Feeling Rushed? Perceived Time Pressure Impacts Executive Function and Stress

Rachel F. Sussman
Department of Psychology and Program in Neuroscience
Brandeis University, Waltham MA USA

Robert Sekuler
Volen Center for Complex Systems and Department of Psychology
Brandeis University, Waltham MA USA
Abstract

The components of executive function (EF) are critical to everyday life, but they can be undermined by adverse psychological states like stress and negative affect. Inadequate time to perform a task is a particularly common stressor that can disrupt EF. Although the impact of actual time pressure on task performance is well-established, little is known about how self-generated, perceived time pressure (PTP) affects EF in the absence of objective time limits. We chose Eriksen’s Flanker task as an index of cognitive inhibition, a key component of EF, and we varied the interval between successive trials, the inter-trial interval (ITI), to proxy PTP. This manipulation strongly affected task performance: shrinking the ITI to increase PTP diminished cognitive inhibition and increased both stress and negative affect. Subsequently lengthening the ITI reversed nearly all of these effects, except stress, which persisted. Multilevel linear regression modeling revealed that PTP and stress significantly predicted inhibition, and exploratory mediation modeling suggested that stress causally mediates the relationship between PTP and inhibition. These findings validate perceived time pressure’s stressor status and demonstrate EF’s sensitivity to changes in PTP.

Keywords: Perceived time pressure, inter-trial interval, executive function, cognitive inhibition, stress, negative affect
Feeling Rushed? Perceived Time Pressure Impacts Executive Function and Stress

Introduction

The processes that constitute executive function (EF) influence how we operate in everyday life. One of these components, inhibition, is responsible for our ability to prioritize goal-relevant information while discounting irrelevant or distracting information (Diamond, 2013; Shields, Sazma, & Yonelinas, 2016). There are two components of inhibition, response and cognitive: response inhibition refers to the processes involved in preventing prepotent responses, while cognitive inhibition instead reflects interference control, i.e. selectively attending to and ignoring information (Shields et al., 2016). However, cognitive inhibition can be compromised by adverse psychological states like stress (Diamond, 2013; Snyder, Miyake, & Hankin, 2015; Shields et al., 2016), perhaps through the redistribution of cognitive resources away from the task at hand and towards coping with the stressor (Hockey, 1997; Steinhauser, Maier, & Hübner, 2007; Plieger & Reuter, 2020; Diamond, 2013; Shields et al., 2016; Mendl, 1999; van Moorselaar & Slagter, 2020; Vogel, Fernández, Joëls, & Schwabe, 2016).

One well known stressor is the pressure of limited time (Maule & Hockey, 1993; Maule, Hockey, & Bdzola, 2000; Gok & Atsan, 2016; Zuzanek, 1998; Zakay, 1993; Orbach, Herzog, & Fritz, 2020; Caviola, Carey, Mammarella, & Szucs, 2017; De Paola & Gioia, 2016). Given how often this stressor is experienced, it has received surprisingly little attention from researchers. One reason may be that time pressure is complex, actually composed of two distinct aspects. One aspect can be described as “objective,” meaning that it reflects an actual limit on the time available to perform a task. An example would be the pressure from a deadline defined in clock time (e.g., Dambacher & Hübner, 2015). This objective time pressure’s subjective counterpart has been even less studied. This subjective aspect of time pressure, which we term perceived time pressure (hereafter, PTP) refers to the sense of time pressure experienced in the absence of
genuine time limits (Zakay, 1990, 1993). An example might be an unfounded belief that an impending deadline is closer than it really is (e.g., Sun & Sekuler, 2021). Interestingly, PTP can be induced merely by encouraging somebody to think about the passage of time, even when time is not relevant to the task at hand (Zakay, 1990; DeDonno & Demaree, 2008). We set out to understand if PTP alone (1) induces a psychological stress response and (2) impacts cognitive inhibition.

For answers, we manipulated PTP by altering the length of the inter-trial interval (ITI), the time between successive trials in an experiment (Sun & Sekuler, 2021). This manipulation was meant to increase participants’ awareness of the task’s global pace without affecting the duration of individual trials or the time available for decision-making (Zakay, 1990). In other words, our manipulation did not impact any aspect of the trials themselves: stimulus duration and response windows were held constant throughout the experiment. Therefore, any time pressure arising from this manipulation of the ITI can be understood as unnecessary and self-generated rather than a result of a change in the task itself. This reflects perceived, not objective, time pressure (Zakay, 1990).

Throughout our project we use ITI duration as a proxy for PTP. We make no commitment to the exact form of the relationship between ITI and PTP, other than that they are monotonically related.

