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Brief article

Challenge and error: Critical events and attention-related errors

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ABSTRACT

Attention lapses resulting from reactivity to task challenges and their consequences constitute a pervasive factor affecting everyday performance errors and accidents. A bidirectional model of attention lapses (error ↔ attention-lapse: Cheyne, Solman, Carriere, & Smilek, 2009) argues that errors beget errors by generating attention lapses; resource-depleting cognitions interfering with attention to subsequent task challenges. Attention lapses lead to errors, and errors themselves are a potent consequence often leading to further attention lapses potentially initiating a spiral into more serious errors. We investigated this challenge-induced error ↔ attention-lapse model using the Sustained Attention to Response Task (SART), a GO–NOGO task requiring continuous attention and response to a number series and withholding of responses to a rare NOGO digit. We found response speed and increased commission errors following task challenges to be a function of temporal distance from, and prior performance on, previous NOGO trials. We conclude by comparing and contrasting the present theory and findings to those based on choice paradigms and argue that the present findings have implications for the generality of conflict monitoring and control models.

1. Introduction

The study of reactivity to errors has had a short but active history. One common finding reported is that of post-error slowing and enhanced performance (Laming, 1968, 1979; Rabbitt, 1966, 1967). Such findings have been subject to considerable and conflicting theoretical speculation (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Castellar, Kühn, Notebaert, & Notebaert, 2010; Dudschig & Jentzsch, 2009; Jentzsch & Dudschig, 2009; Notebaert et al., 2009; Ridderinkhof, 2002). An influential interpretation of post-error slowing is that it reflects a conflict monitoring process that leads to a more cautious response strategy (e.g., Botvinick et al., 2001). Although response slowing, increased caution, and renewed attention to task following errors and even successfully-met task challenges clearly occurs in some contexts, to conclude that such a response style is universal and/or inherently functional, flies in the face of real-world evidence. Such evidence suggests that perceived errors frequently lead to further errors when pilots, surgeons, drivers, or industrial personnel become distracted by initial errors that rapidly become compounded as attention is diverted from ongoing task demands (Reason, 1990; Reason & Mycielska, 1982; Vincente, 2003; West et al., 2006).

Results more compatible with these particular real-world findings have recently been noted using the Sustained Attention to Response Task (SART), an increasingly widely used laboratory test of attention lapses (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). The SART requires continuous responding (key-pressing) to each of a continuous random series of single digits (1–9) except for a rare NOGO digit (3). Attention lapses are assessed by the number of commission errors on these relatively rare NOGO trials, and by speeded response time prior to NOGO errors (Cheyne, Solman, Carriere, & Smilek, 2009; Robertson & Garavan, 2004; Robertson et al., 1997). In contrast to much of the literature on post-error slowing, and consistent with

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the error-begets-error phenomenon, in a recent study we (Cheyne, Carriere, and Smilek, 2009; Cheyne, Solman, et al., 2009) observed that errors on the SART were followed by *increased* rates of error, increased response anticipations (extremely short reaction times, <100 ms), and increased omissions (failure of timely responding within task parameters). Moreover, although we also observed a brief post-error return to baseline (i.e., slowing of response speed relative to pre-error speeding), this was immediately followed by speeding. In general, detailed analysis of these multiple consequences of NOGO trials was consistent with the interpretation that the primary outcomes of task challenges (NOGO trials) were disrupted and disorganized responding, rather than increased caution and task focus. These results were framed in a bidirectional error ↔ attention-lapse model, which stipulates that attention lapses lead to errors on NOGO trials, and that these errors can in turn lead to further attention lapses (Cheyne, Carriere et al., 2009; Cheyne, Solman, et al., 2009). Critically, this model stands in contrast to the common understanding of post-error changes in performance, which are thought to reflect a more cautious strategic response strategy.

In the present paper we focus on the bidirectional error ↔ attention-lapse model in which errors are hypothesized to cause attention lapses, and vice versa. In particular, we propose a challenge-induced entry to this recurrent cycle, whereby task challenges in general lead to attention lapses, and these lapses sustain the bidirectional relationship with errors. By "challenge" we mean exposure to an event or situation that engages or alters adaptive physiological or psychological processes. Task challenge consequences can induce lapses that in turn lead to errors that are themselves a particularly potent consequence leading to further attention lapses. Thus even successful performance following challenge can set off the error ↔ attention-lapse cycle when it leads to offline rumination about performance.

