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Effects of Stroop task duration on subsequent cognitive and physical performance

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A B S T R A C T

The *strength model* of self-control purports to explain why brief cognitive response inhibition tasks impair subsequent isometric handgrip endurance. According to the model, *ego depleting* tasks requiring self-control resources impair performance on subsequent tasks that also require self-control resources. However, several lines of evidence challenge this model, including evidence of improved exercise performance following longer cognitive tasks. Our study investigated the effects of cognitive task duration on (1) subsequent physical endurance performance, (2) concurrent cognitive task performance, and (3) subsequent novel cognitive task performance. Adopting an experimental design, with Stroop task type (incongruent, congruent) and duration (5, 10, 20 min) as between-participant factors, participants ($N = 180$) completed a color word Stroop task, an isometric handgrip to exhaustion task, and a novel 5-min incongruent number word Stroop task. In the handgrip task, endurance performance was worse following incongruent word Stroop than congruent word Stroop for 10-min tasks but not 5-min and 20-min tasks. In the word Stroop task, accuracy was lower and speed was slower following incongruent word Stroop than congruent word Stroop. Importantly, reaction times improved with longer task durations. In the novel number Stroop task, accuracy was higher following incongruent word Stroop than congruent word Stroop. In conclusion, the finding that the *ego depletion* effect was moderated by cognitive task duration is better explained by the *expected value of control model* than the *strength model*.

1. Introduction

A common definition of self-control is the ability to regulate one's thoughts, feelings and actions in order to pursue long-term goals (Baumeister et al., 2007). Self-control is a global psychological resource involving higher order executive processes, such as response inhibition, which can become depleted when used. The *strength model* (or *strength-energy model*) often uses a muscle analogy to explain self-control (Muraven & Baumeister, 2000), and proposes that the more self-control is exerted, the more fatigued it will become, and the more it will deplete the self-control resource. This assumed resource depletion reduces a person's ability to regulate their actions and thereby impacts other activities that require self-control. This *ego depletion* effect is defined as a "temporary reduction in the self's capacity or willingness to engage in volitional action (including controlling the environment, controlling the self, making choices, and initiating action) caused by prior exercise of volition" (Baumeister et al., 1998).

Ego depletion is commonly investigated using the sequential-task paradigm, where participants complete a series of two self-control tasks: the first (manipulation) task is used to deplete global self-control resources, and performance on the second (outcome) task is used to quantify the amount of ego depletion. A meta-analysis of 83 sequential-task studies confirmed a primary effect of reduced performance on the outcome task following the manipulation task, together with secondary effects for self-reported affect, difficulty, effort, and fatigue (Hagger et al., 2010). This evidence provided preliminary support for the strength model, and identified potential underlying mechanisms (e.g., fatigue, motivation) for the ego depletion effect. However, this meta-analysis was later criticized on methodological grounds (Carter & McCullough, 2014), including low ecological validity, weak measures of self-control, high confirmation bias, and positive result publication bias. A re-analysis of the studies (Carter et al., 2015) raised questions regarding the reliability of the phenomenon and putative mechanisms. Additionally, a later and larger meta-analysis, which examined the effectiveness of each depleting task, revealed no support for the ego depletion effect (Dang, 2018). These evidential concerns are compounded by several attempted international multi-laboratory experimental replications that have failed to support the ego depletion effect (Dang et al., 2020; Hagger et al., 2016; Vohs et al., 2021). Finally, in addition to these data-based concerns, the ego depletion effect has also been criticized on conceptual and theoretical grounds (Lurquin & Miyake, 2017). In sum, the evidence supporting the ego depletion effect is mixed at best, and further criticized due to the lack of a plausible identified underlying biological mechanism (Friese et al., 2018).

Nonetheless, the strength model and ego depletion effect have been used to study self-control during exercise and try to understand habitual

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physical activity and optimal performance (Audiffren & André, 2015; McCormick et al., 2019). In the context of exercise and performance psychology, researchers have borrowed the sequential-task paradigm to examine the effects of performing a cognitive task (e.g., Stroop color word interference task that requires response inhibition) on subsequent performance of a physical task. A study by Bray and colleagues (Bray, et al., 2008) demonstrated that endurance performance, on a physical task requiring participants to sub-maximally squeeze a handgrip dynamometer for as long as possible, was reduced by 43% following completion of a brief (220 s) incongruent Stroop task compared to a congruent Stroop (control) task. A follow-up experiment (Brown & Bray, 2017), designed to examine the effect of cognitive task duration on performance of a subsequent physical task, found that the incongruent Stroop task needed to last at least 240 s to impair endurance time in a task requiring participants to squeeze a handgrip dynamometer at 50% of maximum force for as long as possible. Similarly, a study by (Boat et al., 2020) found that longer performance of an initial response inhibition task led to poorer performance (i.e., shorter times) of a subsequent wall-sit exercise task.