**Methods**

**Participants**

Ninety-five Brandeis University undergraduate students between the ages of 18 and 35 years old participated in exchange for course credit. All experimental procedures were approved by Brandeis University’s Committee for the Protection of Human Subjects, and all work was conducted in accordance with the Declaration of Helsinki. All participants provided informed consent. A power analysis done with the pwr package in R (Champely et al., 2018) confirmed the adequacy of our sample size. The analysis showed that 40 participants would be sufficient to detect a significant effect of ITI on
inhibition with 80% power in the regression model we planned.

Data from 18 participants were excluded: eight because of incomplete data, three because of software failures, five because for the experiment, which was conducted online, they used a web browser with suboptimal temporal precision (Bridges, Pitiot, MacAskill, & Peirce, 2020), and two because of consistently low accuracy (below 50%). This left usable data from 77 participants, mean age = 19.19 years, SD age = 1.26 years. Of these participants, 52 were female, and three did not identify as either female or male (two non-binary/genderqueer, one not sure/unknown).

Measures

Apparatus and stimuli. The experimental task was coded in PsychoPy (v.2.4), and run online through the Pavlovia server (Peirce et al., 2019; Pavlovia, 2020). The study used questionnaires that were hosted on the Qualtrics platform (Qualtrics, 2020). Because of restrictions imposed by the COVID-19 pandemic, all testing was conducted online. To make different participants’ testing environments as alike as possible, we adopted techniques that measured and then compensated for variation in participants’ screen sizes and viewing distances. First, to take account of the dimensions of each participant’s computer display, participants adjusted an image of a student ID card on the screen to match their physical Brandeis University student ID card (8.6 cm wide and 5.4 cm tall; Morys-Carter, 2020). Next, each participant’s viewing distance was estimated by a routine that located their blind spot relative to their screen width (Li, Joo, Yeatman, & Reinecke, 2020). These measures of screen size and viewing distance allowed PsychoPy to scale task-related stimuli to the same size in degrees of visual angle (°) for all participants. After completing these calibration procedures, participants were repeatedly encouraged to remain seated in their same position for the rest of the experiment.

Task. To measure cognitive inhibition, we used Eriksen’s Flanker task (Eriksen & Eriksen, 1974; Shields et al., 2016; Diamond, 2013). This task offers high test-retest
reliability and construct validity (Zelazo et al., 2014). In our implementation of the Flanker task, participants saw five horizontally aligned arrow heads (\(<\) or \(>\)\), and judged the direction in which the middle arrowhead pointed, left or right. We call that middle arrowhead the “Target,” and the four arrowheads surrounding it the “Flankers.” On half of the trials, the Flanker and Target arrowheads pointed in the same direction (hereafter, Congruent; for example, \(< < < < \text{ or } > > > > \text{ or } > > > > \text{ or } < < < < \text{ or } > > > > \text{ or } > > > > \text{ or } < < < < \). On the remaining trials, the Flanker and Target arrowheads pointed in opposite directions (hereafter, Incongruent; for example \(> > < > \text{ or } < < > < \)). Each arrowhead was 1° visual angle wide, and neighboring arrowheads were separated 1.25° visual angle center-to-center, making the entire horizontal array 6° wide, as in Lange-Malecki and Treue (2012).

On Incongruent trials, a correct response to the Target direction required participants to override the contradictory influence from the Flanker arrows, and base a decision on information from the Target arrow only. The need for such suppression is why performance on this task is able to reflect cognitive inhibition. Presentations of Congruent and Incongruent stimuli were randomly interleaved throughout the experiment. To calculate the Flanker effect, for each block of trials, we subtracted participants’ mean accuracy on Incongruent trials from their mean accuracy on Congruent trials. This calculation is thought to reflect the participant’s capacity for cognitive inhibition (e.g. Lange-Malecki & Treue, 2012; Berggren & Derakshan, 2013; Pacheco-Unguetti, Acosta, Callejas, & Lupiáñez, 2010; Shields et al., 2016). The speed of individual responses is sensitive to the overall tempo of an experiment (Ellis & Jones, 2010), which would complicate the interpretation of response speed in our experiment. Therefore, we focused mainly on response accuracy as an index of cognitive inhibition.

An onscreen text display reminded participants to use the computer’s keyboard to communicate judgements of the Target’s direction, pressing the “f” key if the middle, Target arrowhead pointed to the left (\(<\) and the “j” key if the middle, Target arrowhead pointed to the right (\(>\)). Note that stimulus-response compatibility was promoted by
mapping a key on the keyboard’s left side to the response for a “left” Target arrowhead and a key on the keyboard’s right side to a “right” Target arrowhead (Bächtold, Baumüller, & Brugger, 1998). The arrowheads were black against a middle grey background.