Internal processing of one's task performance is a form of task-relevant rumination (McVay & Kane, 2010; Watkins, 2010) or task-relevant mind wandering (Cheyne, Carriere et al., 2009; Cheyne, Solman, et al., 2009). Mind wandering refers to periodic and apparently spontaneous attention shifts (Smallwood & Schooler, 2006). Mind wandering, so defined, is not limited to daydreaming but includes all explicit (conscious) cognitive activity not focused on immediate occurrent task demands. It may therefore include attentional focus on non-immediately present or relevant aspects of a task, such as overall evaluation of past performance and anticipated future task demands. Challenge-induced assessments and evaluations of successes and failures on preceding trials will sometimes persist until, and hence potentially have an impact on responsiveness to, the next trial. Importantly, we suggest that both successes and failures on previous task challenges will lead to attention lapses, but that failures to meet challenges might have a more profound impact on attention lapses than successes. Although rumination is typically associated with self-rather than task-focused, cognitions, in the absence of dysphoria rumination has been reported to be associated with high levels of task focus (Smallwood et al., 2002). Task relevant rumination is a form of task appraisal functioning as a form of task-related interference (cf. Smallwood, O'Connor, & Heim, 2004) suggested by findings that both task relevant and task irrelevant rumination are associated with SART errors (e.g., Smallwood, Fitzgerald, Miles, & Philips, 2009).

One prediction following from the error ↔ attention-lapse hypothesis is that performance on trials immediately following a task challenge will be adversely affected, and that this effect will vary as a function of the temporal distance from that challenge. Under the assumption that making an error is more salient, and requires additional processing (e.g. Jentzsch & Dudschig, 2009) compared to a correct withhold on the SART, the impact of NOGO error trials should be stronger and/or more persistent than that of NOGO trials with successful withholds, though both types of NOGO trials will adversely affect performance on subsequent trials. In a previous report we incidentally observed a positive association between error likelihood and the number of GO trials intervening between NOGO trials (Cheyne, Carriere et al., 2009; Cheyne, Solman, et al., 2009). Though interpretation was complicated because frequency of interval length was not controlled in that study, the higher rate of errors following more closely previous NOGO trials is consistent with task-induced attention lapses.

The present study was designed to evaluate in some detail the effects of temporal distance (measured by number of intervening trials) between successive challenge (NOGO) trials on commission errors and response times in order to assess the presence, magnitude, and persistence of the costs of challenge events and to compare this with the effects of trial position across the entire experiment (time-on-task). Our experimental design also allowed us to consider various existing interpretations of performance in the SART task, which we address in the results and in the discussion that follows.

2. Method

2.1. Participants

Participants were randomly selected from a diverse international group of prior respondents to a WWW survey on sleep paralysis, all of whom had previously agreed to be contacted for future research. Of 3000 potential participants contacted for the study, the current sample included 339 participants who completed the SART. The present sample included 229 females and 92 males, and 18 non-specified, with a mean age of 30.06 ($SD = 8.59$; females $M = 30.34$, males $M = 29.38$, $t\ (319) = .90$, $p = .368$). An overlapping set of participants also completed a series of questionnaires, which were used to validate the relation of the SART to everyday cognitive failures in a prior publication (Smilek, Carriere, & Cheyne, 2010).

2.2. Measures

The SART procedure involves digits, from 1 to 9, presented for 250 ms, followed by a mask for 900 ms, for a total digit-to-digit duration of 1150 ms. Participants were instructed to respond with a key press to each digit, except "3". The digits and their font sizes are randomly distributed across trials with equal representation of 48, 72, 94, 100, and 120 point Symbol font in white against a black background. The SART was implemented in Macromedia Flash MX 2004 according to the foregoing specifications. Actual stimulus displays were dependent on the computer equipment used by each participant and viewing distance was not controlled. On a Compaq Presario R3140CA series notebook, with 15.4 in WXGA (1280 × 800) display, used for scale development, stimulus height varied from 8.74 mm (34 px) to 21.33 mm (83 px) and the circular mask diameter was 21.07 mm (82 px).

There are two minor differences between this version of the SART and that originally designed by Robertson and colleagues (1997). First, the mask presented following each digit was changed to an annulus, ⊚, to avoid possible disproportionate masking of the digit 8 by the typical SART mask, ⊗. Second, to ensure equal representation of different interval lengths the intervening number of GO trial digits ("1–2" and "4–9") appearing between NOGO trials ("3") was varied from 0 (i.e., sequential NOGO trials) to 16, with each NOGO to NOGO trial interval being used twice over the course of the task. One consequence of this constraint was that longer interval lengths were associated with increased probability of a NOGO trial as a power function of interval length. This provided an opportunity to make a sensitive test of strategic responding during the SART by examining behavioral change function with increasing interval length (i.e., response slowing and reduced error rates with increasing NOGO probability). This second change also required that the number of SART trials be increased from 225 to 315, increasing the duration of the task from 4.5 min to approximately 6 min, affording a slightly stronger test of the effect of a time-on-task hypothesis. Different interval lengths were randomly distributed over the course of the task, with all participants receiving this same order of digit presentation.

2.3. Procedure

Participants received an informational email inviting them to participate in the study and including a link to the study website (For details see Cheyne, Carriere, & Smilek, 2006). After visiting this website and consenting to participate in the study, participants completed: (1) a short demographic form; (2) a variety of randomly ordered attention related questionnaires; and (3) the SART. At the end of the study participants received a feedback page thanking them for their participation and providing additional information on our research.