To date, few studies have examined the effects of completing a physical task on subsequent cognitive task performance. Brown and Bray (Brown & Bray, 2015) examined the effect of physical task intensity, with participants required to squeeze a handgrip dynamometer at 30%, 50% and 70% of maximum force for as long as possible, on subsequent performance of a 10-min incongruent Stroop task. Overall, the handgrip task improved cognitive task performance relative to baseline. However, the improvement depended on the intensity of the preceding exercise, with the greatest cognitive improvement for the lowest exercise intensity. These improvements in the second task following the first task run counter to the strength model. However, a control group, who held the handgrip at 5 N for 4 min, also improved relative to baseline, and, therefore, the improvements were attributable, at least in part, to a learning effect on the Stroop task.

Sequential-task paradigm experiments have been criticized for focusing on performance of the outcome task and neglecting performance on the manipulation task (Arber et al., 2017). It is assumed that the manipulation task is depleting the global self-control resource, and, therefore, performance should decline as a function of time on task. Contrary to this assumption. Some studies, adopting a dual cognitive domain paradigm, have failed to show an improved performance in the outcome task, which is inconsistent with the strength model. A large study by Bieleke et al. (2021) demonstrated that self-control tasks did not alter subsequent performance, regardless of their duration. Dang et al (Dang et al., 2013) showed that adaptation to the Stroop interference effect (i.e., improved performance with increased time on task) cancelled the ego depletion effect: the extent of the interference effect during a prolonged Stroop task was positively correlated with the number of errors committed in a subsequent 5-min attention task. These findings were explained by *cognitive control theory* (Botvinick et al., 2001), which proposes that the cognitive system monitors the situation and recruits additional resources when response conflicts are detected. According to this theory, in sequential-task paradigm experiments, when participants perform the subsequent outcome task in a new domain, it takes time for cognitive resources to adjust to the new demands, thereby impairing performance. Cognitive control has been defined as the “ability to flexibly adjust behavior in accord with internally maintained goals and away from behaviors that are more automatic but distract from those goals” (Shenhav et al., 2016). The *Expected Value of Control* (EVC) theory (Shenhav et al., 2013) proposes a comprehensive model of the role of the dorsal anterior cingulate cortex function in the context of cognitive control and thereby directly builds on cognitive control theory. The *EVC model* proposes that the extent of cognitive control that is allocated to a task is based upon the expected payoff achieved, the amount of cognitive control required and its associated effort. More specifically, the operation of cognitive control is based upon task identity, task intensity, and maximizing anticipated potential future reward regarding internal (i.e., motivation) and external (i.e., environmental) situational factors.

A state of mental fatigue has been used to explain the ego depletion effect (Englert, 2016). Mental fatigue, defined as a psychobiological state caused by engaging in demanding cognitive activity for a prolonged period (Marcora et al., 2009), impairs subsequent submaximal whole-body endurance exercise (Cutsem et al., 2017). This effect has been attributed to central mechanisms (i.e., greater perceived exertion) rather than peripheral (i.e., cardiorespiratory and muscular) mechanisms. Impairments, due to cognitive task engagement, on shorter duration physical tasks (typically isometric exercises) have also been reported, (Brown et al., 2020). However, no effect was reported concerning the impact of cognitive task duration on physical performance, further highlighting that the role of task duration in this context remains unclear. Furthermore, another review and meta-analysis by Giboin and Wolff (2019) included studies from both the ego depletion (generally shorter duration cognitive tasks) and mental fatigue (generally longer duration cognitive tasks) literatures, and, importantly, concluded that any decrements in subsequent endurance performance were independent of task duration.

In sum, several issues remain to be resolved regarding the sequential-task paradigm. First, the *ego depletion* effect may be better explained by alternative models (i.e., cognitive control, mental fatigue). Second, the importance of the duration of the cognitive task (i.e., time on task learning effects) on subsequent performance of the physical task have yet to be established. Third, the impact of a cognitive task on performance of another cognitive task (i.e., intra-domain near transfer as well as inter-domain far transfer effects) lacks evidence.

2. Present study

Our study was designed to address these issues. Adopting a sequential triple task paradigm, our study purposes were threefold. The first purpose was to investigate the effect of cognitive task duration on subsequent physical task performance. It was hypothesized that the duration of the Stroop color word interference task would be inversely related to subsequent endurance performance on a submaximal handgrip task. The second purpose was to investigate the effect of cognitive task duration on concurrent performance of the cognitive task. It was hypothesized that performance accuracy and speed would deteriorate with increased time-on-task. The third purpose was to investigate the effect cognitive task duration on subsequent novel cognitive task performance. It was hypothesized that the duration of the Stroop color word interference task would be inversely related to subsequent performance speed and accuracy of a Stroop number word interference task.

3. Method

3.1. Participants

Participants were 180 (77 females, 103 males; aged 18.79 ± 1.43 years) undergraduate sport and exercise science students who received course credit for participation. They were asked to abstain from vigorous exercise and alcohol, and to have a regular night’s sleep in the 24 h before testing. They were also asked to refrain from eating (1 h) and consuming caffeine (3 h) before testing. Ethical approval for the study was obtained from the local ethics committee. All participants provided written informed consent. Power calculations using GPower 3.1.5 (Faul et al., 2007) indicated that with a sample size of 180, our study is powered at 80% to detect significant ($p < .05$) between-participant main effects ($f = 0.210$ to 0.233) and interaction effects (f = 249) corresponding to a medium effect size by analysis of covariance (Cohen, 1992).