**Trial structure.** Every participant served in four blocks of trials of 192 trials each (96 Congruent and 96 Incongruent). First, ITIs decreased, to promote increased PTP, and then ITIs increased, to promote decreased PTP. Specifically, ITIs decreased over the first three blocks of trials, from 2 sec in the first block to 1.25 sec in the second block, and then finally 0.5 sec in the third block. Then, ITIs returned to their initial value of 2 sec in the fourth and final block. This selection of ITI values was established during pilot testing to produce a range of accuracies that spanned from chance (50%) to ceiling (100%) performance. Participants were told, “You will have less than a second to make each decision, and you should respond as quickly and accurately as possible. If you don’t respond in time, your decision will be marked as incorrect.” At the start of testing, participants completed 24 practice trials with a constant ITI of 2 s. After each block of trials, participants were instructed to set a one-minute timer and rest for that time. To preserve statistical power within the limits of our available sample size, we did not counterbalance these ITI levels across participants.

To strengthen their possible influence, the four Flanker arrowheads appeared on the screen first, before the Target arrowhead (Lange-Malecki & Treue, 2012). Then, after a random interval of 95, 100, or 105 ms., the central Target arrowhead appeared. All five arrowheads disappeared together 200 ms later, after which participants were allowed up to 450 ms to register their judgement. Right after their response, participants received feedback about their accuracy for 300 ms. Following correct responses, the word “Correct” was displayed in green on the screen along with the pleasant “ding” sound commonly associated with success in video games. Following incorrect responses or the failure to respond in time, the word “Wrong.” was displayed in red along with an unpleasant buzzer sound that is commonly associated with failure in video games. We
included these gamelike elements to promote task engagement and motivation (Miranda & Palmer, 2014). To calibrate the volume of the auditory feedback, participants were instructed to toggle their computer’s volume until the sound was at a comfortable audible level.

Ancillary measures

In order to link behavioral performance with psychological states, we periodically sampled participant’s feelings of stress and negative affect. We took both measures because of accumulating evidence suggesting that these two variables interact to impact EF (e.g., Vinski & Watter, 2013; Qi & Gao, 2020; Finy, Bresin, Korol, & Verona, 2014).

**Stress.** Participants rated their subjective feelings of stress on an eight-point Likert scale (from 0 to 7; Sun & Sekuler, 2021). These ratings will be referred to hereafter as Likert Stress Scale (LSS) responses. As the autonomic nervous system’s sympathetic stress response peaks in the immediate aftermath of a stressor (Plieger & Reuter, 2020), LSS responses were collected before the start of the experiment and after each block of trials.

**Negative Affect.** To measure negative affect, participants completed a short-form version of the Positive and Negative Affect Schedule, which has high convergent validity and test-retest reliability (PANAS; Thompson, 2007; Crawford & Henry, 2004). The negative affect component of this inventory asks participants to rate the extent that they’re experiencing the following emotions on a five-point Likert scale: “afraid”, “nervous”, “upset”, “hostile”, and “ashamed”. The test was completed before block 1, after the highest PTP condition (shortest ITI, block 3), and finally after the lowest PTP condition (longest ITI, block 4).

**Results**

Our analyses examined the relationships among ITI, stress, negative affect, and cognitive inhibition. As explained earlier, we measured stress with a Likert scale (LSS), negative affect with the PANAS inventory, and cognitive inhibition as the Flanker effect.
(accuracy on Congruent trials minus accuracy on Incongruent trials) from the Flanker task. The analyses used several packages in R (version 4.0.3; [R Core Team](https://www.r-project.org) 2020), including tidyverse ([Wickham et al.](https://www.r-project.org) 2019), ez ([Lawrence & Lawrence](https://www.r-project.org) 2016), lme4 ([Bates, Mächler, Bolker, & Walker](https://www.r-project.org) 2015) and mediation ([Tingley, Yamamoto, Hirose, Keele, & Imai](https://www.r-project.org) 2014). Coding and execution were done in RStudio’s integrated development environment (version 1.3.1093; [RStudio Team](https://www.r-project.org) 2020).

We present three complimentary perspectives on our results. First, we describe how the ITI influences the Flanker task’s accuracy and response time. Second, we present a linear mixed effects regression model showing how ITI impacted the Flanker effect, stress, and negative affect while controlling for age and gender. Even though our age range was narrow, we controlled for age because considerable neurodevelopment occurs during the age range of our sample ([e.g. Luciana](https://www.lucianacenter.org) 2013). Finally, we present an exploratory mediation model that assesses whether ITI’s impact on cognition inhibition was related to stress. Ultimately, these analyses show that changing the ITI impacts task performance, and that stress mediates this relationship.