2.4. Analyses

2.4.1. Correct performance and RT following correct and incorrect NOGO trials

Proportion correct was the major performance dependent variable selected, rather than errors, to facilitate visual comparison with RT in the figures. For each subject, for each interval length between successive NOGO trials we calculated the mean conditional probability of a correct withhold given a correct withhold on the previous NOGO trial, P(C|C), and a correct withhold given an error on the preceding NOGO trial, P(C|E). To clarify, hereafter by 'interval length' we refer to the number of intervening GO trials between two successive NOGO trials. Given inevitable differences in performance, for any given interval length a particular subject may have, for example, only correct or, conversely, only incorrect preceding challenge trials and hence not every subject is represented at every interval and sample sizes therefore vary from interval to interval. For correct withholds following prior correct withholds, the numbers of subjects at different intervals varied from 186 to 286. For correct withholds following errors, the numbers of subjects represented at different intervals varied from 177 to 274. RTs following correct (RT|C) and following error (RT|E) NOGO trials at different intervals were assessed when a GO trial followed an NOGO trial after the specified number of interceding GO trials. For RT following correct withholds, the numbers of subjects represented at different intervals varied from 204 to 338. For RT following prior NOGO errors, the numbers of subjects at different intervals varied from 154 to 338. Though there were 17 positions in which a NOGO trial could appear following a preceding NOGO trial, as one of the intervals was zero, there were only 16 in which GO trials could appear, hence the number of factors for analyses of NOGO performance is 17 and for GO RTs only 16. For each measure, values for missing cells were imputed using a linear trend point estimation.

2.4.2. Errors and RT associated with time-on-task

The effect of task duration on errors and RT was assessed by examining the probability of correct response, P(C), over the 35 successive NOGO trials and RT over the 280 successive GO trials for the duration of the task. P(C) for each NOGO trial was the proportion of individuals making an error on that trial.

3. Results

The overall mean proportion correct was .51 (SD = .23. The overall mean RT was 372.02 ms (SD = 81.00 ms). The Pearson product-moment correlation between performance and RT was $r = .61$, $p < .001$.

3.1. Proportion Correct and Interval Length following Error and Correct Trials

A 2 (correct versus error pre-interval trial) × 17 (interval length) repeated-measure ANOVA with proportion correct on subsequent NOGO trials as dependent variable employing Greenhouse-Geisser corrections yielded significant effects for pre-interval trial type, $F(1, 338) = 325.30$, MSE = .237, $p < .001$, interval length, $F(16, 5408) = 34.41$, MSE = .127, $p < .001$, and the pre-interval trial type by interval length interaction, $F(16, 5408) = 11.95$, MSE = .126, $p < .001$. The error results are plotted in Fig. 1A. Performance was significantly below baseline (overall mean) at zero and one-trial intervals following both correct and error trials. Performance on trials follow-

