ($F_{[\text{"Group"}]}$ (1, 26) = .995, p = .328; $F_{[\text{"Test"}]}$ (1, 26) = 68.964, p < .0005, η^2_p = .726; $F_{[\text{"Group"} \times \text{"Test"}]}$ (1, 26) = .069, p = .795).

Change of dual-task context: With respect to the Post-test data (Table 2) "within"-subjects factor "Test condition" [STC; DTCSUBTR; DTCSORT; DTCNB], repeated measures One-way ANOVAs were calculated for each group separately, just missing statistical significance for the EG, but yielding clearly significant results for the CG (F_{EG} (3, 39) = 2.739, p = .056; F_{CG} (3, 39) = 5.471, p = .003, η^2_p = .296). As within-subjects comparisons for the CG-data show, despite overall improvements in performance after single task practice with KR, all Post-test No-KR dual-task conditions still rendered dual-task costs as compared to the No-KR single-task baseline condition (CG: $F_{STC:DTCSUBTR}$ (1, 13) = 10.975, p = .006, η^2_p = .458; $F_{STC:DTCSORT}$ (1, 13) = 11.316, p = .005, η^2_p = .465; $F_{STC:DTCNB}$ (1, 13) = 13.866, p = .003, η^2_p = .516). For the EG, in the Post-test data, statistically significant dual-task costs emerged only for the newly introduced dual-task context (i.e., secondary-task "N-Back"), while performance in those No-KR dual-task conditions, which were practiced before (with KR provided), did not differ from baseline measures (i.e., No-KR STC) any longer (EG: $F_{STC:DTCSUBTR}$ (1, 13) = .446, p = .516; $F_{STC:DTCSORT}$ (1, 13) = .090, p = .769; $F_{STC:DTCNB}$ (1, 13) = 11.275, p = .005, η^2_p = .464).

Thus, with respect to the PD from TP-criterion, dual-task costs found initially in both groups during Pre-test (No-KR condition), when the key-stroke sequence was carried out in parallel with either number subtraction or sorting marbles, were still observable after extensive single-task practice (with KR) during Post-test (No-KR condition) in the CG, but completely disappeared in the EG after extensive dual-task practice of both task combinations (with KR). At the same time, introduction of a *new* cognitive secondary task during Post-test caused significant dual-task costs in both groups.

Table 2

Primary task performance measures: AE with respect to TMT-criterion of KSS [ms]

Practice condition (KR provided)	Test condition (No KR)	Pre-test *M*	Pre-test *SD*	Post-test *M*	Post-test *SD*
EG Dual-task practice with alternating secondary tasks: Subtracting numbers; Sorting marbles	STC	437.37	(281.51)	391.95	(299.16)
	DTC_{SUBTR}	552.83	(237.45)	370.61	(182.43)
	DTC_{SORT}	517.21	(170.25)	229.33	(77.43)
	DTC_{NB}	---		421.80	(199.41)
CG Single-task practice	STC	281.22	(111.87)	191.07	(93.62)
	DTC_{SUBTR}	455.24	(173.03)	263.46	(119.16)
	DTC_{SORT}	505.70	(236.63)	315.89	(153.67)
	DTC_{NB}	---		367.41	(147.02)

Annotations: Reported are group means and standard deviations (in parentheses) of the dependent measure TMT ("Total movement time") in the key-stroke sequence (KSS) for each test series. AE: Absolute error relative to the TMT-criterion [ms]. All other abbreviations are identical to those in Table 1.

Primary task: total movement time (TMT)