**Data preparation.** To account for participants’ adjustment to the changed ITI, the first five trials at the start of each block were excluded from analysis. Overall, participants failed to respond within the allowed time limit (450 ms after the arrowheads disappeared) on only 3.84% of all trials; these trials were excluded from analysis. A two-way ANOVA showed that the number of missed trials varied with the trial’s Congruency ($F(1, 76) = 43.41, p < .001$) and block (ITI; $F(3, 228) = 3.77, p = .014$), as well as their interaction ($F(3, 228) = 7.39, p < .001$). In particular, trials were disproportionately missed on Incongruent trials and during the first block of testing. For each participant and condition, we derived two dependent measures from the Flanker task: the mean percent correct responses (accuracy) and the mean response time on correct trials. The Flanker effect was then calculated as the difference in accuracy across congruent and incongruent trials.
**ITI, accuracy and response time.** Figure 1 shows how variation in the ITI impacts Flanker task accuracy and response time. At each ITI in Panel A, we see a strong Flanker effect, that is, accuracy with *Congruent* stimuli is well above that for *Incongruent* stimuli. Additionally, in Panel B, response times to *Incongruent* stimuli are longer than times to *Congruent* stimuli.

*Figure 1.* **Panel A.** Mean response accuracy as a function of the ITI in successive blocks of trials. Note that ITI decreases over Blocks 1-3 and resumes its original value for Block 4. The dashed vertical line separates blocks over which ITI is decreasing from the block in which the original ITI has been restored. Results from *Congruent* trials are shown in blue; results from *Incongruent* trials are shown in red. Error bars extend one within-subject standard error above and below condition means. **Panel B.** Mean response times on correct trials shown in the same format as in Panel A.

**Analysis for Blocks 1 to 3.** As ITI decreases from 2 sec to 0.5 sec, response accuracy to each type of stimulus declines, and response time to both types of stimuli decreases as well. Importantly, Panel A shows that with decreasing ITI, the gap between the two accuracy curves grows: in other words, that the size of the Flanker effect increases. Relatedly, Panel B shows that with decreasing ITI, the gap between the two response time curves shrinks; taken together with Panel A, this suggests that as the ITI...
Table 1
ANOVA on results from Blocks 1-3

A: Accuracy

<table>
<thead>
<tr>
<th>Effect</th>
<th>df’s</th>
<th>F value</th>
<th>p</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITI</td>
<td>2, 152</td>
<td>104.40</td>
<td>&lt;.001</td>
<td>0.58</td>
</tr>
<tr>
<td>Congruency</td>
<td>1, 76</td>
<td>548.00</td>
<td>&lt;.001</td>
<td>0.88</td>
</tr>
<tr>
<td>ITI $\times$ Congruency</td>
<td>2, 152</td>
<td>15.49</td>
<td>&lt;.001</td>
<td>0.17</td>
</tr>
</tbody>
</table>

B: Response time

<table>
<thead>
<tr>
<th>Effect</th>
<th>df’s</th>
<th>F value</th>
<th>p</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITI</td>
<td>2, 152</td>
<td>60.74</td>
<td>&lt;.001</td>
<td>0.44</td>
</tr>
<tr>
<td>Congruency</td>
<td>1, 76</td>
<td>393.90</td>
<td>&lt;.001</td>
<td>0.84</td>
</tr>
<tr>
<td>ITI $\times$ Congruency</td>
<td>2, 152</td>
<td>29.66</td>
<td>&lt;.001</td>
<td>0.28</td>
</tr>
</tbody>
</table>

quickens, participants prioritize speed more than accuracy for Incongruent trials.

A pair of two-way within-subjects ANOVAs examined performance across Blocks 1 to 3, when ITI was shrinking from 2 sec to 0.5 sec. One ANOVA, on accuracy data, is summarized in Table IA, the other, on response times, is summarized in Table IB. The effects represented in the ANOVAs were ITI, the time separating successive trials, and Congruency, the type of stimulus, Congruent or Incongruent. For both dependent measures, performance changed significantly. In addition, performance with both dependent measures showed a significant interaction between ITI and Congruency.

**Restoration of the long ITI: Comparing Blocks 1 and 4.** In the experiment’s fourth and final block, the ITI was restored to its original value. We were interested in whether this would restore performance to its original level as well. To test this, we used paired t-tests. One paired t-test revealed that accuracy did not differ reliably between the two blocks: Block 1 ($M = 0.82$, $SD = 0.11$) and Block 4 ($M = 0.81$, $SD = 0.14$; $t(76) = 0.78$, $p = .439$, $d = .09$). This approximate equivalence can be seen in Figure 1 by comparing the leftmost and rightmost data points for each Congruency condition. The analogous analysis for response times told a different story. Mean response times in Block 1 tended to be longer than those in Block 4 ($M = 0.48$ seconds, $SD = 0.04$, $M = 0.46$, $SD = 0.04$, respectively; $t(76) = 4.02$, $p < .001$, $d = .46$). This relationship held for
both Congruent and Incongruent trials (Congruent trials: $M_{Block1} = 0.45$, $SD_{Block1} = 0.04$, $M_{Block4} = 0.44$, $SD_{Block4} = 0.04$, $t(76) = 3.17$, $p = .002$, $d = .361$; Incongruent trials $M_{Block1} = 0.52$, $SD_{Block1} = 0.05$, $M_{Block4} = 0.50$, $SD_{Block4} = 0.05$, $t(76) = 4.79$, $p < .001$, $d = .545$).