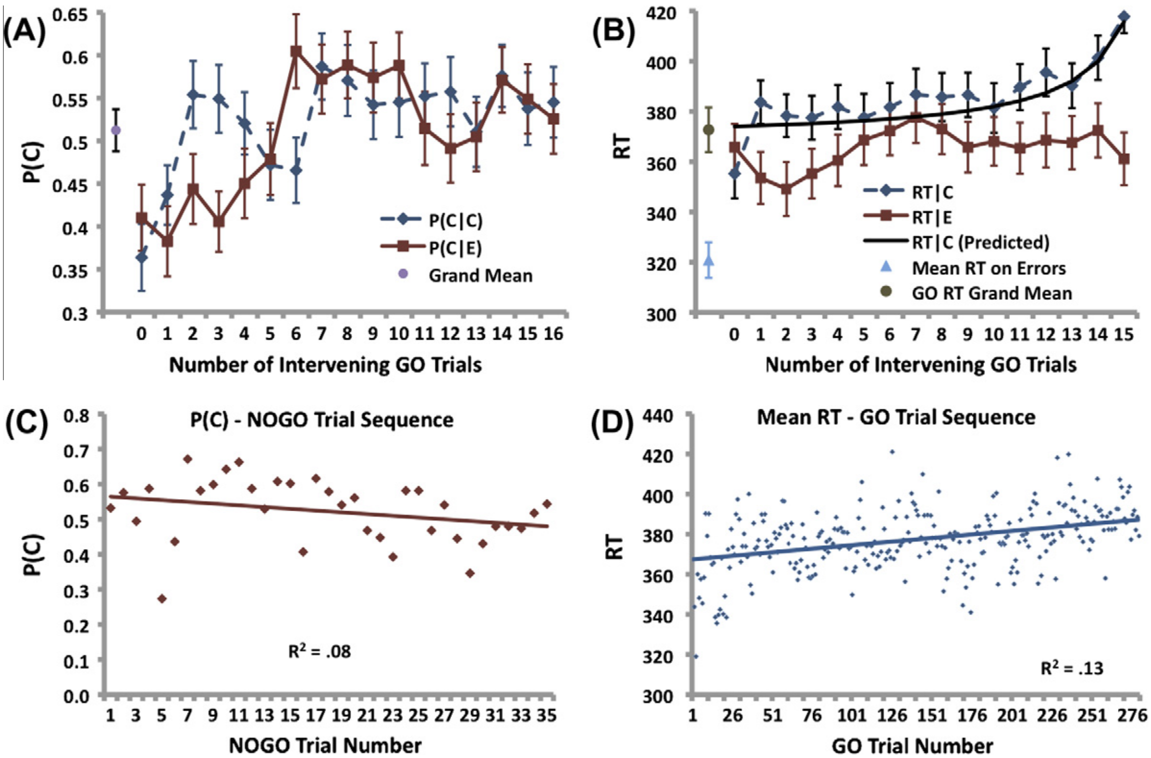

Fig. 1. (Panel A) Mean probabilities of correct withholding on NOGO trials following incorrect (P(C|E) and correct (P(C|C) NOGO trials at each of 17 intervals lengths between NOGO trials. Error bar depict 95% confidence intervals. (Panel B) Mean RT on GO trials following incorrect and correct NOGO trials at each of 16 interval lengths between NOGO trials. Error bars depict 95% confidence intervals. (Panel C) The correlation between performance on NOGO trials and their ordinal positions across all 35 NOGO trials. (Panel D) The correlation between RT on GO trials and GO trial number across 280 GO trials.

ing a correct NOGO withhold, P(C|C), rapidly improved over the following three interval lengths then briefly declined, finally recovering to levels equal to baseline by interval 7. Performance on trials following an error, P(C|E), improved in a generally linear fashion until interval 6, when it briefly exceeded baseline and P(C|C).

3.2. RT and interval length following error and correct trials

A 2 (correct versus error pre-interval trial) × 16 (interval length) repeated-measure ANOVA with subsequent GO RT as dependent variable employing Greenhouse-Geisser corrections yielded several significant effects. There was a significant effect for pre-interval trial type, $F(1, 338) = 48.38$, MSE = 16872.51, $p < .001$, an effect of interval length, $F(15, 5070) = 15.44$, MSE = 6769.64, $p < .001$, and a pre-interval trial type by interval length interaction, $F(155, 070) = 15.45$, MSE = 4882.88, $p < .001$. The results are plotted in Fig. 1B. RTs following correct and incorrect NOGO trials were faster than the overall RT mean on the trial immediately following a prior NOGO trial and not significantly different from one another. RT|C quickly recovered to baseline on succeeding trials and slowed markedly at the longest intervals. RT|E showed protracted speeding, being significantly faster than RT|C at intervals 1–4, followed by recovery to baseline levels, and no changes thereafter. RT|E did not show the long interval length slowing observed for RT|C, and dropped significantly below RT|C at intervals 11–15.

3.3. Evidence for strategic responding

To check for evidence of strategic responding across interval lengths we correlated the probability of a NOGO (P(NOGO)) trial at each interval length with P(C|C), P(C|E), RT|C, and RT|E across interval lengths (Table 1). P(NOGO) was significantly and robustly associated with RT|C, but not RT|E or accuracy measures. As P(NOGO) is also significantly associated with Interval length, a multiple regression analysis assessed the independent effect of P(NOGO) on RT|C over and above that of Interval length (Table 2). Interval length was entered first as a predictor of RT|C, followed by a second step in which P(NOGO) was added. The beta for Interval length became nonsignificant, whereas the beta for P(NOGO) was still significant,

Table 1
Pearson product-moment correlations among Interval length (Number of GO trials intervening between NOGO Trials), probability of NOGO trial P(NOGO), correct performance following correct P(C|C) and error (C|E) NOGO trials, and RT following correct (RT|C) and error RT|E NOGO trials. Coefficients in bold are significant at $p < .05$. Ns = 17 except for RT correlations where $N = 16$.

	P(NOGO)	P(C|C)	P(C|E)	RT|C	RT|E
Interval length	**0.73**	**0.57**	**0.63**	**0.83**	0.46
P(NOGO)		0.27	0.26	**0.86**	0.15
P(C|C)			**0.52**	**0.61**	0.20
P(C|E)				0.45	**0.74**
RT|C					0.13

Table 2
Multiple regression analysis predicting RT|C from Interval length and P(NOGO).

Predicting RT|C	β	t	p
Step 1			
Interval length	.83	5.52	.001
Step 2			
Interval length	.35	1.48	.161
P(NOGO)	.57	2.38	.033
	R^2 = .78, $F(2, 13)$ = 23.15, p < .001		

indicating mediation of the Interval length effect on RT|C by P(NOGO). Thus, there was evidence for possible strategic slowing as the likelihood of the next NOGO trial increased following correct but not error NOGO trials (Compare RT|C and RT|C predicted by P(NOGO) in Fig. 1B). This slowing was not, however, reflected in significantly improved performance.

3.4. Effect of time-on-task

A Pearson product-moment correlation coefficient was calculated between successful withholding and NOGO trial ordinal position across all 35 NOGO trials, yielding a non-significant negative correlation, $r = -.28$, $p = .10$ (Fig. 1C).[1] Pearson correlations were also computed between RT and GO trial number across 280 GO trials yielding a significant positive correlation $r = .37$, $p < .001$ (Fig. 1D). RT increased slightly with time-on-task, which would, given the robust negative association of RT and commission errors, appear be contrary to a hypothesis of vigilance decrement over time.