3.2. Experimental design and procedure

The study employed an experimental design with two between-participant factors: task type (incongruent Stroop, congruent Stroop) and duration (5, 10, 20 min). Participants attended one laboratory session. Participants were asked to remain seated on a stool throughout and face a computer monitor positioned at eye level 1 m away. After obtaining the participant's maximal voluntary contraction (MVC) grip force (see below), they were randomly allocated to one of six groups, which differed in terms of task and duration (see below). To increase task motivation, performance scores were displayed on a whiteboard. Participants completed three sequential tasks – Stroop color word task, handgrip task, Stroop number task – with self-report ratings before and after each task (see Fig. S1, Supplementary Materials). Several experimenters were present during all tasks to instruct the participants. No verbal encouragement was provided.

3.3. Maximum voluntary contraction

Participants were instructed to squeeze a handgrip as hard as possible for several seconds in order to obtain their MVC (Cooke et al., 2011). They were not aware that the MVC informed the subsequent physical tasks. Participants held a bespoke handgrip dynamometer (Radwin et al., 1991) in their dominant hand, placed on their knee, with their arm flexed at approximately 100°. Participants performed a maximal contraction of the handgrip dynomometer and the peak force was recorded. This was repeated three times, with each contraction separated by a 1-min rest to allow for recovery; the largest peak force achieved was recorded as the MVC. If the second highest peak force was not within 5% of the highest, another contraction was performed.

3.4. Cognitive task

The cognitive task was the congruent or incongruent color word Stroop task. Task duration was 5, 10 or 20 min. The incongruent Stroop task (Stroop, 1935) required participants to indicate the font color (red, blue, green and yellow) of a color word from two possible answers displayed in a black font in the bottom left and right corners of the display with a corresponding left (Z) or right (/) keyboard button press. Participants received verbal and written instructions (Fig. S2, Supplementary Materials) prior to the task. In the congruent task, the word was displayed in the same color as its meaning, whereas in the incongruent task they were different. Only the incongruent Stroop task requires response inhibition and working memory (Milham et al., 2003), which could deplete the global self-control resource as proposed by the strength model of self-control. For both tasks, the stimulus was presented for 2500 ms or until a response was made, followed by a fixation cross for 500 ms. The task was implemented with E-Studio (version 2.0.1.97, Psychology Software Tools, Inc., USA). Performance was measured by reaction time (ms) and accuracy (% correct).

3.5. Handgrip task

The physical task required participants to maintain an isometric hold of the handgrip dynamometer with their dominant hand at 30% of their MVC for as long as possible (see Fig. S3, Supplementary Materials). Visual feedback was given to participants via a single 40 mm wide by 55 mm high dual-color (green, red) 7-segment light emitting diode panel that indicated the percent of their MVC, above or below the 30% threshold, their current grip force represented. Green numbers indicated a force equal to, or greater than, 30% MVC, whereas red numbers indicated a force less than 30% MVC. Participants were instructed to maintain a grip force that ensured a low green number for as long as possible. Task performance was determined by the duration of the isometric hold and was measured from task onset to the point when grip force fell below 30% MVC for more than 2 s. Force was measured via a Power 1401 (Cambridge Electronic Design Limited, UK) multi-channel analogue-to-digital convertor (16-bit resolution at a sampling rate of 2.5 kHz) and the output continuously recorded on a computer using Spike 2 software (version 6.06).

3.6. Novel cognitive task

The novel cognitive task was a 5-min incongruent number Stroop task. Participants were required to indicate how many words were displayed from a list of number words (between one and four) of the same type (e.g., two, two, two); the correct answer was the number of words in the list (e.g., three) whereas the incorrect answer included the number that the words represented (e.g., two). The two possible answers (e.g., 'two' or 'three') were displayed in black font in the bottom left and right corners of the display, and participants responded with either a left (Z) or right (/) keyboard button press. Participants received verbal and written instructions (Fig. S4, Supplementary Materials) prior to the task. The task was implemented with E-Studio (version 2.0.1.97, Psychology Software Tools, Inc., USA). Performance was measured by the reaction time (ms) and accuracy (% correct).

3.7. Psychological state measures

Fatigue and exertion. The cognitive tasks were rated immediately following completion for mental exertion and mental fatigue on 10-point category ratio (CR-10) scales. The mental exertion scale was anchored with the extreme descriptors "nothing at all" and "maximal mental exertion". The mental fatigue scale was anchored with the extreme descriptors "nothing at all" and "totally exhausted". Participants were reminded that these scales related to mental tiredness and exertion and not physical sensations. Following the cognitive and physical task, items (exhausted, sleepy, tired, worn-out) from the fatigue subscale of the profile of mood states (POMS) were rated on a 5-point scale with anchors of 1 "not at all" and 5 "extremely" (Terry et al., 2003). Ratings of perceived exertion (RPE) were given verbally immediately at task failure on a 10-point CR-10 scale (Borg, 1982), anchored with the descriptors "nothing at all" and "maximal". The standard instructions for the scale (Borg, 1998) were read to participants prior to each physical task.

