Anatomy of an error: A bidirectional state model of task engagement/disengagement and attention-related errors

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Abstract

We present arguments and evidence for a three-state attentional model of task engagement/disengagement. The model postulates three states of mind-wandering: occurrent task inattention, generic task inattention, and response disengagement. We hypothesize that all three states are both causes and consequences of task performance outcomes and apply across a variety of experimental and real-world tasks. We apply this model to the analysis of a widely used GO/NOGO task, the Sustained Attention to Response Task (SART). We identify three performance characteristics of the SART that map onto the three states of the model: RT variability, anticipations, and omissions. Predictions based on the model are tested, and largely corroborated, via regression and lag-sequential analyses of both successful and unsuccessful withholding on NOGO trials as well as self-reported mind-wandering and everyday cognitive errors. The results revealed theoretically consistent temporal associations among the state indicators and between these and SART errors as well as with self-report measures. Lag analysis was consistent with the hypotheses that temporal transitions among states are often extremely abrupt and that the association between mind-wandering and performance is bidirectional. The bidirectional effects suggest that errors constitute important occasions for reactive mind-wandering. The model also enables concrete phenomenological, behavioral, and physiological predictions for future research.

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Introduction

The type of error in question is an attention-related action or cognitive error caused by a loss of attentional engagement in an ongoing primary task (Reason, 1990; Reason & Mycielska, 1982). Task disengagement and its sources have been studied under a number of rubrics including absent-mindedness (Cheyne, Carriere, & Smilek, 2006; Reason & Lucas, 1984), mind-wandering (Kane et al., 2007; Smallwood & Schooler, 2006; Wegner, 1997), stimulus-independent thought (Antrobus, 1968; Teasdale, Lloyd, Proctor, & Baddeley, 1993; Teasdale, Segal, & Williams, 1995), task-unrelated/related thought (Giambra, 1995; Smallwood, Baracaia, Lowe, & Obonsawin, 2003; Smallwood, O’Connor, Sudberry, Haskell, & Ballantine, 2004; Smallwood, Obonsawin, & Heim, 2003; Smallwood, Obonsawin, & Reid, 2003; Smallwood et al., 2004), tune outs and zone outs (Schooler, 2002; Schooler, Reichle, & Halpern, 2005; Smallwood, McSpadden, & Schooler, 2007), and mind pops (Kvavilashvili & Mandler, 2004). Whatever label is used, current approaches to attentional task disengagement agree that the core phenomenon consists of a state of reduced allocation of attentional resources to environmental task-related stimuli (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997; Smallwood & Schooler, 2006; Smallwood et al., 2007). Conditions promoting such task disengagement arising from mind-wandering include protracted, unvarying, familiar, repetitive, and
undemanding tasks and task environments (see Smallwood and Schooler (2006) for a review). Although distinctions between
mind-wandering with and without awareness (Hester, Foxe, Molholm, Shpaner, & Garavan, 2005; Schooler, 2002; Schooler et al.,
2005; Smallwood et al., 2007) imply different modes or states of attentional disengagement or decoupling (Smallwood &
Schooler, 2006), these have not been conceptually analyzed in terms of underlying cognitive processing failures. We propose a
model of attentional engagement/disengagement consisting of three distinct states, describe their cognitive, phenomenological, and
performance characteristics, and suggest real-world examples of each. We propose and assess behavioral markers for each state
using an established sustained attention task and relate these markers to behavioral performance and to self-reported everyday
mind-wandering and cognitive failure.

**States of attentional disengagement: a three-state model**

**Task engagement: to what do we attend when we attend to a task?**

The present model of mind-wandering and task disengagement assumes that successful task performance in everyday tasks
such as reading a book, listening to a speaker, or driving a vehicle, has the following attentional requirements. First, at the most
demanding level, attentional resources must be allocated to occurrent, dynamic, and focal features of a task that change from
moment to moment. In the language of intentionality theories, occurrent attentional concerns correspond to intentions-in-action
(Searle, 1983), immediate intentions (Brand, 1984), present-direct intentions (Bratman, 1987), and proximal (Mele, 1992) or
P-intentions (Pacherie, 2008). Dynamic features are cues that guide moment-to-moment task performance including feedback
regarding the adequacy of ongoing performance. These are often, though not exclusively, semantic features such as specific
word/phrase/sentence meanings during a reading/listening task, or critical meaningful changes in a driving environment such as
traffic signals, object visibility, surface features, turns, and the behavior of other vehicles.