Regarding TMT (i.e., the parameter component of the primary task), initial learning (KR provided) again yielded similar results in both groups (EG: M = 300.45, SD = 128.89; CG: M = 345.59, SD = 104.48). With respect to the Pre-test – Post-test data (no KR), however, statistical outcomes related to TMT deviate from the TP-results in two respects (Table 2): First, TMT performance in the No-KR STC ("pure" learning) improves from Pre-test to Post-test in the CG (F (1, 13) = 11.561, p = .005, η^2_p = .471), but not in the EG (F (1, 13) = .265, p = .615). Second, while in the CG, Post-test comparison of TMT data across the four different test conditions (STC; DTC_{SUBTR}; DTC_{SORT}; DTC_{NB}) again revealed significant dual-task costs for all three DTC (CG: $F_{STC:DTCSUBTR}$ (1, 13) = 5.840, p = .031, η^2_p = .310; $F_{STC:DTCSORT}$ (1, 13) = 10.021, p = .007, η^2_p = .436; $F_{STC:DTCNB}$ (1, 13) = 17.846, p = .001, η^2_p = .579), this was not the case in the EG. Here, TMT error not only decreased to (DTC_{SUBTR}) or below the level of STC (DTC_{SORT}) from Pre- to Post-test in the two dual-task conditions practiced before, but *did not increase again* when a new secondary task was introduced in the DTC_{NB}. (EG: $F_{STC:DTCSUBTR}$ (1, 13) = .068, p = .798; $F_{STC:DTCSORT}$ (1, 13) = 6.210, p = .027; $F_{STC:DTCNB}$ (1, 13) = .111, p = .744).

Secondary tasks

Performance data of the three *secondary tasks* (SUBTR: subtracting numbers; SORT: sorting marbles; N-Back: repeating letters) are reported in Table 3. Pre-test secondary-task data was subjected to a 2 x 2 x 2 ANOVA (factors "Group"[EG; CG], "Secondary task"[SUBTR; SORT], and "Test condition"[STC; DTC]). Here, only the repeated measures main effect "Test condition" reached level of significance ($F_{[\text{"Test cond"}]}$ (1, 26) = 15.721, p = .001, η^2_p = .377), while both EG and CG did not differ in any respect ($F_{[\text{"Group"}]}$ (1, 26) = .003, p = .959; $F_{[\text{"Group" x "Test cond"}]}$ (1, 26) = .036, p = .852). These dual-task costs with respect to secondary task performance completely carried over to Post-test in the CG, as a 3 (secondary tasks) x 2 (test conditions) ANOVA calculated for the Post-test secondary task data of that group indicated ($F_{CG\ [\text{"Test cond"}]}$ (1, 13) = 9.924, p = .008, η^2_p = .433; no further significant results). In the EG, the same 3 x 2 ANOVA yielded significant results for both the main effect "Test condition," as well as for the interaction ($F_{EG\ [\text{"Test cond"}]}$ (1, 13) = 6.783, p = .022, η^2_p = .343; $F_{EG\ [\text{"SecTask" x "Test cond"}]}$ (2, 1.617) = 4.975, p = .022, η^2_p = .277). As the respective between-subjects comparisons confirmed, in this case dual-tasking provoked performance deteriorations during Post-test, only for the newly applied N-Back task, but not for those that were practiced before in parallel to the key-pressing sequence.

Table 3

Secondary task performance measures: Error frequencies [h]

Practice condition (KR provided)	Secondary Task	Tests (No KR) Pre-test *M* *SD*	Post-test *M* *SD*
	SUBTR – STC	0.79 (1.05)	0.14 (0.36)
EG	SUBTR – DTC	3.14 (4.13)	0.07 (0.27)
Dual-task practice with alternating	SORT – STC	0.00 (0.00)	0.00 (0.00)
secondary tasks:	SORT – DTC	1.93 (4.13)	0.21 (0.43)
Subtracting numbers; Sorting marbles	N-Back – STC	---	0.07 (0.27)
	N-Back – DTC	---	0.79 (1.12)
	SUBTR – STC	0.57 (0.94)	0.29 (0.61)
	SUBTR – DTC	1.71 (1.86)	0.86 (1.35)
CG	SORT – STC	0.07 (0.27)	0.00 (0.00)
Single-task practice	SORT – DTC	3.64 (6.88)	0.29 (0.61)
	N-Back – STC	---	0.00 (0.00)
	N-Back – DTC	---	0.57 (0.94)

Annotations: Reported are group means and standard deviations (in parentheses) of absolute error frequency [h] for each of the three secondary tasks. EG: Experimental group [n = 14; practice of criterion task under dual-task condition with two different secondary tasks ("Subtracting numbers"; "Sorting marbles") alternating every 20 trials]. CG: Control group [n = 14; practice of criterion task under single-task condition]. STC: Single-task condition, 20 trials. DTC: Dual-task condition. SUBTR: Subtracting numbers. SORT: Sorting marbles. N-Back: Repeating letters, delayed by 1.

