Does Dual Tasking Expend Limited-Resource Executive Processes?

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Abstract. The study of human ability to perform two tasks simultaneously has a long history in cognitive science, even preceding modern experimental psychology. Such studies have multiple practical implications for understanding human-machine interaction, and ergonomics in general, as well as addressing fundamental questions about human cognitive architecture. Typically studied through experimental psychology methods, it is generally found that dual-tasking impairs overall performance, compared to performing tasks individually. This has been interpreted as the cost incurred when centralised, executive control resources are expended. However, there is some indication that dual-task performance may not require executive control. In this research paper we describe an experiment conducted to investigate the effect of a secondary task on the performance of two different versions of a widely-used assessment of executive function, the Trail Making Test. In contrast to the executive theory of dual task performance, we found that conditions involving routine task performance were more affected by a secondary task of foot tapping, relative to performance of the executive, task switching conditions. In addition, using a task variant that required random, free choices of response, we found no evidence that the performance of a secondary task impaired performance. Taken together, these results suggest that dual-task performance does not necessarily expend limited-resource executive processes.

Keywords: Executive function · Dual tasking · Trail making test · Divergent thinking · Cognitive control · Multitasking · Free choices.

1 Performing two tasks simultaneously (dual tasking)

It is a well-known fact that attempting to do two things simultaneously tends to result in performance in both, which is worse than if they were performed alone. In fact, the oldest known psychology experiment, performed in 6th-century

China, is on dual-tasking. The scholar Liu Xie asked people to draw a circle with their right hand, while simultaneously attempting to draw a square with their left hand, demonstrating that the performance of both drawings was impaired [41]. In that case, the interference can be understood as due to the dual-activation of brain regions involving manual responses [40].

The inability to perform two tasks at optimal levels simultaneously is an important factor in many aspects of behavioral sciences. It is of particular relevance to fields such as human-machine interaction, in which multiple tasks and sources of information may be processed at the same time, and in ergonomics in general [36]. However, it has been mainly researched in experimental cognitive psychology, where it is closely linked to the concept of executive function.

1.1 Executive functions and dual-task performance

The psychological concept of executive function, also known in neuroscience as cognitive control, describes a range of top-down cognitive control processes that produce intelligent, goal-directed behavior when schema-based, habit, or otherwise route procedures seem likely to fail. The concept developed originally in computer science in the 1950s, and from there was adapted for use within cognitive and neurosciences [29]. It has since been applied to many other fields of behavior sciences, such as education [31], due to its explanatory power.

The first theory to apply executive functions, within a cognitive science framework, was the Supervisory Attentional System of Norman and Shallice 1980 [25]. That model is still widely used as the basis for understanding high-level, top-down cognition [35]. Part of the reasoning behind the 1980 model was to account for the decrement in performance observed when people attempt to perform two quite different tasks simultaneously. However, even very different tasks that require quite different motor output show dual-tasking effects [25], suggesting that they are depleting some central cognitive resource, usually interpreted under the concept of executive function, particularly the Norman and Shallice model of 1980.

Such is the influence of that model that dual-tasking is now widely applied as an experimental method to decrease executive processing capacity when investigating the contribution to other processes [13]. Dual-tasking is, therefore, routinely interpreted as being an executive function [19].

Evidence from neuroscience also suggests that dual-tasking involves a single, limited resource [29]. For example, when two quite different tasks are performed simultaneously, such as sentence processing and mental rotation, the pattern of brain activation is substantially less than the sum of the two activations when the tasks are performed separately. This suggests that there is some limiting factor, be it attentional or neurophysiological, which is behind the limits on performance [16]. This is also consistent with theory in cognitive neuroscience that posits a multiple-demand system within the primate brain, involving specific frontal and parietal cortical regions, which, as it sounds, deals with any cognitive task that is highly demanding of resources [10]. That multiple-demand system is therefore modality independent and domain-general, and involved with performing a range of different tasks that are commonly described as demanding executive control, or fluid intelligence [11]. That central processing resource, though, is limited, as indicated by increasing brain activation with increased cognitive load, within the multiple-demand system, but not in other brain regions [12].

Furthermore, dual-task performance research has often supported a central bottleneck model. This suggested that although peripheral processes may occur in parallel, selecting which response to make uses a central resource that is temporarily dedicated to the task that is focused upon. That central response selection, therefore, has to process information in a serial fashion. If dual-tasking is required, there has to be switching between tasks for access to that central response selection system [26].

