Engagement matters: pupil and mental effort mediate depletion effect on subsequent physical tasks

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Abstract

Self-control depletion theory claims to account for between-task performance changes in terms of the consumption of a limited cognitive resource. Dual-task designs have been used to demonstrate that increased self-control on an initial effortful task predicted a decreased use of self-control on a later categorically distinct effortful task, suggesting a limited resource model. These accounts struggle to identify specific mechanisms linking them to rational theories of effort, and the reported effect size has recently come into question. Subject engagement during the depleting task is often assumed, but systematic disengagement may account for inconsistencies in the observed effect. We recreated a common dual-task depletion paradigm using a computer-automated design allowing for measurement of individual task performance as well as pupil size. We found evidence that task engagement measures do indeed account for some individual variation in the depletion effect, offering a possible explanation for inconsistent group-level effects.

Keywords: Effort, Decision-making, Control, Depletion, Pupil

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1 Background

Why do we sometimes feel physically drained after a long day at the office? Going to the gym, cooking dinner, or even deciding what to watch on Netflix may feel more effortful than it does on the weekend. It seems intuitive that performance should decrease over time for physically strenuous tasks to prevent injury, but why should this be the case for mental performance? The physiological constraints of cognition are unknown, but tasks that engage executive functions are associated with a sense of mental effort. The perception of effort is now thought to be centrally generated (not an afferent feedback signal from metabolically strained tissue) [1]. Resource-depletion models capture a nonrational (i.e., not based upon explicit value calculation) aspect of performance deterioration on effortful tasks.

Resource-depletion theories explain performance reductions in terms of the “depletion” of some limited resource in proportion to the duration and magnitude of expended cognitive control [2,3]. Dual-task designs have been used to demonstrate that increased self-control on an initial effortful task predicted a decreased use of self-control on a later effortful task [6,7]. Mechanistic accounts of limited metabolic resources [4,5] are challenged by observations that increasing the future reward for continuing a demanding task seems to mitigate the immediate performance drop. These finding support models that frame self-control as a type of limited cognitive resource. Performance reductions predicted by self-control depletion theory (i.e., Ego Depletion) have now been supported by hundreds of studies, incorporating the use of conscious inhibition on effortful tasks demanding physical, mental, emotional, and appetitive control [8]. However, the theory has not provided clear neurophysiological or computational targets. In addition, a recent pre-registered, multisite study of a classic dual-task pairing produced a null finding, reinforcing questions about effect size inflation from publication bias [9,10].

Due to inconsistent reports from depletion studies, we sought to recreate a classic self-control depletion paradigm using an automated format capturing individual changes in performance and engagement. Can we find a depletion effect in an automated paradigm? Accounting for individual differences in task engagement may reveal a reason for the inconsistent reports of the depletion effect. Is performance on the depleting task and overall engagement necessary to produce a depletion effect?

2 Methods

This study was designed to recreate the classic self-control depletion findings reported in the literature [8]. The depleting task, “crossing out E’s”, was chosen for the reported large effect size. All blocks of the task were computer-automated using Matlab. Pupillometry data was recorded at 30 Hz using an Eye Tribe eye tracker. The dependent physical effort task was created to match the effort in squeeze-bar tasks, where subject must maintain a certain grip over time. Instead of a grip bar, this study required subjects to tap the left and right arrow keys on a keyboard as quickly as possible. This alternating, “running” motion of the fingers on one hand was maintained above an individually set threshold rate (70% of maximum individual tap rate) for as long as possible.

Depleting Task, Mental Effort. In the first crossing out “E’s” task subjects were instructed to click on as many “E’s” as possible on a page of random letters in paragraph format over 4 minutes (forming a habit of clicking all “E’s”). This was followed by a second page where participants were randomized to either a control group (where the instructions were the same as the first page) or an experimental depletion group (where they were instructed to cross out “E” as long as it was not directly next to or one space away from any vowel—requiring inhibition of previously formed habit and holding rules in working memory). A circle appears around an “E” only after a correct click.

Dependent Measure, Physical Effort. The above task was followed by the dependent measure where participants were instructed to press the left and right arrow keys in an alternating fashion using only one hand. Participants’ time above their individualized threshold rate was measured. Times above threshold
were normalized by the threshold value. A difference in the total time that subjects performed above threshold between conditions was the main expected effect.

Subjects completed a repeated-measures crossover version of the dual-task paradigm. Condition grouping was randomly assigned to complete two blocks of easy (control) tasks followed by two blocks of hard (depleting) tasks or vice versa for a total of four blocks for a 50-minute total time. A total of 77 subjects completed the study (38/39 per order condition).

3 Results and Discussion

3.1 Physical performance declines after difficult mental task, but only before crossover

The main predicted effect of decreased physical performance following difficult mental tasks was not present across all blocks, but was present between groups on the first block. A trend in the predicted direction (greater performance after easy) was observed before the difficulty crossover, but not on blocks after. This modest, but significant effect resembles the same trend seen in an earlier behavioral study (no pupillometry) and a replication study — no other null-finding studies or data have been excluded. Non-parametric one-way ANOVA was used to detect group difference.

3.2 Pupil diameter is smaller during difficult mental task

Pupil diameter was significantly smaller during the difficult mental effort task. This reduction in mean pupil size was not due to differences in pupil event related potentials (pERP) associated with finding target
“E’s”. The significant reduction in pupil is still present when pERP’s are computed with a freely varying baseline.

3.3 Pupil diameter during the difficult mental task correlates with mental performance

A reduced pupil diameter on a task designed to produce increases in cognitive demands was an unexpected result. Increases in mental workload are generally associated with increased arousal, resulting in increases in pupil size. We then investigated if decreased pupil size was representing systematic task disengagement by subjects. To do this we quantified performance on each page of the mental effort task as a mean reward rate (response accuracy/inter-response interval) as correct response per second. This measure captures the tradeoff between speed and accuracy to quantify total mental performance. For example, 80% accuracy with correct clicks every 2 second would yield a high score of 0.4 (0.8/2). High accuracy with long response times or low accuracy with fast response times produce middling scores (1.0/10 = 0.1 or 0.2/2 = 0.1).

Individualized difference scores were created by subtracting page 2 (difficult) from page 1 (control). These scores were averaged across both difficult blocks and then correlated with average pupil size difference scores calculated in the same way. It was found that higher relative mental performance correlated with decreased relative pupil diameter. This correlation suggests that smaller pupil size reflects task engagement.
3.4 **Pupil diameter and performance on difficult mental task correlates with physical performance**

Relative pupil diameter and mental performance on difficult blocks were then separately correlated with subsequent physical performance for each subject averaged across both difficult blocks. It was found that lower relative mental performance (dM) predicted greater subsequent physical performance. This finding suggests that the performance changes observed after difficult mental tasks (the depletion effect) is mediated not only by categorical task difficulty, but also by individual performance on the difficult task (i.e., greater mental performance leads to greater depletion effect). Similarly, greater relative pupil size (dP) predicted higher subsequent physical performance (T). This is consistent with an interpretation that decreased pupil size is indicative of increased task engagement with an associated increase in cognitive performance. Multiple regression analysis (T ~ dP + dM) with a follow-up mediation analysis (using R’s “mediation” package [16]) revealed a total effect of dP and dM where the effect of mental performance is mediated by pupil diameter.

Overall these findings suggest that the inconsistent results reported in the self-control depletion literature may be due in part to the failure to control for individual subject engagement on the depleting task. Using experimental paradigms that allow for quantification of individual performance on the depleting task combined with pupillometry (an increasingly affordable and non-invasive psychometric tool) offer a method for controlling for task engagement.

4 **References**