Second, additional attentional resources must be dedicated to monitoring the stable background task environment and goals
(e.g., reading an instruction manual, listening to a lecture, and driving to work). As Pacherie (2008) notes, P-intentions, or what we
have called occurrent attention, must integrate overarching prior intentions (i.e., distal or D-intentions) concerning task goals and
performance with the current task conditions. That is, in maintaining task set some attentional resources must be given over to
general task parameters and goals.

Third, successful task engagement typically has implicit and explicit performative aspects. Attentional resources must
therefore also be allocated to the on-line recruitment, guidance, and maintenance of task responses (e.g., maintenance of saccades
down a page; taking notes during a lecture, manipulation of the control surfaces of a vehicle).

Clearly anything that interferes with, or places challenges on, any of these three aspects of task-related attention will increase
task failures. Note that the foregoing analysis, as well as the subsequent model of task disengagement, assumes adequate
knowledge, skill, and motivation on the part of the performer. As noted at the outset, the error in question occurs despite optimal
training, competence, and motivation of the performer. The present analysis is focused on the withdrawal of attentional resources
from an external task rather than on important issue of the nature of the allocation of resources to internal processing (see
Smallwood, Baracaia, Lowe, and Obonsawin (2003), Smallwood, Heim, Rigby, and Davies (2006), and Smallwood et al. (2004,
2007)).

**Task disengagement: states of inattention**

*State 1:* The model proposes three discrete states of attentional disengagement. Based on the foregoing task analysis, it
follows that the attentionally most demanding dynamic level will be most vulnerable to mind-wandering leading to occurrent task
inattention. Occurrent task inattention (State 1) consists of an often brief and/or partial waning of detailed processing of moment-
to-moment stimulus meaning. The essential characteristic of State 1 is a transient disengagement of attention from the dynamic
features of the task (e.g., the content of the present reading passage or lecture or the current movements and signals of the vehicle
ahead). Individuals are aware of such inattention some of the time during State 1 (Hester et al., 2005; Schooler, 2002; Schooler et
al., 2005; Smallwood et al., 2007) and likely experience dual consciousness or divided attention (Smallwood et al., 2007) in
which they are aware of the transient intrusions of trains of interfering thoughts, which they may attempt to suppress. The
phenomenology of this state is nicely captured in the metaphor of “tuning out” (Schooler, 2002; Schooler et al., 2005; Smallwood
et al., 2007). State 1 inattention is brief and unstable, and likely to be affected by incidental events, errors, and near-misses.
Near-misses will be common at this early state compared to later states and attentional resources will often be sufficient to detect
incipient slips before they become overt errors. Nonetheless, because of its ubiquity in human performance, transient focal task
inattention may well be responsible for the majority of errors despite its comparatively brief and mild character.
Anatomy of an error: A bidirectional state model of task engagement/disease... performance for brief, and sometimes surprisingly extended, periods. Mind-wandering in this state is less likely to be conscious of the environment decreases though the individual continues to show well-practiced automatic responding. In everyday terms we characterize this as “going through the motions”. For simple repetitive tasks this minimal engagement may suffice for adequate performance for brief, and sometimes surprisingly extended, periods. Mind-wandering in this state is less likely to be conscious (cf. O’Connell et al., 2007; Smallwood et al., 2007) and has been succinctly characterized as “zoning out” (Smallwood & Schooler, 2006). The individual may be alerted by blatant errors but will be less sensitive to near-misses. State 2 can normally be maintained for more than a few seconds only in a relatively quiet, uneventful environment and/or during very tedious and undemanding tasks. Such tasks and environments are, however, not uncommon. Reading, for example, is generally performed in the absence of spontaneously changing conditions. We therefore sometimes find ourselves well beyond that last point of recall of what we have been reading, but clearly have continued to scan down the page some way before recovering task awareness. Another such experience is waiting in a car at traffic lights for a green light. When traffic beside us begins to move and we may move with the traffic in response to peripheral background features of the driving environment rather than appropriate cues (i.e., traffic signals) for correct task performance. Thus, if the light change signaled a left turn for vehicles in the lane beside us, we might find that we have anticipated the relevant light change to find ourselves in the middle of the intersection moving against a red light – at which point we are likely to quickly recover full lucidity. Note, however, that attentional resources at such points are required to process the error itself. Such error-induced task-relevant processing can, ironically, further compromise task performance, and hence lead to further errors (see bidirectionality thesis below). This is one way in which errors beget errors.