Interest and enjoyment. Task interest and enjoyment was measured using the interest/enjoyment subscale of the intrinsic motivation inventory (McAuley et al., 1989). Participants were presented with seven items (e.g., "I enjoyed doing this activity very much", "I would describe this activity as very interesting"), and responded on a 7-point scale, with anchors of 1 "not true at all" and 7 "very true".

3.8. Statistical analysis

Statistical analysis was carried out using SPSS 27 software (SPSS: An IBM Company, Chicago, IL, United States). Statistical significance was set at $p \leq .05$. All data values were expressed as mean ± standard deviation of the mean ($M \pm SD$) unless otherwise stated. Partial eta-squared (ηp2) was reported as the effect size, with values of 0.02, 0.13 and 0.26 indicating small, medium and large effects, respectively (Cohen, 1992). All ANOVA tests included sex as a covariate to control for the effects of any imbalance in the number of males and females in each group. Significant ANCOVA effects were followed by least significant difference post-hoc tests.

4. Results

4.1. Group allocation

The random group allocation resulted in 7, 14 and 15 females and 23, 16 and 15 males allocated to the congruent group with cognitive task duration of 5, 10 and 20 min respectively. In the incongruent condition, 14, 12 and 15 females and 16, 18 and 15 males were allocated to cognitive task duration of 5, 10 and 20 min respectively.

4.2. Handgrip task performance

Performance on the word Stroop task, handgrip task, and number Stroop task are shown in Table 1. A 2 group (incongruent, congruent) by 3 duration (5, 10, 20 min) ANCOVA, with sex as covariate, on grip hold duration in the handgrip task yielded a group main effect, $F(1, 173) = 3.90$, $p = .05$, $\eta^2 = 0.02$, and a group-by-time interaction effect, $F(2, 173) = 3.29$, $p = .04$, $\eta^2 = 0.04$. Overall, endurance time was 12% shorter after the incongruent Stroop (153 ± 63 s) compared to the congruent Stroop (173 ± 75 s). As can been seen in Table 1, endurance was only shorter following incongruent Stroop compared to congruent Stroop for the 10-min tasks. Finally, a 2 group (incongruent, congruent) ANCOVA, with sex as covariate, on the MVC, yielded no group differences in handgrip strength, $F(1, 177) = 3.50$, $p = .06$, $\eta^2 = 0.02$, between the incongruent ($M = 439 \pm 113$ N) and congruent groups ($M = 429 \pm 99$ N).

4.3. Color word stroop task performance

Separate 2 group by 3 duration ANCOVAs, with sex as covariate, were performed on the percentages of correct responses and reaction times in the color word Stroop task. This yielded a condition main effect for reaction times, $F(1, 173) = 225.91$, $p < .001$, $\eta^2 = 0.56$, with faster responding in the congruent task (590 ± 84 ms) than the incongruent task (817 ± 122 ms). For reaction times, there was no main effect for duration, $F(2, 173) = 2.82$, $p = .06$, $\eta^2 = 0.03$, and no group-by-duration interaction effect, $F(2, 173) = 0.59$, $p = .56$, $\eta^2 = 0.01$. The percentage of correct responses analysis yielded no main effects for group, $F(1, 173) = 2.94$, $p = .09$, $\eta^2 = 0.02$ ($M_{congruent} = 96 \pm 3\%$, $M_{incongruent} = 96 \pm 3\%$), duration $F(2, 173) = 0.51$, $p = .60$, $\eta^2 = 0.01$, and group-by-duration, $F(2, 173) = 2.54$, $p > .05$, $\eta^2 = 0.03$.

To explore changes in cognitive task performance with practice, we computed reaction times and accuracy in four 5-min blocks of the 20-min tasks, and ran 2 group (incongruent, congruent) by 4 block (0–5, 6–10, 11–15, 16–20 min) ANOVAs on performance scores. The reaction time analysis revealed a group-by-block interaction effect, $F(3, 55) = 4.17$, $p = .01$, $\eta^2 = 0.19$. The incongruent group responded progressively faster from the first to fourth block: 880 ± 103 ms, 832 ± 143 ms, 775 ± 146 ms, and 756 ± 151 ms. In contrast, the congruent group responded the same throughout: 592 ± 103 ms, 592 ± 143 ms, 581 ± 144 ms, and 564 ± 143 ms. Although the analysis on the percentage of correct responses scores yielded a block main effect, $F(3, 55) = 5.45$, $p < .001$, $\eta^2 = 0.26$, (Block 1: 96.35 ± 2.75%, Block 2: 95.63 ± 3.85%, Block 3: 95.67 ± 3.25%; Block 4: 95.83 ± 3.17%), no group-by-block interaction effect emerged.

Table 1
Performance scores on the color word Stroop, handgrip, and number word Stroop tasks as a function of task type (congruent, incongruent) and duration (5, 10, 20 min). Data presented as *M* ± *SD*.