**Discussion.** These results show that changing ITI strongly impacts both accuracy and response time. Assuming that reduced ITI increases PTP, these effects of changing ITI are consistent with the idea that PTP can influence task performance on a task of cognitive control.

The significant interaction effects in the ANOVAs carry particular theoretical importance, as they inform the ITI’s impact on the Flanker effect (the difference between Congruent and Incongruent trials), our measure of cognitive inhibition. We found in particular that the Flanker effect grows as the ITIs decrease and then shrinks as the ITIs increase. Figure 1 suggests that this change in the Flanker effect arises from the ITI’s disproportionate effect on Incongruent trials. This finding supports the idea that increasing PTP not only globally undermines performance, but also diminishes the cognitive inhibition required to filter out the distracting Flanker arrowheads (on Incongruent trials).

**Multilevel linear regression analysis**

**Regressions on cognitive inhibition.** We used multilevel linear regressions to characterize the amount that cognitive inhibition (the Flanker effect, as characterized by accuracy on incongruent trials subtracted from accuracy on congruent trials) depended on ITI, stress, and negative affect while controlling for age and gender.

Figure 2 shows that decreasing ITI (Blocks 1 and 3) and then increasing it (Block 3 and 4) impacts cognitive inhibition (the Flanker effect), stress, and negative affect. Shortening the ITI has two kinds of effects: it decreases cognitive inhibition, as shown by the increased Flanker effect (Figure 2A), while it increases both stress (Figure 2C) and negative affect (Figure 2E). Conversely, restoring the ITI to its original longer value reverses these effects (Figure 2B, D, and F), completely for both cognitive inhibition and
negative affect.

A pair of regression analyses explored whether the ITI, stress, negative affect, and the interaction between the latter two predicted changes in cognitive inhibition (the Flanker effect). The first regression examined the effects associated with a decrease in ITI from 2 sec to 0.5 sec (Block 1 to Block 3), and the second regression examined the effects with an increase in ITI from 0.5 sec to 2 sec (Block 3 to Block 4). Note that the difference between the ITIs was the same (1.5 sec) for both regressions, but opposite in sign, facilitating comparisons across the two models. The model output is summarized in Table 2 for decreasing ITI (from Block 1 to Block 3), and in Table 3 for increasing ITI (from Block 3 to Block 4). Compared with the null model in Equation 1, the full model for decreasing ITI as shown in Equation 2 produced the superior fit ($AIC_{null} = 423.97$, $AIC_{full} = 422.07$, $\chi^2(7) = 15.883$, $p = .026$).

\[
\text{Cognitive Inhibition} \sim \text{ITI} + (1|\text{ParticipantID})
\]  

\[
\text{Cognitive Inhibition} \sim \text{ITI} + \text{Stress} + \text{NegativeAffect} + \\
\text{Stress} : \text{NegativeAffect} + \text{Age} + \text{Gender} + (1|\text{ParticipantID})
\]  

Table 2 shows that with a 1.5 sec decrease in ITI from Block 1 to Block 3 (to proxy increasing PTP), ITI explained significant variance in the Flanker effect ($p < .001$), while stress explained a borderline amount of variance in the Flanker effect ($p = .053$). In contrast, neither negative affect nor the interaction between stress and negative affect explained appreciable variance in the Flanker effect.

Similarly, as shown in Table 3, while ITIs were increasing (to proxy decreasing PTP), ITI again accounted for significant variance in the Flanker effect, as did stress,
Figure 2. Panels A, C, and E depict the mean effects of decreasing ITI (increasing PTP; Block 1 to Block 3) on measures of cognitive inhibition (the Flanker effect), stress, and negative affect. Panels B, D, and F depict the mean effects of increasing ITI (decreasing PTP; Block 3 to Block 4) on cognitive inhibition, stress, and negative affect. In all panels, error bars represent plus and minus one within-subject standard error. Note that the changes in the Flanker effect, stress, and negative affect are not equal in size.

while neither negative affect nor the interaction between stress and negative affect explained significant variance in the Flanker effect.