State 2: In State 1 the individual maintains awareness of the general task environment. That is, attention to task set remains active but with loss of sensitivity to moment-to-moment task variations. In State 2, attention to the generic task-relevant aspects of the environment decreases though the individual continues to show well-practiced automatic responding. In everyday terms we characterize this as “going through the motions”. For simple repetitive tasks this minimal engagement may suffice for adequate performance for brief, and sometimes surprisingly extended, periods. Mind-wandering in this state is less likely to be conscious (cf. O’Connell et al., 2007; Smallwood et al., 2007) and has been succinctly characterized as “zoning out” (Smallwood & Schooler, 2006). The individual may be alerted by blatant errors but will be less sensitive to near-misses. State 2 can normally be maintained for more than a few seconds only in a relatively quiet, uneventful environment and/or during very tedious and undemanding tasks. Such tasks and environments are, however, not uncommon. Reading, for example, is generally performed in the absence of spontaneously changing conditions. We therefore sometimes find ourselves well beyond that last point of recall of what we have been reading, but clearly have continued to scan down the page some way before recovering task awareness. Another such experience is waiting in a car at traffic lights for a green light. When traffic beside us begins to move and we may move with the traffic in response to peripheral background features of the driving environment rather than appropriate cues (i.e., traffic signals) for correct task performance. Thus, if the light change signaled a left turn for vehicles in the lane beside us, we might find that we have anticipated the relevant light change to find ourselves in the middle of the intersection moving against a red light – at which point we are likely to quickly recover full lucidity. Note, however, that attentional resources at such points are required to process the error itself. Such error-induced task-relevant processing can, ironically, further compromise task performance, and hence lead to further errors (see bidirectionality thesis below). This is one way in which errors beget errors.

State 3: Discussions of mind-wandering have traditionally stressed the “decoupling” of conscious processing from on-line environmental sensory information as attention is directed inward to thoughts and feelings (Schooler et al., 2005; Singer, 1966; Smallwood & Schooler, 2006). This has led to an important focus on changes in the individual’s access to representations of environmental stimuli during mind-wandering (Smallwood & Schooler, 2006). Attention can, however, also be drawn away from motor behavior as evidenced in action slips (Reason, 1979; Reason & Mycielska, 1982). Hence, in State 3 there are also gross behavioral indicators of mind-wandering. The individual may be unresponsive to all but the most intrusive aspects of the task environment. In real-world situations, such as reading, we cease even moving down the page and stare – blank, unmoving, and unseeing – at the page; or we fail to drive on at all, even after the light has turned green and the traffic around us has moved on, until we are roused by an insistent honking behind us or the crunching of metal. Ultimately, the internal train of thought may initiate a new stream of action. In some cases, the individual may even wander physically, getting up from a work station, for example, to engage a colleague in a discussion concerning the intruded thought. Thus, conditions permitting, mind-wandering can lead to a change of the primary task.

Relations among states: In addition to specifying three discrete states of attentional engagement/disengagement, the three-state model also postulates specific relations among states and the relations of the states to specific errors. First, the model holds that the three states of mind-wandering are often sequential in that an individual will move from state to state. Second, because the states, though discrete, are functionally and sequentially related, the three-state model holds that individuals with a propensity of being in one state of disengagement should also show a bias to enter other states of disengagement. Nonetheless, the hypothesis of qualitative differences among the different states the model leads to the prediction that each level of attentional disengagement will potentially contribute independently to cognitive and action failures.

Testing the three-state model

We next describe the Sustained Attention to Response Task (SART) that constitutes a controlled context to assess the model and provide distinct indicators for each of the three states. Although we claim considerable generality for the state model of task disengagement, the specific behavioral indicators of each of the three states of mind-wandering will vary according to the nature
of the task and hence critical features of each task must be analyzed to determine such indicators for that task. Thus, we next propose indicators relevant to the SART for each of the three states and test a set of novel predictions that emerge from the three-state model.