Task	Congruent Stroop			Incongruent Stroop		
	5-min	10-min	20-min	5-min	10-min	20-min
Color Word Stroop						
Correct (%)	97.20 ± 1.83	95.43 ± 2.81	96.23 ± 3.18 [b]	95.20 ± 3.00 [a]	95.87 ± 2.65	95.92 ± 2.89 [d]
RT (ms)	594 ± 84	595 ± 75	580 ± 95	885 ± 144 [a]	834 ± 145 [b]	817 ± 122 [c]
Handgrip						
Endurance (s)	162 ± 56	186 ± 69	172 ± 96	151 ± 63	130 ± 49 [b]	178 ± 69
Number Word Stroop						
Correct (%)	87.57 ± 3.07	86.03 ± 3.87	86.23 ± 2.98	88.00 ± 3.13	88.17 ± 2.07 [b]	87.87 ± 2.65 [c]
RT (ms)	889 ± 134	865 ± 130	899 ± 131	861 ± 105	859 ± 100	871 ± 114

Superscripts [a], [b] and [c] indicate significant ($p < .05$) difference from 5-min, 10-min and 20-min congruent Stroop groups, respectively. Superscript [d] indicates significant ($p < .05$) difference from 5-min incongruent Stroop group.

4.4. Number word stroop task performance

Separate 2 group by 3 duration ANCOVAs, with sex as a covariate, were performed on the percentage of correct responses and reaction times for the number word Stroop task. This showed a group main effect for the percentage of correct responses, $F(1, 173) = 9.99$, $p = .002$, $\eta^2 = 0.06$, with the congruent group ($M = 86.61 \pm 3.36\%$) less accurate than the incongruent group ($M = 88.01 \pm 2.62\%$). There was no duration main effect, $F(2, 173) = 0.95$, $p = .39$, $\eta^2 = 0.01$, and no group-by-duration interaction effect, $F(2, 173) = 1.07$, $p = .35$, $\eta^2 = 0.01$. However there were significant differences for tasks of 10 and 20 min with the congruent group ($M = 86.05 \pm 3.01\%$ for 10 min and $M = 86.26 \pm 3.01\%$ for 20 min) less accurate than the incongruent group ($M = 88.16 \pm 3.01\%$ for 10 min and $M = 87.90 \pm 3.01\%$ for 20 min). In the case of reaction times, there were no effects for group, $F(1, 173) = 1.48$, $p = .23$, $\eta^2 = 0.01$, ($M_{congruent} = 884 \pm 131$ ms, $M_{incongruent} = 863 \pm 105$ ms) or group-by-duration, $F(2, 172) = 0.25$, $p = .78$, $\eta^2 = 0.00$.

4.5. Ratings

Fatigue and exertion. A series of 2 group by 3 duration ANCOVAs, with sex as a covariate, were performed on POMS ratings of general fatigue (Table 2). At baseline, there were no group, $\mathbf{F}(1, 173) = 0.03$, $p = .86$, $\eta^2 = 0.00$, or duration, $F(2, 173) = 0.19$, p - = .83 $\eta^2 = 0.00$, differences in general fatigue. After the color word Stroop task, there were duration, $F(2, 173) = 13.25$, $p < .001$, $\eta^2 = 0.13$ ($M_{5\text{-min}} = 2.26 \pm 0.85 < M_{10\text{-min}} = 2.79 \pm 0.95 < M_{20\text{-min}} = 3.08 \pm 0.87$), and group-by-duration, $F(2, 173) = 4.62$, $p = .01$, $\eta^2 = 0.05$, effects, with more fatigue experienced by the 10-min congruent group than the 10-min incongruent group. After the number word Stroop task, there was a group-by-duration interaction effect, $F(2, 173) = 3.36$, $p = .04$, $\eta^2 = 0.04$, with greater general fatigue among the 10-min and 20-min congruent groups than the respective incongruent groups.

A series of 2 group by 3 duration ANCOVAs, with sex as a covariate, were performed on ratings of mental fatigue at baseline and following the Stroop tasks (Table 3). At baseline, analysis revealed no group, $F(1, 173) = 0.52$, $p = .82$, $\eta^2 = 0.01$, or duration, $F(2, 173) = 1.04$, $p = .36$, $\eta^2 = 0.10$, differences in mental fatigue. For the color word Stroop task, the analysis revealed a main effect for duration, $F(2, 173) = 21.01$, $p < .001$, $\eta^2 = 0.20$ ($M_{5\text{-min}} = 3.00 \pm 1.95 < M_{10\text{-min}} = 4.83 \pm 2.19 < M_{20\text{-min}} = 5.02 \pm 2.05$), and a group-by-duration interaction effect, $F(2, 173) = 5.48$, $p = .01$, $\eta^2 = 0.06$. Similarly, to the general fatigue ratings, mental

Table 2
General fatigue (POMS ratings) at baseline, following the color word Stroop task, and following the number word Stroop task as a function of task type (congruent, incongruent) and duration (5, 10, 20 min). Data presented as *M* ± *SD*.