Discussion

Does dual-task practice differentially affect temporal sequence and parameter control?

Primary-task performance in both groups (EG & CG) improved significantly from Pre- to Post-test in the No-KR condition under DTC, as well as (with respect to the TP) under STC. Improvements under STC indicate that the temporal sequence structure was learned equally well in both groups. Dual-task costs were initially present in both groups and for both learning criteria (TP and TMT) in the No-KR Pre-test condition. In the CG, in spite of general performance improvements, these dual-task costs did not decrease after single-task practice. On the other hand, in the EG dual-task costs completely vanished with respect to those primary-secondary-task combinations that were practiced alternately before. Accordingly, elimination of dual-task costs can be entirely accounted for by the treatment condition specific to the EG (i.e., *dual*-task practice). In this group, however, dual-task costs re-appeared at their full extent with respect to the TP of the KSS, when a new cognitively demanding secondary task (the N-Back task) was introduced in the Post-test, while TMT performance remained unaffected by this change of dual-task context.

These mixed results are difficult to be reconciled with either of the two mutually exclusive explanatory concepts (Blischke, 2001; Manzey, 1988) referred to in the introduction. Although the experimental apparatus in the present study does not allow for temporal micro-analyses, thus precluding any direct evidence of intra-trial task-switching or grouping strategies, the TP results can be interpreted best in the context of Integrated Task Processing (ITP): Complete elimination of dual-task costs follows dual-task (EG), but not single-task practice (CG), and is strictly restricted to the DT context(s) experienced during practice. These findings seem to rule out generic central processing mechanisms being gradually relieved from relative timing (i.e., temporal sequence control) in the course of (dual-task) practice. TMT results, on the other hand, can best be explained in the context of Structural Displacement (SDP): The fact that there was no re-appearance of dual-task costs in the EG for the temporal parameter variable when the dual-task context was changed during Post-test, definitely contradicts ITP, and suggests the temporal task parameters are no longer supervised by any cognitive processing mechanisms (e.g., working memory) at the end of (dual-task) practice.

The apparent conflict in these contradictory lines of interpretation deduced from the results of the present study may be resolved, however, considering the following explanations.

Sequential movement patterns yield precedence to cognitive control

Learning, in the present study, took place *explicitly* and involved declarative knowledge. Also, both the criterion movement, as well as all of the secondary tasks used in this experiment, were *sequentially* structured. This made them especially apt for subjects resorting to strategies of integrated task processing. According to hierarchical control models (e.g., Meyer & Kieras, 1997), this would imply a continuous need for strategic decisions, thus getting the executive control level (i.e., some kind of "general purpose" processor) heavily involved. Dual-task costs initially observed in both groups, then could be attributed to the choice of conservative forms of task prioritization, response grouping and task switching, all aimed at minimizing errors, but still working insufficiently at this early stage. More practice was required to improve task control in general, but only dual-task practice also served to facilitate such strategies of executive control, and did so – unexpectedly – even in the light of alternating dual-task context every 20 trials. In line with Manzey's concept of Integrated Task Processing, this would explain reduction of dual-task costs in the EG (but only for the task combinations practiced), while lack of any dual-task practice prevented subjects in the CG from improving this kind of executive functions for simultaneous pursuit of primary and secondary tasks.