1.2 Is dual-task performance really dependent on executive functions?

Many tasks can become automated with learning and can then be performed simultaneously with other tasks with little or no reduction in the performance of any of the tasks. The classic example is driving a car, which for most people becomes highly automatized [37], allowing them to perform other tasks, such as carrying on a conversation or listening to a podcast. In tasks in which procedures have become automatized and in which there is little perceptual or motor conflict, multiple tasks can be performed with minimal interference [23].

However, when this is not the case, dual-tasking effects are often observed, with the performance of one or both tasks impaired when performed simultaneously. Many authors have argued that in such circumstances, top-down executive control is required, and is the factor limiting performance [19, 23, 25, 3, 28].

Nevertheless, there are some problems with that assumption. One of these is the factor analytic work that provided classification of the types of cognitive processes that require centralised executive control. Comparing the performance of multiple different cognitive tests, and examining the patterns of intercorrelations, several research groups have concluded that there are partially separable, through interdependent executive functions of i. updating working memory, ii. switching between different foci, and iii. response inhibition. However, dual-task performance was found to be independent of these core executive functions [24]. While most complex cognitive tasks that are described as involving executive control draw on one or more of those three core functions, dual-task performance appears to be independent.

Furthermore, inhibition, working memory, and switching are generally considered to be executive functions that are closely related to each other, sharing some common processing demands; again, dual tasking appears to be independent of that common processing. Dual-tasking also appears to have a different relationship with normal ageing than the other supposed executive functions. Dual-tasking performance, when compared to the core executive functions of working memory updating, switching, and inhibition, shows substantially less decline with normal healthy ageing [15], and in some studies appears to show no decline at all [2]. Related to this are the patterns of decline in abnormal cognitive ageing. Studies of patients with Alzheimer's disease have suggested that they have a specific impairment of dual-tasking ability, independent of any general resource-limited processor impairment, suggesting that the healthy human brain contains an independent processing system that supports dual tasking [18].

1.3 Current study

One way to address these issues is through experimental cognitive psychology. If dual-tasking requires centralised, limited-capacity executive resources, we would expect it to impede task performance on tasks with an obvious executive component more than tasks that require simple routines. Some widely used tests in cognitive psychology have both executive and routine conditions. The classical example is the Stroop Task; the executive condition involves naming the ink colors that words are written in. While a routine condition, used in many versions, requires participants to name color blocks [9]. In both conditions, the motor output is the same, i.e., saying color names. Another example is the Trail Making Test [33]. In that test, participants are required to use a pencil to draw lines joining sequential numbers on a page (task A). That is considered the routine condition. Performance is compared with that on the executive condition, which requires that the participant alternate between numbers and letters (task B). Again, in both the executive and routine conditions, the motor output is the same. However, in the executive condition, the participant must switch between two different foci. Task performance on the routine condition appears to involve mainly visuospatial ability, while the executive load condition requires switching and working memory [38]. There are several different trail-making tests available [33, 9, 20, 30]. We used versions of the trail-making test in the current study that have been validated for use in Thailand, where the experiment was conducted.

A further benefit of trail-making tests is that there are convergent and divergent response versions available. We have recently argued that tasks that require divergent responses (i.e., several possible correct responses are possible) may be more challenging of limited executive resources than traditional versions that require convergent responding (i.e., only individual, specific responses are considered correct [29]).

Below, we describe an experiment performed on the effect of dual tasking on trail-making task performance, using both convergent and divergent forms of the test. As a secondary task, we used an auditory-synchronised foot tapping task. This was chosen as it would not interfere directly with upper limb movements, has been used in many previous studies of executive function as a secondary task [34, 4], and performance is known to be sensitive to available cognitive reserves [21]. It was hypothesised that dual tasking would impact task performance, and that would vary by the executive load of the task and whether the task was convergent or divergent in nature.

2 Experimental Methods

2.1 Participants

The participants of this study consisted of 36 undergraduate students from Social Science majors (Psychology, Language and Communication, and Law) at Chulalongkorn University and Srinakharinwirot University, Thailand. The mean age of the participants was 20.7 (SD = 1.70). Three participants were male, 32 were female, and one participant identified as other gender. All participants had normal vision or corrected to normal, and none had a known motor disorder. Participation was voluntary, and the participants could choose whether to receive course credits or a small cash payment as compensation.