4. Discussion

The results revealed several significant effects of time since last NOGO challenge (interval length) on subsequent NOGO performance and GO response times. NOGO challenge trials were followed by decreased accuracy of performance on NOGO trials and speeded response time on GO trials. Both errors and response times recovered more rapidly following correct trials relative to error trials. Response time recovered after one intervening GO trial following a correct NOGO trial, but required 4–5 trials to recover after a NOGO error. Performance on NOGO trials was depressed for two trials after a correct NOGO withhold, followed by a rapid but unstable recovery (See Intervals 5 and 6 in Fig. 1A). Following a NOGO error, subsequent performance on NOGO trials recovered more slowly over the course of 5–6 trials. There was some evidence of slight performance enhancement from trials 6–10 following NOGO incorrect and/or correct trials (Fig. 1A). The effects of total time on task were more modest and mixed. Proportion of correct withholds on NOGO trials did show a small but nonsignificant decrease across all NOGO trials, whereas reaction times slowed modestly but significantly over GO trials.

Overall, these results are consistent with the hypothesis that challenges imposed by NOGO trial in the SART lead to attention lapses that often disrupt performance on following trials. In addition, they provide evidence that challenges imposed by NOGO trials also lead to attention lapses when participants respond correctly suggesting that the attention lapses are not limited to erroneous responses, but are a generally characteristic of reactivity to challenges. Post-error effects were, however, larger than post-correct effects, presumably because participants engage in more evaluate internal thoughts following an error. This difference in recovery rate following correct versus incorrect NOGO responses may suggest that the immediate effects (i.e., lasting up to a second) reflect automatic conflict monitoring (but see below), whereas the longer-lasting post error effects reflect more explicit rumination lasting many seconds in the present task. This long-lasting rumination phase appears to be quite dysfunctional for immediate post-error performance on a continuous performance task such as the SART. Critically, our findings lead to a interpretation of error reactivity different from one in which post-error behaviors is taken to reflect a more cautious response strategy (see Botvinick et al., 2001) as well as findings from previous studies using choice reaction time tasks (e.g., Laming, 1968, 1979; Rabbitt, 1966, 1967).

4.1. How and why are SART results different from those of choice reaction time?

SART errors and response times following errors yield patterns of response very different from, indeed opposite to, classic choice reaction time (CRT) paradigms, which produced response time slowing and reduction in errors following errors both of which returned to baseline over a series of trials (Laming, 1968, 1979; Rabbitt, 1966, 1967). Despite superficial similarities between SART and CRT paradigms, there are several critical differences that could plausibly lead to such dramatic differences in outcomes. In the context of the SART, the mask is on whenever the stimulus is off and so cannot be an informative (warning) cue about when the stimulus might appear. Hence, the subject must use the temporal patterning to estimate the onset of the next stimulus in order to minimize response time, which is one of the performance requirements. The constant ISI essentially serves as a temporal warning signal. That 89% of trials are GO trials likely creates a prepotent bias to respond based on the temporal interval. On the other hand, the subject must wait for stimulus identification in order to decide to withhold the prepotent response and achieve the other SART requirement (i.e., accuracy). Viewed in this way the SART is effectively a stop-task with infrequent stop trials requiring sustained attention to make rapid identification of stimuli in order to inhibit the prepotent response. This is a very different kind of challenge from that presented by the CRT paradigm, often self-paced (e.g., Rabbitt, 1967), which requires a choice decision and a positive response on every trial. In the CRT context, there are always two positional possibilities that vary randomly from trial to trial and therefore there is no prepotent response

[1] A reviewer noted extremely poor performance on the fifth NOGO trial (see Fig. 1C). This value is a modest outlier at 2.76 *SD*s from the mean. Recalculating the correlation with this value removed yielded a significant effect, $r = -.45$, $p < .007$.

to which to default, hence none to inhibit. Thus, although errors may well induce offline rumination in the CRT paradigm it can only produce delayed responding until recovery, reorientation, and decision. The reorientation may, under mild distraction, in healthy populations, and given sufficient inter-trial intervals lead to improved performance for a few trials. On this view, however, neither the slowing nor the improved performance reflect a reliable functional strategy, but are instead a purely incidental side-effect of the characteristics of the CRT (Notebaert et al., 2009). On the bidirectional error ↔ attention-lapse account, things can, and often do, turn out less favorably when, on a distracted SART trial, the prepotent response effectively ends the trial before a (delayed) decision has been made. This different pattern of responding between the two paradigms will continue as long as the error generated rumination continues or reactivates. Notably, both SART and CRT tasks are, in fact, in agreement about the duration of such rumination following errors (between 5 and 10 s; see Table 1A and B and Laming, 1968, 1979; see also Smallwood, McSpadden, Luus, & Schooler, 2008).

4.2. Alternative interpretations

Our results speak not only to the general issue of post-error processing, but also directly to the main theories of performance in the SART. In what follows we review the main theories of behavior in the SART and show that our findings cannot be sufficiently explained by any of the existing alternative theories of the SART.