Triple-task demands overload the frontopolar executive control system

In the present study, the criterion movement in each trial required subjects to meet two learning goals at the same time: (a) produce the requested temporal pattern, and (b) match the required total movement time. Thus, the criterion task, *in itself, already incorporated a dual-task structure*, and the dual-task conditions in the present experiment actually imposed *triple-task demands* on our subjects. We argue that it might be these facts, in conjunction with some new findings from neuropsychology, that could account for the disparity in the Post-test EG results regarding TP and TMT: While the cognitive executive-level functions referred to above were physiologically attributed to frontal associative brain structures previously, only recent characteristic features of this system, with respect to multitasking behaviors, were established (cf. Charron & Koechlin, 2010). Most importantly, these authors point out that the human frontal function seems "limited to accurately driving the pursuit of two concurrent goals at one time" (ibid., p. 363). More specifically, the medial frontal cortex (MFC), as well as the dorsal anterior cingulate cortex and pre-supplementary motor area, bilaterally drive single-task performance, but divide for disentangling and concurrently driving two independent tasks (dual-task performance). In this latter case, the anterior prefrontal cortex (APC, also: "frontopolar cortex", i.e., the anterior-most part of the frontal lobes) and lateral prefrontal cortex both subserve cognitive branching. Thus, they allow for the temporary maintenance of one task in a pending state during the performance of the other task, and integrate rewards expected from either of the two concurrent tasks in order to establish the most appropriate strategic decision(s) with respect to task prioritization. Despite their involvement in dual-task performance, and different from MFC, dual-task situations revealed no functional dichotomies in these frontopolar brain regions. Thus, Charron and Koechlin (2010) argue "that these regions in both hemispheres jointly control the serial execution of tasks rather than processing them independently" (ibid., p. 363). Also, when a triple-task condition was introduced, subjects in the Charron and Koechlin (2010) study showed increased error rates only when returning to the pending tasks. That is, because there are just two medial frontal cortices, each able to take responsibility for processing one task only, the APC (i.e., the human cognitive-volitional system) cannot effectively coordinate more than two sequentially structured tasks simultaneously.

Considering this, we argue that subjects in the EG during each trial block of dual-task practice (but actually always handling a triple-task) predominantly gave *preference* to the two *sequential* components (i.e., the TP of the primary task, and the respective secondary task), while at the same time, more or less, *disregarding* the primary task's *parameter* component (i.e., TMT). Control of TMT was gradually shifted to some slow-learning, non-cognitive mechanism (a "special purpose" processor in terms of hierarchical control theory), possibly to be associated with cerebellar functions, since the cerebellum is thought to play a prominent role in movement adaptation and automated parameter control (cf. Doyon et al., 2009). This would account for poor TMT-learning measures in the EG, and could also explain why dual-task costs did not reappear for the temporal parameter component in this group when a new secondary task (N-Back) was introduced. Hence, the seemingly mixed behavioral results in the EG could be readily explained by an interplay of Integrated Task Processing (with regard to TP) and Structural Displacement (with regard to TMT). In the CG, the cognitive system would have maintained control of both primary-task components (i.e., relative timing and overall sequence duration) throughout all single-task practice, with subjects developing effective strategies of ITP, which did well even for the No-KR single-task retention trials during Post-test. These strategies in the CG-subjects became inadequate, however, as soon as any one of the experimental dual-task contexts was introduced, because this always enforced concurrent cognitive control of an additional third task, and neither of the primary-task components were automatized in the course of single-task practice so far.

Conclusion

Summing up the results of the present experiment, dual-task practice, incorporating a temporally structured motor primary task and cognitively demanding secondary tasks, did not result in automatic control of the primary task's relative timing (i.e., its temporal pattern). Instead, as indicated by complete reduction of dual-task costs only for those task combinations which were practiced, implementation of integrated task processing strategies was supported. At the same time, there was some evidence for concurrent automatization of the primary task's overall duration parameter, possibly due to structural displacement, which in turn may have compromised the parameter learning rate. These results clearly contradict findings from earlier experiments, incorporating a dynamic force parameter production skill as a primary task (Blischke, 2001). While the CMJ task was essentially ballistic in nature and required subjects to control only one movement *parameter* (i.e., vertical acceleration impulse), the key-pressing task in the present study not only was *sequentially* structured, but also demanded simultaneous control of *two* dependent measures (i.e., TP *and* TMT). Thus, the sequential structure of both primary and secondary tasks in the present experiment may have favored involvement of cognitive control mechanisms associated with systematic activation of prefrontal cortical structures. This may actually have prevented automatization of temporal pattern production in the EG, confining processes of structural displacement to the primary task's temporal parameter component only. So at present, it remains to be seen if *sequentially* structured motor skills are amenable to automatization by dual-task practice at all. Future experiments will have to clarify this issue.