2.2 Materials

To study the effect of dual-task on executive functioning, The Color Trail Test [20] and the Choice Trail Test [30], were used in this experiment. This allowed us to include a task type factor in the analysis to examine whether divergent or convergent task types had an effect.

The Color Trails Test was developed as a variant of the classic trail making tests [33] with a reduced language-specific limitation by replacing English-language alphabet letters with colors [20]. This adaptation makes it more suitable for use in Thailand, where the experiment was run. As with other trail making tests, it has an executive and a routine condition. The executive part, behaviorally, is that the participant must switch between different foci, i.e., numbers and colors.

The routine task requires drawing a line connecting circles from the starting point (labelled ‘1’) to the last point (labelled ‘25’) in ascending order. The circles are scattered across the page, and odd numbers are labelled on pink circles while even numbers are placed on yellow circles. In this routine condition, participants can ignore the colors and only pay attention to the number sequences. The executive task is referred to here as the switching condition. Performance also involves joining circles on a page, the circles labelled with numbers 1-25. However, each number (excluding number 1, the starting point, which is always pink) appears twice, once on a pink circle and another time on a yellow circle. Participants are required to connect the numbers on the circles in an ascending manner, but also need to switch between the two colors (e.g., pink one, yellow two, pink three, etc.). It is this switching aspect that makes the trail making tests demanding of executive attention [38].

The original Color Trails Test included only one routine and one switching trial [20]. To allow multiple data collection trials, additional parallel versions were produced for this experiment. As the tasks require lines to be drawn on paper, it was important to maintain consistency of the total distance drawn in each trail. Thus, the total distance of the line drawn from number one to 25 was controlled to be within the range of plus or minus 5% from the original version.

The Choice Trails Test was developed as a variant of the Color Trails Test. The main difference is that this variant requires decisions to be made before each of the 24 lines drawn to complete a trial in the switching condition [30]. Similarly to the Color Trails Test, participants are required to draw a line ascendingly from a circle labelled '1' up to number '25'. This time, instead of two colors, each number that a line is to be drawn to appears four times, in four color circles: pink, violet, blue, and yellow. We varied the brightness of these colors so that even participants with color blindness would be able to distinguish them. In the routine task of this test, participants have to link numbers on the pink circles while ignoring the others. Meanwhile, the switching task requires the participants to follow these instructions:

1. Draw a line from number 1 to 25 by alternating between different colors, meaning that they should not draw a line to the same color circle consecutively.
2. Try to use all four colors equally.
3. Do not use any strategy, such as intentionally repeating the same pattern of colors (i.e., always selecting colors in the same sequence throughout the test).

This forced participants to make a decision as to which color they would draw a line to next, without a definitive correct answer. Completion time was recorded, and participants had to restart from the previous number in case of mistakes. Multiple trials of the Choice Trails Test were also created, and the total distance of each was controlled in the same manner as in the Color Trails Test.

2.3 Procedure

The research was conducted individually for each participant face-to-face in an experimental session that took approximately one hour. All participants gave written informed consent to participate, as part of the research protocol that had been approved by the local research ethics committee. Following informed consent, basic demographic information was collected. Prior to the experiment proper, practice trials were administered for both the Color Trails and the Choice Trails Tests to allow the participants to familiarise themselves with the procedure. Then, the experiment was conducted. In each trial, an A4 page was presented to the participant, and their task was to join the circles on the page in ascending order. Participants were instructed to complete the tasks as fast and accurately as possible. Participants were instructed to start drawing a line when instructed by the experimenter, and the completion time was recorded in seconds when the participant reached number 25. The experimenter continually observed performance, and if any mistakes were made during the trial, participants would be instructed to redraw a line from the previous number. The number of mistakes was not recorded, but the time spent to complete the test would increase when participants had to go back to correct their mistakes.

In total, there were 8 experimental conditions. For ease of comprehension of the experimental design, these are shown in Table 1. These 8 conditions were produced by three experimentally-manipulated factors, described in more detail below: *Task Type* (2 levels), *Requirement* (2 levels), and *Dual-tasking* (2 levels).

Table 1. Experiment design summarizing the 8 conditions and 16 separate data collection trials.