**Regressions on stress and negative affect.** Considering ITI’s impacts on the ancillary measures alone, decreasing ITIs (increasing PTP) worsened stress ($\beta = .579$, $t(76) = 5.10$, $p < .001$) and negative affect ($\beta = .314$, $t(76) = 2.86$, $p = .005$). Conversely,
Table 2
Multilevel linear regression results of the Flanker effect following a 1.5 sec decrease in ITI. Estimates are standardized $\beta$ coefficients. Gender effects are expressed relative to the female group. SE = standard error; LL = lower limit; UL = upper limit.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Estimate</th>
<th>SE</th>
<th>95% LL</th>
<th>95% UL</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.31</td>
<td>1.22</td>
<td>-.989</td>
<td>3.61</td>
<td>.284</td>
</tr>
<tr>
<td>Inter-Trial Interval (ITI)</td>
<td>.541</td>
<td>.148</td>
<td>.254</td>
<td>.832</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Stress</td>
<td>.188</td>
<td>.096</td>
<td>.002</td>
<td>.370</td>
<td>.053</td>
</tr>
<tr>
<td>Negative Affect</td>
<td>.098</td>
<td>.108</td>
<td>-.107</td>
<td>.307</td>
<td>.367</td>
</tr>
<tr>
<td>Stress*Negative Affect</td>
<td>-.032</td>
<td>.078</td>
<td>-.180</td>
<td>.116</td>
<td>.681</td>
</tr>
<tr>
<td>Age</td>
<td>-.077</td>
<td>.063</td>
<td>-.197</td>
<td>.043</td>
<td>.229</td>
</tr>
<tr>
<td>Gender (Male)</td>
<td>-.246</td>
<td>.176</td>
<td>-.579</td>
<td>.087</td>
<td>.167</td>
</tr>
<tr>
<td>Gender (Non-Binary/Genderqueer)</td>
<td>-.693</td>
<td>.501</td>
<td>-1.641</td>
<td>.256</td>
<td>.171</td>
</tr>
<tr>
<td>Gender (Not sure/Unknown)</td>
<td>.081</td>
<td>.697</td>
<td>-1.239</td>
<td>1.399</td>
<td>.908</td>
</tr>
</tbody>
</table>

Increasing ITIs (decreasing PTP) improved stress ($\beta = -.348$, $t(76) = -3.29$, $p = .002$) and negative affect ($\beta = -.282$, $t(76) = -3.56$, $p < .001$).

**Lingering effects of PTP.** The Flanker effect during blocks 1 ($M = 0.26$, $SD = 0.16$) and 4 ($M = 0.27$, $SD = 0.20$) did not differ ($t(76) = -0.55$, $p = .581$, $d = .06$); the same is true for negative affect in Blocks 1 ($M = 8.03$, $SD = 3.57$) and 4 ($M = 8.14$, $SD = 3.61$; $t(76) = -0.318$, $p = .752$, $d = .04$). However, stress was elevated in Block 4 ($M = 3.47$, $SD = 1.58$) compared to Block 1 ($M = 3.00$, $SD = 1.78$; $t(76) = -2.34$, $p = .022$, $d = .27$), showing that the ITI’s effect on stress continued for some time after its level was
Discussion. These analyses explored the relationships between the ITI, cognitive inhibition, stress, and negative affect. The first set of analyses show that cognitive inhibition, as indexed by the Flanker effect (Congruent accuracy minus Incongruent accuracy), can be predicted by increasing and decreasing ITI as well as stress, but not negative affect or the interaction between stress and negative affect. Since PTP is approximated by ITI, these results strongly suggest that increasing PTP and stress undermine cognitive inhibition; conversely, decreasing PTP and stress benefits cognitive inhibition.

The second set of analyses show that the ITI, or PTP, directly impacts both stress and negative affect, and the third set of analyses show that changes in the ITI, or PTP, have transient impacts on cognitive inhibition and negative affect but not stress. It’s interesting to note that this slower recovery in stress parallels the slower recovery of RT compared to that of accuracy seen in the previous set of results: it seems that response latency, a graded measure, can be more sensitively related to stress than the binary measure of response accuracy.

**Exploratory analysis: Trial-to-trial carryover**

In response to literature from Cheng, Luis, and Tremblay (2008) and Cheng, Manson, Kennedy, and Tremblay (2013) showing that visual information can linger across trials with ITIs less than five seconds, we tested if the direction of the target arrow (“<” or “>”) on trial \(n\) influenced response key judgements on trial \(n+1\), and if ITI moderated this effect.