4.2.1. Strategic responding

One plausible alternative interpretation of the effect of interval length on errors and response times following task challenges is that the results reflect an explicit strategic approach to the task (Helton, Head, & Russell, 2011; Helton, Weil, Middlemiss, & Sawers, 2010). For example, subjects may calculate that as time following the last challenge trial passes the occurrence of the next challenge trial becomes increasingly likely and hence allocate more attentional resources to the task as interval length increases. The SART, and the present version in particular, provides for a sensitive test of the use of such a strategy, as the probability of the appearance of a NOGO trial increases dramatically after 9–10 trials following the last NOGO trial. Consistent with this hypothesis, there was indeed a marked slowing of response times consistent with the predictions of the power function following a correct NOGO trial (Fig. 1B). In contrast, there was no such relation for response times following errors suggesting that errors interfered with the use of this strategy. Further, even following correct NOGO performance, the use of this strategy was not matched by a corresponding improvement in performance. Performance levels following correct and error performance overlap consistently from trials 7 to 16 (Fig. 1A). Thus, although subjects appear to be capable of detecting and strategically responding to strong temporal cues for NOGO trials, their performance is not thereby improved. Moreover, the implementation of such strategies appears to be very fragile in the face of failure to meet challenges successfully.

4.2.2. Periodic oscillations

Another alternative hypothesis is that endogenously driven attention lapses occur at periodic intervals with durations that correspond to the average inter-challenge interval lengths and persist through challenge trials producing bouts of errors. Sonuga-Barke and Castellanos (2007), for example, argue for endogenous slow oscillations with a period of about 10 s (see also Bellgrove, Hawl, Gill, & Robertson, 2006; Johnson, Kelly, et al., 2007; Johnson, Robertson, et al., 2007). If so, then challenges closer together will more likely fall within a period of inattention to the task. Such a hypothesis requires the assumption that periods of inattention and attention persist through challenge trials relatively unaffected, or resume immediately, an assumption at odds with observations of marked performance changes across pre- and post-challenge trials (e.g. Cheyne, Solman, et al., 2009). This hypothesis is also inconsistent with different period lengths in performance and response time changes following correct versus error prior NOGO trials. Moreover, this alternative hypothesis does not predict an increase in errors following correct NOGO trials given that correct performance is evidence that one is in an attentive period and so correct responses should be associated with subsequent reduction in errors. Alternatively, it is possible that the observed oscillation period of approximately 10 s is itself an artifactual consequence of the mean interval time between challenge presentations on the SART. Finally, it is also possible that endogenous cognitive rhythms were being re-set by periodic significant task events acting as *zeitgebers* entraining one of a potentially large range of resonant frequencies. Indeed, stimulus-synced increases in the power of certain frequency components of EEG recordings have been observed following both correct and incorrect responses, with further modulation on the basis of correct versus incorrect responding (Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells, 2008).

It is possible, of course, that there exist episodic or periodic fluctuations of attention of greater than the under 20 s durations reported here. For example, Eichele and colleagues report decreases in default mode deactivation from 6 to 30 s prior to errors (Eichele et al., 2008). Indeed, the present results are consistent with this finding in that events influencing errors will precede the resulting errors by variable intervals, although, in the present study, the most salient events do occur in closest proximity to their consequences. It is also possible, however, that longer term fluctuations in attention may affect vulnerability to challenge-event and error-induced reactivity. It would be of interest, for example, to investigate evidence of decreases in default network deactivation prior of challenge-induced errors (cf. Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011). Perhaps lapsing into default mode, rather than, or in addition to, directly increasingly the probability of error renders the individual more susceptible to overreaction to NOGO challenges and errors because such events become more unexpected and surprising. There is an inherent irony in the possibility that, if, having drifted off task, being brought back to the task demands by challenges and errors, temporarily withdraws one's resources from bearing upon the most immediate task demands, an irony not uncommon in emergencies and accidents (e.g., Reason, 1990).

4.2.3. The "mindless" hypothesis

According to this hypothesis, because the task is simple and repetitive, subjects are presumed gradually to become prone to mind wander, responding in an increasingly rapid and automatic ("mindless") manner over time, indexed by speeded response time resulting in increased NOGO errors (Robertson & Garavan, 2004; Robertson et al., 1997). This time-dependent claim for errors is rather striking given the brevity of the standard SART, about 5 min. Given substantial error rates (Cheyne, Solman, et al., 2009; Helton, Kern, & Walker, 2009; Manly, Robertson, Galloway, & Hawkins, 1999; Robertson et al., 1997; Smallwood et al., 2009), automatic responding must begin early and/or increase rapidly. The evidence for time-on-task effects is, however, sparse and mixed, with evidence for increasing, decreasing, and stable error rates over trials (Helton et al., 2009; Johnson, Kelly, et al., 2007; Johnson, Robertson, et al., 2007; Smallwood et al., 2004). The present findings indicate stable or modestly increasing error rates, and, inconsistent with the notion of increased automatic (speeded) responding over time, an increase in response time across time-on-task. That is, given the negative association of RT and commission errors (e.g., Cheyne, Carriere, et al., 2009; Cheyne, Solman, et al., 2009; Robertson et al., 1997) and that reported task unrelated thought had been reported to be associated with pre-error speeding (Smallwood et al., 2004) that increasing RTs would appear to reflect, either directly or indirectly, on-task engagement.