	Task Type	
	Color Trails Test (convergent responses)	Choice Trails Test (divergent responses)
	Without tapping	
Requirement		
Routine	2 trials	2 trials
Switching	2 trials	2 trials
	With tapping	
Routine	2 trials	2 trials
Switching	2 trials	2 trials

Color and Choice Trails Tests comprised of four conditions, with 16 trials: four color routine trials, four choice routine trials, four color switching trials, and four choice switching trials. To assess dual-task performance, half of the trials in each condition were tapping trials. During tapping trials, participants had to tap their feet alternatively according to the sound of a metronome set at 120 BPM while completing the trials. This means that each participant had to complete the tasks normally without foot tapping for eight trials, two trials for the color routine, two for the choice routine, two for the color switching, and the last two for the choice switching condition. The participants were asked to do another eight trials while tapping their feet.

To counterbalance the order of the tasks, participants were randomized into four groups, which completed the four conditions in different orders. Two groups completed the Color Trails Test first, while another two groups started with the Choice Trails Test. One from each of the two groups completed the tapping conditions first, while another completed the no-tapping conditions first. The order of the test versions within each condition was also randomized. For example, one participant might complete version A, C, B, and lastly, D, for the choice switching task, while another person might complete the same task starting from D, C, A, and then B. The test versions were also randomized for each task. For instance, version A of the color routine might be in the tapping condition for one participant, but could be in the no-tapping condition for another person.

2.4 Statistical methods

The experiment was analysed as a factorial design with 3 factors: Task Type (Color Trails or Choice Trails Tests), Requirement (Routine or Switching), and

Dual-tasking (No-tap or Tap). As there were two trials in each condition, the mean score on each condition was taken as the dependent variable. For null-hypothesis testing, a significance threshold of .05 was used. All analyses were conducted with SPSS v29. Effect sizes are given as partial eta-squared (η_p^2).

3 Experimental Results and Analysis

One participant used a strategy on several trials that was not noticed and corrected at the time by the researcher, and so their data was excluded. For the remaining 35 participants, distributions of the eight task completion time variables were analysed with Kolmogorov-Smirnov tests. Of the eight distributions, two differed significantly from normal ($p < .05$). Log transformations were applied to all data, which produced distributions, none of which differed from normal (all $p > .144$). The log-transformed data are therefore used for all parametric statistical tests on task completion times. However, mean raw scores for each condition are shown in Table 2.

Table 2. Raw mean ($\pm SD$) task completion times in seconds for all experimental conditions.

	Single task		Dual-tasking	
	Routine	Switching	Routine	Switching
Color Trail Making	28.38 (7.43)	50.62 (10.30)	35.09 (12.23)	54.68 (15.32)
Choice Trail Making	22.88(4.96)	39.24 (7.91)	26.24 (6.91)	42.00 (10.49)

The experiment included three different factors: 1) Task Type (i.e., Color Trails Test or Choice Trails Test), 2) Requirement (i.e., performing a routine of joining numbers in sequence versus switching between colors while joining numbers in sequence), and 3) Dual Tasking (i.e., normal task performance, or while performing the secondary foot tapping task). As each of these factors has two levels, this produced a 2*2*2 within-subjects factorial experimental design with 8 independent conditions. The effect of these factors on task completion times was assessed with a factorial ANOVA.

Each of the three main effects revealed statistically significant differences in task performance. The significant main effect of Task Type (Color Trails versus Choice Trails Test), $F(1,34) = 86.585$, $p < .001$, $\eta_p^2 = .718$, indicates that overall, the Color Trails Test took longer to complete than the Choice Trails Test. This likely indicates that the standard Color Trails Test has some features that may slow performance, such as a greater need for visual scanning, compared to the Choice Trails Test.

The significant main effect of task Requirement (routine or switching), $F(1,34) = 752.210$, $p < .001$, $\eta_p^2 = .957$, indicates that the switching trials (which involved always joining different colors in numerical sequence) took longer to complete than the routine trials (which always involved joining numbers in numerical sequence without any need to switch between colors). This can be seen graphically in Figure 1, as the times on the switching conditions were substantially higher than on the routine conditions. This likely indicates that the invocation of top-down executive control slowed performance.

The significant main effect of dual-tasking, $F(1{,}34) = 23.832$, $p < .001$, $\eta_p^2 = .412$, indicates that overall, performance of a secondary task slowed performance. Again, this can be seen graphically in Figure 1.