We ran a generalized linear mixed-effects logistic regression, where response key (“f” or “j”, reflecting “<” and “>” decisions, respectively) was predicted by the arrow direction on the previous trial, the ITI in the block of trials, the interaction of those two variables, and a random effect of participant ID. In \(R\), the model code can be written:
Response $\sim$ PreviousTargetDirection + ITI +
PreviousTargetDirection : ITI + (1|ParticipantID) \hspace{2cm} (3)

We found that the previous trial’s direction did have a reliable influence on the current trial’s key press ($\beta = -.427$, $p < .001$), but this effect was not significantly influenced by ITI (main effect: $\beta = -.003$, $p = .826$; interaction: $\beta = .002$, $p = .925$). While the visual overlap effect described by Cheng et al. (2008, 2013) is apparent in our data, it is unlikely to account for our findings because the previous trial’s influence on the current trial is not moderated by ITI.

**Exploratory mediation analyses**

To elucidate the relationships between ITI, stress, and cognitive inhibition (Flanker effect), we ran exploratory mediation models to assess whether stress causally mediates the relationship between ITI and inhibition. Figure 3A shows that there is a significant mediation effect of stress on the relationship between ITI and the Flanker effect when ITIs are decreasing (PTP is increasing; ACME = .024, $p = .004$), with a significant direct effect (ADE = .096, $p < .001$) and total effect (effect = .120, $p < .001$). Similarly, Figure 3B shows that there is a significant mediation effect of stress when ITIs are increasing as well (PTP is decreasing; ACME = -.016, $p = .006$), with significant direct effects (ADE = -.093, $p < .001$) and total effects (effect = -.109, $p < .001$) too. These analyses show that PTP (as indexed by ITI) may exert effects on inhibition via stress, and serve as a reminder that the psychological effects of PTP are important to consider when understanding its surprising effects on EF.

**General Discussion**

This study examined the relationships between PTP (as proxied by changing ITIs), cognitive inhibition, stress, and negative affect during Eriksen’s Flanker task. First, we
show that increasing PTP worsens accuracy, cognitive inhibition (the Flanker effect), stress, and negative affect, and speeds response times. Decreasing PTP reverses these effects, even back to baseline for accuracy, cognitive inhibition and negative affect. We then show that PTP and stress predict inhibition in multilevel models, and in an exploratory analysis we show that stress causally mediates the relationship between PTP and cognitive inhibition.

We found that simulating time pressure by manipulating ITIs has real behavioral and psychological consequences (Endres et al., 2020; Sun & Sekuler, 2021; Compton, Heaton, & Ozer, 2017; Young, Sutherland, & McCoy, 2018; Shields et al., 2016). As previously explained, changing ITIs does not induce objective time pressure: participants
had the same amount of time to process and respond to every stimulus regardless of the ITI level. So, we show that merely the experience of *feeling* rushed—regardless of whether or not you actually *are* rushed—impairs executive functioning and induces distress (Frankenhaeuser, 1986). This study specifically indicates that PTP can impair inhibition, complimenting similar findings in cognitive flexibility (Sun & Sekuler, 2021) and decision-making in general (Maule et al., 2000).

That said, the observed behavioral effects of PTP are similar to those found in conditions of objective time pressure (De Paola & Gioia, 2016; Endres et al., 2020). According to an account from Payne, Bettman, and Johnson (1988), decision-makers adjust their strategies to optimize effort and accuracy in response to time pressure (Payne et al., 1988; Gok & Atsan, 2016; Dambacher & Hübner, 2015). These strategic changes include acceleration (speeded processing; Spiliopoulos, Ortmann, & Zhang, 2018; Gok & Atsan, 2016) and filtration (increased selectivity in information acquisition; Oh et al., 2016; Spiliopoulos et al., 2018; Maule et al., 2000; Gok & Atsan, 2016). *Acceleration*, evidenced by speeded information processing, is demonstrated here with decreased response times, and *Filtration*, selective information processing, is also apparent through enhanced selective attention to Flanker arrows (evident in reduced inhibition). This latter finding aligns with work from Dayan and Solomon (2010), who argue that under time pressure, it is optimal under Bayesian inference to selectively attend to the distracting Flanker arrows, as this strategy enables participants to make decisions most quickly even at the cost of accuracy. Thus, this study shows that participant’s responses to PTP mimic those observed under conditions of objective time pressure.

Manipulating the duration of the ITI is likely to affect the cognitive processes needed for the next trial. As Vallesi and Shallice (2007) explain, cognitive changes during the ITI can be understood by a dual-process account involving (1) changes in motor readiness, and (2) a strategic monitoring process during which the arrival time of
the next stimulus is updated. Although longer ITIs benefit performance by restoring cognitive resources (Vallesi & Shallice, 2007), allowing participants to adequately prepare for the next trial (Vallesi, Lozano, & Correa, 2013) and alleviating performance losses associated with task switching if applicable (Meiran, Chorev, & Sapir, 2000), ITIs also risk being too long, which could induce boredom, fatigue, and/or mind-wandering (Sun & Sekuler, 2021; Compton et al., 2017). In contrast, short ITIs facilitate sustained arousal (Vallesi et al., 2013), but can also undermine effective decision making (Compton et al., 2017; Young et al., 2018). It is clear that ITIs, despite their presumed independence from the experimental task itself, can affect decision-making in many ways. More work is needed to find the ideal (“Goldilocks”) ITI value, one that is neither too long nor too short (de Jonge, Tabbers, Pecher, & Zeelenberg, 2012). Knowing that value or range of values could help to reconcile experimental results across studies.