4.2.4. Resource depletion

Our present reinterpretation of the SART shares some features with a recent critique by resource theorists of the mindlessness hypothesis as an explanation of SART performance (e.g., Grier et al., 2003; Helton, 2009; Helton et al., 2005, 2009; Helton & Warm, 2008). The relevance of resource theory for vigilance decrement is the notion of "resource depletion" following long or demanding periods of sustained attention. The mindlessness theory of sustained attention underlying the development of the SART advanced by Robertson and colleagues is implicitly based, like the resource depletion theory, on declining vigilance over time. We agree with, and our results corroborate, the resource theorists' argument that SART errors, given the brevity of the test, are not often the result of resource depletion. Nonetheless, although the mindless interpretation may need revising, the present results are consistent with the claim that the SART is a sensitive and useful measure of failures of sustained attention understood as *transient* fluctuations in attention including those precipitated by reactions to NOGO challenges, in the form of task-relevant rumination about task performance. Although failures of sustained attention have traditionally focused on negatively accelerated decrements in vigilance over time, it was noted very early on that declines were not smooth and were characterized by marked fluctuations, with performance waxing and waning over very short periods of time (Deese, 1955). Moreover, the resource depletion hypothesis does not speak to the effects of NOGO challenges or the different effects of correct and error NOGO trials.

4.2.5. Individual differences

Another alternative possibility, not inconsistent with the bidirectional error ↔ attention-lapse model is that the differences between responses to correct and incorrect NOGO trails might reflect an individual difference whereby subjects prone to mind wandering contributed more data for performance and response time following errors. Supplementary analysis comparing high and low error subjects, however, replicated the patterns in Fig. 1A and B, in detail, and equally well for both groups, though individual differences in reactivity to NOGO challenges remains a possibility. We also replicated the results for males and females separately, and for older and younger subjects separately, observing similar functions for all groupings. Overall, these robust effects of interval length are consistent with the hypothesis of immediate and persisting reactance to challenges.

4.2.6. Spontaneous episodic mind wandering

Mind wandering can, of course be precipitated by intermittent spontaneous top-down "current concerns" (Smallwood, 2010; Smallwood, Fishman, & Schooler, 2007), both task-relevant and task-irrelevant (Smallwood, O'Connor, Sudberry, Haskell, & Ballantyne, 2004; Smallwood & Schooler, 2006). Although a hypothesis regarding spontaneous mind wandering is silent with regard to challenge-induced episodes, such episodes might, like spontaneous endogenously driven mind wandering, lead to cascading effects deepening mind wandering (cf. Smallwood, 2011a). Such effects might well explain the relatively long-term effects, especially of unsuccessfully met challenges. Smallwood and colleagues have presented evidence of a shift from slow to fast responding over a period of up to 10 s prior to a SART error (Smallwood et al., 2007) and associated with daydreaming (Smallwood, 2011b). The period of 10 s is consistent with the time course of reactions to task-relevant challenges.

4.3. Cognitive control versus challenge-induced bidirectional error ↔ attention-lapse

As noted earlier, in certain paradigms requiring subjects to respond both rapidly and accurately, pre-error speeding and post-error slowing has been reported for some time. Post-error slowing has been described as an adoption of a more conservative response threshold reflecting strategic control adjustments. Thus, following a series of correct trials, subjects are assumed to lower their threshold criteria in the service of faster responding, thereby increasing the probability of errors. When an error is committed, the response threshold is reset to a higher level to avoid future errors (e.g., Brewer & Smith, 1984; Rabbitt & Rogers, 1977; Rabbitt & Vyas, 1981). This hypothesis implies constant online modulation and control of performance to optimize speed-accuracy trade-offs (Bernstein, Scheffers, & Coles, 1995; Cohen, Dunbar, & McClelland, 1990; Gehring and Fencsik, 2001). These hypotheses have been incorporated into recent conflict monitoring models of cognitive control. The conflict monitoring and cognitive control (CMCC) model (Botvinick et al., 2001; Jones, Cho, Nystrom, Cohen, & Braver, 2002; Yeung, Botvinick, & Cohen, 2004) postulates an interaction of online monitoring of conflicts associated with and arising from task errors coupled with rapid engagement of control strategies. Errors are occasions of strong conflict leading to increased response thresholds that bias the speed-accuracy trade-off ratio. As Jentzsch and Dudschig (2009) point out, such a strategy would be effective given sufficiently long intervals between the previous response and the succeeding challenge (RSIs). For increasingly short RSIs, however, slowing would eventually become counter-productive. Also problematic for any functional strategic argument is the observation that post-error slowing appears to be greater for shorter than longer RSIs (Sanders, 1998). Shorter RSIs may also lead to less accurate responding (Dudschig & Jentzsch, 2009; Laming, 1979; Rabbitt & Rogers, 1977). Such observations lead Jentzsch and Dudschig to suggest that post-error slowing is automatic rather than an executive strategic move. The foregoing considerations are problematic for any hypothesis suggesting that response slowing involves the rapid engagement of control strategies.