Task	Congruent Stroop			Incongruent Stroop		
	5-min	10-min	20-min	5-min	10-min	20-min
Baseline	1.95 ± 1.01	2.16 ± 0.83	2.11 ± 1.17	2.10 ± 0.79	2.10 ± 0.83	2.1 ± 1.01
Color Word Stroop	2.04 ± 0.77	3.05 ± 0.95 [a]	3.17 ± 0.88 [a]	2.48 ± 0.87	2.53 ± 0.88 [b]	2.98 ± 0.86 [c, d]
Number Word Stroop	2.37 ± 0.75	2.95 ± 0.86 [a]	3.16 ± 0.99 [a]	2.88 ± 0.92	2.63 ± 0.95	2.89 ± 0.99

Superscripts [a] and [b] indicate significant ($p < .05$) difference from 5-min and 10-min congruent Stroop groups, respectively. Superscripts [c] and [d] indicate significant ($p < .05$) difference between 5-min and 10-min incongruent Stroop groups, respectively.

Table 3
Mental fatigue (CR-10 ratings) at baseline, following the color word Stroop task, and following the number word Stroop task as a function of task type (congruent, incongruent) and duration (5, 10, 20 min). Data presented as $M \pm SD$.

Task	5-min	Congruent Stroop		Incongruent Stroop		
		10-min	20-min	5-min	10-min	20-min
Baseline	1.43 ± 1.77	2.31 ± 1.76	2.15 ± 2.55	1.97 ± 1.85	1.87 ± 1.73	2.26 ± 1.77
Color Word Stroop	2.59 ± 1.98	5.60 ± 2.00 [a]	5.33 ± 2.33 [a]	3.41 ± 1.94	4.07 ± 2.12 [b]	5.07 ± 1.76 [c, d]
Number Word Stroop	3.85 ± 1.99	5.28 ± 2.06 [a]	5.23 ± 2.77 [a]	4.46 ± 2.67	3.89 ± 2.28 [b]	4.58 ± 2.07

Superscripts [a] and [b] indicate significant ($p < .05$) difference from 5-min and 10-min congruent Stroop groups, respectively. Superscripts [c] and [d] indicate significant ($p < .05$) difference from 5-min and 10-min incongruent Stroop groups, respectively.

fatigue was greater after the 10-min congruent task than the 10-min incongruent task. Mental fatigue following the number word Stroop task did not differ by group, $F(1, 173) = 1.05$, $p = .31$, $\eta^2 = 0.00$.

Separate 2 group by 3 duration ANCOVAs, with sex included as a covariate, were performed on ratings of mental exertion following the color word Stroop and number word Stroop tasks. Results for the color word Stroop task revealed a duration main effect, $F(2, 173) = 9.07$, $p < .001$, $\eta^2 = 0.95$, with ratings of 4.07 ± 2.19, 5.54 ± 2.24 and 5.26 ± 1.98 in the 5-min, 10-min and 20-min tasks, respectively. Importantly, there were no group differences in mental exertion following the cognitive tasks. A 2 group ANCOVA, with sex as a covariate, on ratings of perceived exertion following the physical task revealed no group effect, with average exertion ratings of 2.59 ± 1.78 in the congruent group and 2.24 ± 1.37 in the incongruent group.

Interest and enjoyment. A 2 group by 3 task (color word Stroop, handgrip, number word Stroop) ANCOVA, with sex as covariate, on task interest and enjoyment revealed a main effect for task, $F(2, 176) = 6.78$, $p < .001$, $\eta^2 = 0.07$, with higher ratings in the handgrip task ($M = 3.76 \pm 1.03$) than both the color word Stroop ($M = 3.24 \pm 1.07$) and number word Stroop ($M = 3.34 \pm 0.96$) tasks. Neither the group main effect, $F(1, 177) = 0.66$, $p > .42$, $\eta^2 = 0.00$, nor the group-by-task interaction effect, $F(2, 176) = 1.38$, p = .26, $\eta^2 = 0.02$, were significant.

5. Discussion

Adopting a triple task paradigm, this is the first study, to our knowledge, to investigate the *ego depletion* effect in relation to subsequent performance of both a physical task and another novel cognitive task as a function of the duration of a prior cognitive task. The three study purposes were to investigate the effects of cognitive task duration on (1) subsequent physical endurance performance, (2) concurrent cognitive task performance, and (3) subsequent novel cognitive task performance.