Of the two-way interactions between factors, both the interaction of Task*Requirement ($F(1{,}34) = 0.203$, $p = .655$, $\eta_p^2 = .006$) and Task*Dual Tasking ($F(1{,}34) = 1.591$, $p = .216$, $\eta_p^2 = .045$) were not significant. These suggest that the completion times on the Color Trails Test and Choice Trails Test are quite similar in their sensitivity to the effects of switching and dual tasking.

In contrast, the Requirement*Dual-tasking interaction was significant, $F(1{,}34) = 9.947$, $p = .003$, $\eta_p^2 = .121$. This indicates that dual-tasking affected performance differentially based on task requirements. Visual examination of the means in Table 2 indicates that this was opposite to what was expected; dual tasking had its greatest impact on performance during the routine tasks (joining up numbers in sequence), relative to the more complex switching tasks. The interaction (based on transformed data) is visible in Figure 1. As a way to summarize this, the relative slowing of responses from single to dual-task performance in the routine conditions was about 24% for the Color Trails Test and 15% for the Choice Trails Test. The equivalent slowing percentages in the switching conditions of the same tests were only 8% and 7% respectively.

For the final part of the ANOVA analysis of task completion times, we examined the three-way interaction of Task*Requirement*Dual tasking. This was found to be non-significant ($F(1{,}34) = 1.455$, $p = .236$, $\eta_p^2 = .041$). This indicates that overall, the Color Trails Test and the Choice Trails Test are equally affected by the combination of task-switching and dual-tasking requirements.

An advantage of the Choice Trails Test is that, because participants make free choices for each response in the switching condition, it is possible to estimate their ability to respond randomly [30]. That analysis requires response-by-response analysis at the level of the individual participant in this experiment, 24 responses in each trial (i.e., 384 data points per participant). We have recently argued that experiments in cognitive psychology could use more temporally dense data [7]. This is possible in the Choice Trails test, as every choice made (i.e., every color selected is recorded and contributes data points) rather than the single task completion time measure more commonly used with trail making tests. This allowed us to calculate how well participants were at generating random responses, which was part of the task objectives.

The ability to respond randomly is frequently considered a resource-demanding executive process [5, 8]. We compared randomness estimates between the single and dual-task conditions. This analysis is only available in conditions in which choices are made by the participant, that is, the switching trials of the Choice Trail Test. This was used to generate summary randomness scores. As the difference scores between conditions were normally distributed, this was performed with a parametric test, a simple one-way paired-sample ANOVA. However, there was no significant difference, $F(1,34) = 0.17$, $p = .896$, $\eta_p^2 = .001$. This indicates that the performance of a secondary task did not influence executive task performance as measured by the randomness of responses. This again suggests that dual-tasking did not affect executive control processes.

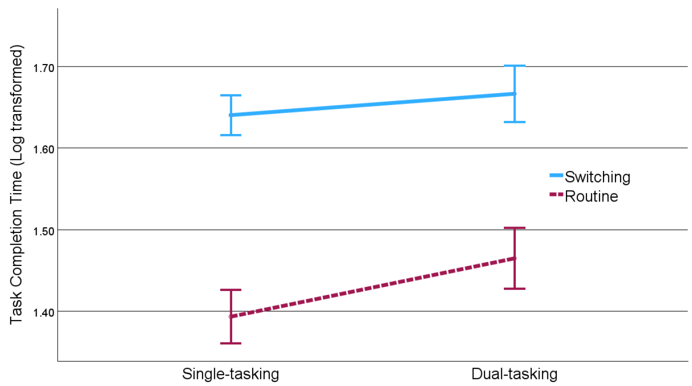

Fig. 1. Mean task completion times (+ 95%CIs) for the switching and routine requirements in single- and dual-tasking conditions.

4 Discussion

We found that dual-tasking caused greater slowing of performance on a task that is supposedly routine and non-executive, compared to one that is widely considered to involve executive control [1, 17, 32, 20, 9, 38]. This was found with two versions of the classic trail making assessment method [20, 30], one of the most widely-used assessments of executive functioning. Furthermore, in one of those tasks, in which free choices of response were made, the performance of a secondary task had no impact on the randomness of responses. As deliberately responding randomly is considered to expend central executive resources [5, 8], this further suggests that secondary task performance (foot tapping) had no impact on top-down executive control of performance in the main task.