Although the concept of post-*error* slowing has been widely studied, from the beginning it was clear that similar, though possibly weaker, effects obtained following correct performance as well (Laming, 1979; Rabbitt & Rogers, 1977). Moreover, the so-called post-error slowing is sometimes computed only with reference to immediate pre-error response time, which may often *pre*-error speeding (Cheyne, Carriere, et al., 2009; Cheyne, Solman, et al., 2009; Dudschig & Jentzsch, 2009), so that a post-error return to baseline would be interpreted as post-error 'slowing'. Indeed, this interpretation can be applied to the present results as responding on error trials is extremely rapid relative to overall response times (see Fig. 1B). Moreover, although post-correct performance changes are less persistent than those following errors, the immediate effects are very similar and, given that pre-correct responding is typically much slower than pre-error responding, these changes can actually demonstrate a greater local pre-post difference (see Fig. 5, Cheyne, Solman, et al., 2009; Cheyne, Carriere, et al., 2009).

The challenge-induced bidirectional error ↔ attention-lapse model is not inconsistent with the conflict monitoring component of the CMCC model, but does differ from the control component in postulating that the immediate consequences are not inherently or necessarily strategic, at least not in the immediate sense intended in the CMCC model. Rather, on the present view, challenge events (regardless of success or failure) evoke explicit online evaluation of current performance, anticipated future performance, and even broader task and non-task relevant personal evaluations of competence, interest, motivation, commitments, etc. This view does not, however, necessarily entail the hypothesis that such evaluations represent failures of executive control of attention (McVay & Kane, 2010). The specific consequences of such task evaluations will depend on the level and depth of off-task rumination. At low levels, such thoughts partially compromise performance as suggested by Smallwood (2010), whereas at deeper levels they can indeed lead to a collapse of on-task attention as suggested by McVay and Kane (2010). Both of these outcomes are accommodated by a three-state model of attention lapses (Cheyne, Solman, et al., 2009). Response adjustments following challenges may not reflect an online control strategy with immediate strategic benefits, but instead reflect interference caused by long-term meta-processing of overall performance – including strategies that may be implemented to the subject's advantage on future trials. Whether or not this processing involves explicit evaluation and forward planning of current and potential future strategies, such rumination does likely require some allocation of executive resources affecting ongoing occurrent performance (Cheyne, Carriere, et al., 2009; Cheyne, Solman, et al., 2009; Smallwood, 2010). In other words, post-error processing entails short-term costs in terms of allocation of resources to the ongoing task demands, but has possible long-term payoffs in terms of future improved performance.

The challenge-induced bidirectional error ↔ attention-lapse model does have some similarities to the capacity-limited error-monitoring model (Dudschig & Jentzsch, 2009; Jentzsch & Dudschig, 2009; Welford, 1959, 1980), whereby diminishing central resources compromise ongoing performance. Indeed, it has been recognized that error evaluation is time consuming and resource demanding, and can therefore interfere with subsequent performance (Dudschig & Jentzsch, 2009; Gehring and Fencsik, 2001; Hochman and Meiran, 2005; Jentzsch & Dudschig, 2009; Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996) though it has generally been seen as inherently automatic and relatively short-term. In contrast to this low level error monitoring process, which is hypothesized to create a bottleneck for several-hundred milliseconds, we hypothesize that task challenges may induce explicit performance evaluation as a high level conscious process that may potentially occur over extended periods of seconds or even minutes. Although both task related and task unrelated cognition are task-interfering, relative to occurrent task demands, task-related cognition is more likely reflect higher levels of task motivation and greater medium to long-term task engagement. Many real-world tasks requiring forward planning and/or anticipation of changes in task demands will likely benefit substantially from strategic task-related thoughts.

5. Concluding remarks

In the present task, challenge trials lead to pervasive immediate negative effects on ongoing performance, lasting 6–7 s, as well as longer term interference with strategic adjustment of response times. Attention lapses, the turning of attention away from continuous monitoring of ongoing tasks, are potentially a pervasive consequence of meeting life's everyday moment-to-moment challenges – and of succeeding or failing to meet of those challenges. Such challenges are common during everyday activities such as having conversations, driving, and during work-related and recreation activities, and periods of testing and scrutiny. Typically, we meet each challenge expeditiously, often automatically, and move on. Nonetheless, there are inevitable cognitive costs entailed in coping with even minor challenges as we consciously and unconsciously analyze and evaluate those events, our reactions to them, and the consequences of each. This processing of recent critical events requires cognitive resources and thereby effectively reduces capacity to cope with subsequent challenges, particularly when they follow one another in rapid succession. Coping with such pervasive sources of mind wandering and attention lapses, recognizing and managing them in a mindful manner, may represent as important a skill as managing long-term depletion of attentional resources.

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