The relationships between PTP, stress, and negative affect deserve further exploration. PTP (both increasing and decreasing) significantly predicts stress and negative affect, a finding which validates PTP as an empirical stressor. In turn, stress predicts cognitive inhibition in conditions of increasing and decreasing PTP. This expands previous demonstrations that the experience of stress is associated with diminished executive function (Sänger, Bechtold, Schoofs, Blaszkewicz, & Wascher, 2014; Shields et al., 2016; Thayer & Lane, 2000). Yet, neither negative affect nor the interaction between stress and negative affect independently explained significant variance in inhibition, in contrast with previous findings (e.g. Vinski & Watter, 2013). This could be because negative affect primarily acts to potentiate the effects of stress on task performance (Vinski & Watter, 2013; Pessoa, Padmala, Kenzer, & Bauer, 2012; Finy et al., 2014).

Limitations and future directions

One of the limitations of this study is that the brief duration of the ITIs, particularly the shorter ITI's, could have enabled cross-trial influence. Previous studies using quick
ITIs have noted that visual information can bleed across subsequent trials and influence performance (Cheng et al., 2008, 2013). Future work could compare how relative changes in longer ITIs impact executive functioning. Another limitation to generalizing our results is the lack of counterbalancing between conditions of increasing and decreasing PTP and therefore sudden versus gradual changes in ITI. A follow-up study would do well to assess how the effects we observed change when ITIs are randomized, both between and within blocks. Randomizing the ITI across trials could have also diffused any effects of ITI on the visual overlap effect just described. Future studies would also benefit by examining how biomarkers of stress, such as heart rate variability, blood pressure, cortisol levels, or salivary alpha-amylase levels, change with PTP.

**Conclusions**

Our study explored the effects of perceived time pressure (PTP) on the executive function of cognitive inhibition. Although participants had the same amount of time to process and respond to every trial in Eriksen’s Flanker task, the systematic variation of the inter-trial interval (ITI) to manufacture PTP profoundly affected task performance and associated psychological states. Increasing PTP, simulated with decreasing ITIs, sped response times and worsened accuracy, cognitive inhibition (the Flanker effect), stress, and negative affect. Decreasing PTP, fabricated with increasing ITIs, reversed these effects, even back to baseline for accuracy, inhibition, and negative affect. Multilevel modeling revealed that PTP and stress predicted inhibition, and exploratory mediation modeling suggested that PTP impacts inhibition both directly and indirectly with stress as a causal mediator.

We validate the subjective experience of perceived time pressure as a stressor and a disruptor of task performance. While this study focused on inhibition, preliminary evidence suggests that this effect generalizes to other executive functions like cognitive flexibility as well. These results emphasize the importance of interventions to lower stress as a way to promote EF in everyday life. Similarly, strategies to avoid perceived
time pressure could benefit EF as well: time adequacy was related to high academic performance in college students (Nonis, Hudson, Logan, & Ford, 1998) and improved task-oriented behavior in employees (Lee et al., 2017). Future studies would do well to assess how different biomarkers of stress inform these effects.

Declarations

Funding

This work was supported by the National Institutes of Health (R90DA033463).

Competing interests

The authors declare they have no competing interests.

Studies in humans and animals

The work described in this study has been carried out in accordance with the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study.

Declaration of interest

Declarations of interest: none

Submission declaration and verification

This work has not been published previously, is not under consideration for publication elsewhere, is approved by all authors, and if accepted will not be published elsewhere in the same form.

Open practices statement/Research data

The data and materials for this experiment are available in the Open Science Framework (OSF) repository, at https://osf.io/c3tfm/. The experiment was not preregistered.

CRediT author statement

Rachel Freed Sussman: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing - Original Draft and Reviewing and
Editing, Visualization, Funding Acquisition.

Robert Sekuler: Conceptualization, Methodology, Resources, Writing - Reviewing and Editing, Supervision, Project Administration.

Acknowledgments

We thank Hannah Snyder for her guidance with the design and analysis of this project. We also thank Mercedes Villalonga and Claire Pontbriand for help with data analysis.
References


Gok, K., & Atsan, N. (2016). Decision-making under stress and its implications for


Animal Behaviour Science, 65(3), 221–244.