5.1. Subsequent endurance performance

The first study purpose was to investigate the dose-response relationship concerning the effect of the duration of a cognitive response inhibition task (relative to a control task) on subsequent physical endurance performance. We hypothesized that cognitive task duration would be inversely related to subsequent endurance performance. Contrary to expectation, this hypothesis was not supported by our findings. An *ego depletion* effect (i.e., worse endurance performance following incongruent than congruent color word Stroop task) was found for 10-min but not for 5-min and 20-min task durations. This observation is consistent with a previous study (Brown & Bray, 2017) showing that incongruent Stroop tasks lasting 2-min and 4-min did not impair subsequent isometric handgrip task performance at 50% MVC. However, another study (Bray et al., 2008) reported that endurance performance on a 50% MVC isometric handgrip task was reduced by 43% (14 s) after completing just 3 min and 40 s of an incongruent Stroop task compared to a congruent Stroop task. Based on this finding, we expected an *ego depletion* effect for handgrip endurance performance following a 5-min Stroop task. This non-replication may be attributed to slight methodological differences between the two studies, including the force requirement and the use of a baseline condition. Specifically, we required participants to squeeze the dynamometer at a lower intensity (i.e., 30% MVC), eliciting less muscle activity during the task, which is likely to have required less self-control resources (Brown & Bray, 2015). Unlike our protocol, Bray and colleagues included a baseline assessment of isometric endurance performance before the Stroop task. This initial endurance task may have impacted subsequent endurance performance because of residual increased peripheral physiological fatigue and/or increased consumption of central resources used to precisely regulate and maintain force production close to the 50% MVC requirement.

In line with expectation, we observed a deleterious effect of a 10-min color word Stroop task on subsequent physical task performance; with endurance reduced by 43% (56 s) after the incongruent task relative to the congruent task. This observation is consistent with previous findings (Brown & Bray, 2017) showing that incongruent Stroop tasks lasting 6-min, 8-min, and 10-min uniformly impaired subsequent isometric handgrip task performance at 50% MVC. However, their study did not investigate the effects of Stroop tasks longer than 10 min, and therefore, we cannot compare our findings for a 20-min task. According to the *strength model*, we should have observed the greatest impairment in endurance performance following the longest Stroop task, as previously reported (Boat et al., 2020) and hypothesized. However, our findings agree with the vast majority of research studies (for review see Giboin & Wolff, 2019) noting a non-linear relationship between cognitive task engagement and subsequent physical performance.

Although maximal muscular contractions require high self-control, motivation, and mental effort to fully recruit all motor units in the muscles, it is often reported that performing a prior cognitive task does not affect subsequent maximal muscular contractions (Martin et al., 2015; Pageaux et al., 2013). This provides further evidence against the *strength model* as an explanation of impaired exercise performance following brief cognitive tasks. Instead, the *EVC model* offers a better explanation for our findings. Specifically, 5 min of the incongruent Stroop task was insufficient time to impair the ability to switch between the two control-demanding tasks and select the appropriate signal identity required for the physical task following engagement in the short duration response inhibition task. Therefore, this cognitive task duration did not impact the following physical outcome task. When the task duration was doubled to 10 min a decrease in performance was observed. As postulated by the *EVC model,* this could be due to an increase in the inherent cost of engaging control as time progressed, which varies with the intensity of the signal required and/or the increase in Stroop task errors and associated demands of error monitoring. However, when this was doubled again to 20 min, the detrimental effect on performance was diminished, possibly due to adaptation (e.g., learning) (and a reduced intrinsic task cost) to the color word Stroop response inhibition task (see below).

5.2. Concurrent cognitive performance

The second study purpose was to investigate performance on the cognitive task as a function of task duration. Based on the *strength model,* we hypothesized that cognitive performance would decrease with time due to a progressively depleted resource pool. Contrary to expectation, no such decrement was observed for either the congruent or incongruent tasks. In agreement with the classic Stroop effect (Macleod, 1991), the incongruent task was associated with slower reaction times, indicative of the higher cognitive processing demands imposed by response inhibition, compared to the congruent task. The percentage of correct responses was the same for the incongruent and congruent tasks, indicating that this slowing effect was independent of response accuracy.

To explore potential task learning and adaptation effects in the Stroop task, we divided the 20-min task into 5-min blocks. In the congruent Stroop task, performance did not vary with time on task. However, in the incongruent task, performance speed and accuracy improved with time. Reaction times decreased progressively every quarter until the last, suggesting adaptation to response inhibition demands, thereby having no impact on subsequent physical task performance relative to the congruent group. Consistent with our findings, previous studies have reported improved performance (i.e., decreased reaction time) on the incongruent color word Stroop test relative to baseline, even when separated by a physical depletion task (Brown & Bray, 2015). Additionally, learning effects on the incongruent Stroop task have been documented: response accuracy was higher after 144 trials than 48 trials (Dang et al., 2013), reaction times decreased across six 64-trial blocks (Davidson et al., 2003), and faster reaction times in the second of three 50-trial blocks (Edwards et al., 1996). Indeed, practice effects are well established for the Stroop task (Macleod, 1991). Importantly, these time on task performance improvements are compatible with the *EVC model* which contends that the allocation of attentional resources to the task at hand are likely to improve performance, rather than the *strength model*, which contends that performance should deteriorate due to a reduction in the global self-control resource.

5.3. Subsequent novel cognitive performance

The third study purpose was to investigate the effects of the duration of a cognitive task on subsequent novel cognitive task performance. We hypothesized that cognitive task duration would be inversely related to subsequent cognitive performance, namely, response speed and accuracy on a number word Stroop task. We found faster reaction times following the incongruent than the congruent color word Stroop task, whereas correct responses did not differ between the task types. These effects were not moderated by the duration of the color word Stroop task. The finding that reaction times in the Stroop number word task were faster following the incongruent Stroop color word task implies learning or adaptation to response inhibition during the initial cognitive task, which persists and transfers to the subsequent novel cognitive task. Importantly, this finding supports the *EVC model* and opposes *the strength model*.