These findings challenge many existing theories that consider dual-tasking to be essentially an executive function [19, 23, 25, 3, 28]. In fact, experimental results similar to ours have been described previously. Like us, Hegarty et al [14] found that dual tasking seemed to impair the performance of tasks with low, more than high, executive load. In addition, our results corroborate Miyake et al.'s classic factor analytic work on the unity and diversity of executive functions. That analysis found that dual-tasking appeared to be functionally independent of the other interrelated components of executive control [24].

If dual-tasking is not depleting central resources for cognitive control, in what stage of processing is it influencing performance? Some theories, with experimental support, suggest that the bottleneck in processing is not just at a central response selection stage, but rather there are bottlenecks at several stages, particularly motor output selection [6]. As the routine task used in this experiment, basically joining numbers up in sequence by drawing lines between them, is generally considered as mainly a visuomotor task [38], much of the processing time in normal performance is likely on motor output selection. This may be why a secondary task, also involving motor responses, has such an impact. In contrast, the 'executive' tasks that included switching between colors took longer to complete even without dual-tasking (this was confirmed in the experiment reported here). Thus, a smaller proportion of the overall performance time in the executive condition was taken up by motor response selection, and consequently, the motor response bottleneck had a lesser influence.

Stemming from that observation, one potential criticism of the current research is that both tasks used in the dual-tasking experiment required motor output with a limb, albeit with a hand and arm in one task, and the feet in the other. Often, for dual-tasking research, it is recommended that different output modalities be used, often manual and oral responses [19]. That we used two different limbs could have produced some conflict at the level of motor control. From a purely biological perspective, this could be argued against as the cortical representation of the hand and foot is in quite different parts of the motor cortex [27]. Nevertheless, at the behavioral level, hand and foot movements can facilitate each other, or impede each other, depending on the similarity of the actions performed [22]. Thus, it could be argued that foot tapping impaired performance on the routine task due to motor-response conflicts. However, it should also be noted that both the routine and switching conditions involved essentially identical motor responses (i.e., joining the numbers 1 to 25 on a page). It seems that foot tapping disproportionately affected the routine conditions. This could perhaps be because of the simplicity of the routine tasks; much of the processing required for performance is motor output.

Furthermore, it is likely that the secondary task, tapping feet alternatively to the rhythm of a metronome, was not something that could be performed automatically, and was using cognitive resources. Although motor tasks such as foot tapping have traditionally been viewed as separate from cognitive processing, more recent research suggests that cognitive and motor control are largely shared processes in the brain [39]. An example of this is that the multiple-demand system, said to underlie fluid intelligence and executive function [10] is partly localised to the precentral gyrus (i.e., the primary motor cortex) [12]. Consequently, simple tasks such as toe tapping to a metronome beat are substantially impaired even in cases of mild cognitive impairment [21].

Nevertheless, our results still indicate that dual tasking in this experimental paradigm did not impair performance on a task that is widely thought to require executive control (the trail making switching condition). This is because inclusion of the free-choice response aspect (i.e., individual responses in the Choice

Trails Test) also allowed us to show, with a very different measure (randomness of choices), that dual-tasking appears to have had little impact on executive control. Taken together with the analysis of response time data, we found no evidence that inclusion of a secondary task of foot tapping expended limited executive processing resources during trail making test performance.

Related to that, we also examined the distinction between convergent and divergent responding. We included that analysis as we have previously argued, on theoretical grounds, that tasks requiring free choices, that is, they have a divergent aspect, should be more consuming of centralised executive resources. However, we found that the convergent task (Color Trails Test) was performed similarly to the divergent task (Choice Trails Test). This suggests that they appear to be equally demanding of top-down control, as shown by the significant cost of switching on response times.

5 Conclusion

Both trail making tasks were susceptible to dual-tasking. They appear to measure similar processes. However, it is likely that dual tasking in this study mainly impacted the non-executive aspects. This is revealed in two ways: one is that the interaction suggested that the performance of the routine conditions was slowed more by a secondary task than by the switching conditions. The other indicator is that performing a secondary task did not affect the randomness of participants' responses. It seems likely, therefore, that the dual-tasking manipulation mainly disrupted peripheral aspects of performance, rather than expending limited, centralised executive resources.

Consequently, we conclude that dual-task performance should not necessarily be considered as expending limited-resource executive processes. In some cases, that may be correct, but in others, such as with the trail making tests described here, dual-task interference has a greater impact on the non-executive, compared to the executive processing component.

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