References

Blischke K. Automation of voluntary movements: Old and recent findings from dual-task analysis. Journal of Human Kinetics, 2000. 4 (Supplement): 39-55

Blischke K. Automatisierung einer großmotorischen Kalibrierungsaufgabe durch Prozeduralisierung [Automatization of a gross-motor calibration task by proceduralization]. psychologie und sport, 2001. 8: 19-38

Blischke K. & Reiter C. Bewegungsautomatisierung durch Doppeltätigkeits-Üben [Movement-automatization by dual-task practice]. Spectrum der Sportwissenschaften, 2002. 14: 8-29

Blischke K, Zehren B, Utter T, & Brückner S. Doppeltätigkeits-Übung zeitstrukturierter Finger-Bewegungsfolgen [Dual-task practice of temporally structured finger movement sequences]. Zeitschrift für Sportpsychologie, (in press)

Charron S & Koechlin E. Divided representation of concurrent goals in the human frontal lobes. Science, 2010. 328: 360-363

Doyon J, Bellec P, Amsel R, Penhune, V., Monchi, O., Carrier, J., Lehéricy, S., & Benali, H. Contributions of the basal ganglia and functionally related brain structures to motor learning. Behav Brain Res, 2009. 199: 61-75

Heuer H. Motor learning as a process of structural constriction and displacement. In W. Prinz & A. F. Sanders (Eds.), Cognition and motor processes (pp. 295-305), 1984. Berlin: Springer

Heuer H. Models for response-response compatibility: The effects of the relation between responses in a choice task. Acta Psychol, 1995. 90: 315-332

Keele SW, Ivry R, Mayr U, Hazeltine E & Heuer H. The cognitive and neural architecture of sequence representation. Psychol Rev, 2003. 110 (2): 316-339

Koch I. The role of crosstalk in dual-task performance: evidence from manipulating response-code overlap. Psychol Res-Psychol Fo, 2009. 73: 417-424

Manzey D. Determinanten der Aufgabeninterferenz bei Doppeltätigkeiten und ressourcentheoretische Modellvorstellungen in der Kognitiven Psychologie [Determinants of task interference in dual-task activities and resource-theoretical model conceptions in cognitive psychology], 1988. Köln: Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR)

Manzey D. Doppelaufgabeninterferenz: Neue theoretische und methodische Perspektiven für ein altes Paradigma [Dual-task interference: New theoretical and methodological perspectives on an old paradigm]. In R. Daugs & K. Blischke (Eds.), Aufmerksamkeit und Automatisierung in der Sportmotorik (pp. 79-96), 1993. Sankt Augustin: Academia.

Meyer DE & Kieras DE. A computational theory of executive processes and multiple-task performance. Part 1. Basic mechanisms. Psychol Rev, 1997. 104: 3-65

Müller H & Blischke K. Motorisches Lernen [Motor learning]. In B. Strauß & W. Schlicht (Hrsg.), Grundlagen der Sportpsychologie (pp. 159-228), 2009. Göttingen, Bern, Toronto, Seattle: Hogrefe

Pashler H & Johnston JC. Attentional limitations in dual-task performance. In H. Pashler (Ed.), Attention (pp. 155-189), 1998. Hove, UK: Psychology Press.

Wickens C D Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.). Varieties of attention (pp. 63-102), 1984. New York: Academic Press.

Wickens CD Multiple resources and mental workload. Hum Factors, 2008. 50 (3): 449-455

Acknowledgements

Part of this work was presented in a poster presentation at the annual conference of the North American Society for the Psychology of Sport and Physical Activity (NASPSPA), June 10th-12th, 2010, at Tucson, AZ, USA (Abstract published in conference proceedings: Blischke, K., Zehren, B., Wagner, F., Utter, T. & Brueckner, S. Movement automatization by dual-task practice: Restricted to non-sequential movements? Journal of Sport & Exercise Psychology, 2010. 32 (Supplement): 64)

Corresponding author

Prof. Dr. Klaus Blischke
Saarland University, Institute of Sport Science
P.O. Box 15-11-50
66041 Saarbruecken, Germany.
phone: +49-681-302-4172
fax: +49-681-302-4091
e-mail: k.blischke@mx.uni-saarland.de