5.4. Task ratings

Interest and enjoyment, reflecting intrinsic motivation (Intrinsic Motivation Inventory, 1994), did not vary by task type and duration, indicating that participants were equally motivated to perform the tasks. This may be because, at least in part, they were encouraged to perform by social evaluation and comparison, with performance displayed on a noticeboard in the laboratory. We expected that mental exertion, mental fatigue and general fatigue would be higher in the incongruent than congruent tasks, but where task-related differences were found (i.e., in the 10-min and 20-min tasks), the opposite occurred (see Tables 2 and 3). Accordingly, the shorter endurance performance following the 10-min incongruent color word Stroop condition cannot be attributed to increased mental fatigue caused by the cognitive task. Additionally, if mental fatigue was the cause of the decreased physical performance, we would have expected to see an increase in the overall perceived exertion rating for the physical tasks, however, no differences were detected. Studies have typically used prolonged duration (90 min) of the AX Continuous Performance Test (AX-CPT) cognitive task to induce a state of mental fatigue when investigating its impact on whole-body endurance exercise (MacMahon et al., 2014; Marcora et al., 2009). In these studies, performance varies across the AX-CPT task, with a 5% reduction in the accuracy of correct responses in the first 15 min relative to the last 15 min (Marcora et al., 2009), and with no change from the first to last 3-min periods (MacMahon et al., 2014). It is possible that a 3-min period may have been too short to measure performance differences due to task adaptation in the very early periods of the task, which may be masked when performance is measured over a longer period (i.e., 15 min). We observed an increase in reaction time and number of correct responses in the first three 5-min blocks of the 20-min incongruent color word Stroop task; the plateauing of performance in the last 5-min block suggests learning and adaptation to response inhibition effects. Interestingly, if the task duration was increased past 20 min, it is possible that a state of mental fatigue would have developed and task performance would have deteriorated (Cutsem et al., 2017).

5.5. Limitations and directions

Our study findings should be interpreted considering potential study limitations. First, perceived exertion was only rated retrospectively about the entire physical task, whereas it would have been useful to characterize its development during the task. However, pilot testing indicated that the requirement to provide ratings during the task was distracting and caused premature termination. Second, we employed an active control task; the congruent Stroop task may have induced a mild state of mental fatigue and impaired performance on the subsequent task. Instead, we could have employed a passive control task (e.g., watching an emotionally neutral documentary) that would not induce fatigue or affect subsequent performance. Third, we used a triple rather than the typical double sequential task paradigm. It is therefore difficult to contextualize our performance effects on the Stroop number word task. Future studies would do well to adopt the triple paradigm to examine the ego depletion effect because it can use tasks from the same and different domains, thereby providing further insight into the effect of domain switching on the ego depletion effect. Fourth, we only examined tasks that lasted between 5 and 20 min. Shorter and longer tasks could be included to paint a fuller picture of the effects of task duration on the ego depletion effect (e.g., characterize learning and adaptation effects). Finally, no ratings of boredom were taken, which could have been a confounding factor. Recent research (Mangin et al., 2021) and discussion (Englert et al., 2021; Wolff & Martarelli, 2020) has argued that a boring control task (such as a congruent word Stroop) can be as depleting as a demanding cognitive manipulation task (such as an incongruent word Stroop) and accounts for some of the discrepancy in the ego depletion research. The potential role of boredom has also been accounted for by the *EVC model* (Bieleke et al., 2023) warranting its consideration in this study. However, we did take ratings of interest and enjoyment which could be expected to be the inverse of state boredom measures. There were no group differences in ratings of interest/enjoyment between the congruent and incongruent conditions, which implies we can reduce the likelihood of, but not completely rule out, boredom as a factor when interpreting our findings. Importantly, future research should evaluate the ego depletion effect with respect to the *EVC model*.

6. Conclusion

The present study used a triple sequential task (cognitive – physical – cognitive) design to investigate the *ego depletion* effect in the physical and cognitive domains. We demonstrated that a response inhibition cognitive (color word Stroop) task impairs subsequent endurance performance on a submaximal handgrip task, but only following a 10-min task and not following 5-min and 20-min tasks. It is likely that the brief 5-min and long 20-min cognitive tasks did not impair subsequent physical performance because the former created insufficient response inhibition and the latter allowed adaptation to response inhibition. The response inhibition cognitive task facilitated performance on a novel (number word Stroop) cognitive response inhibition task, suggesting positive transfer between the two different cognitive tasks. These key findings are compatible with the *EVC model* rather than the *strength* *model*. The *strength model* has faced multiple challenges and criticisms (see Introduction) and was originally developed to explain the *ego depletion* effect in everyday contexts rather than exercise. However, research on the *ego depletion* effect for physical tasks shows that the *EVC model* better accounts for the adaptation to task demands, which improve performance, and for the improvement in performance when switching to a novel task domain.

Declaration of competing interest

The authors declare no conflict of interests.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2023.102459.

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