The SART

The Sustained Attention to Response Task (SART: Robertson et al., 1997) is a measure of sustained attention and mind-wandering. Failures of sustained attention as measured by the SART have been related to an increasing number of real-world problems and psychological variables, including self-reported everyday attention failures (Cheyne et al., 2006), general cognitive failures (Manly et al., 1999; Robertson et al., 1997), as well as specifically attention-related cognitive errors (Cheyne et al., 2006), conditions such as ADHD (Bellgrove, Hawi, Gill, & Robertson, 2006; Bellgrove, Hawi, Kirley, Gill, & Robertson, 2005; Johnson, Kelly, et al., 2007; Johnson, Robertson, et al., 2007; Manly et al., 2001; Mullins, Bellgrove, Gill, & Robertson, 2005), TBI (Dockree et al., 2004; Manly et al., 2003; O’Keeffe, Dockree, & Robertson, 2004; Robertson et al., 1997 but see Whyte, Grieb-Neff, Gantz, & Polansky, 2007), boredom (Cheyne et al., 2006), and depression (Carriere, Cheyne, & Smilek, 2008; Smallwood et al., 2007), as well as the neurophysiology of attention (Bellgrove, Hester, & Garavan, 2004; Dockree, Kelly, Foxe, Reilly, & Robertson, 2007; Dockree, Kelly, Robertson, Reilly, & Foxe, 2005; Dockree et al., 2004; Fassbender et al., 2006; Garavan, Hester, Murphy, Fassbender, & Kelley, 2006; Hester, Fassbender, & Garavan, 2004; Hester et al., 2005; Kaufman, Ross, Stein, & Garavan, 2003; O’Connell et al., 2007).

SART Indices of attentional disengagement

The SART is a GO/NOGO continuous performance task in which the NOGO stimulus appears infrequently. SART NOGO errors are typically interpreted as analogs to real-world action slips caused by failures of sustained attention rather than failures of inhibition (Manly et al., 1999; Robertson et al., 1997). SART performance also provides several behavioral indices of off-task mind-wandering that could potentially lead to NOGO errors.

The first and most critical of these indices is the *speeding of response times* (RTs), especially on GO trials immediately preceding NOGO errors. The suggestion that fast RTs index off-task mind-wandering is supported by (1) observations of negative correlations between overall RTs and total NOGO errors across subjects (Cheyne et al., 2006; Manly et al., 1999; Robertson et al., 1997), (2) evidence of shorter mean sRTs in the trials immediately prior to NOGO trials leading to SART errors (Manly et al., 1999; Robertson et al., 1997) and shorter RTs prior to error NOGO trials than prior to successful NOGO trials (Cheyne et al., 2006), (3) reports of an association between task-unrelated thought and speeded RTs during SART performance (Smallwood et al., 2004), (4) the finding that as target probability decreases GO RTs decrease and errors increase (Manly et al., 1999) presumably because infrequent NOGO trials provide opportunities for increased mind-wandering, and (5) reports of shorter RTs and more errors with absence of awareness during probe-caught mind-wandering (Smallwood et al., 2007).

Second, we draw attention to another potential index of mind-wandering in the SART, namely, responses on GO trials that are too fast to be responses to the GO stimuli, but rather appear to be anticipations of the presentation of GO stimuli. In reexamining our own SART data, we noted a striking pattern of RTs across trials (see Fig. 1). It is evident in Fig. 1, which provides RT data across 225 trials for each of three subjects, that the records reveal many impossibly fast RTs (Mean = 55.85; SD = 19.52). Anticipations are qualitatively different from normal RTs evidenced by a clear band of latencies essentially free of data points below the majority of RTs and above the extremely short RTs. Extremely fast RTs (less than 100 ms) have been noted on the SART before (e.g., Johnson, Robertson, et al., 2007) and these anomalous values have been replaced with RTs from adjacent trials. It occurred to us, however, that these events might provide distinctive information about task disengagement. Anticipations may reflect speed-accuracy trade-offs, possibly encouraged by the fixed inter-trial interval generally used in the SART. Some recent versions of the SART have employed variable ITIs to discourage speed-accuracy trade-offs. This apparent refinement may, however, conceal an important phenomenon. Anticipations would seem to fit well our description of State 2 mind-wandering. Anticipations are too fast for the individual to have processed the immediately relevant stimulus and hence are consistent with the notion of responding without the moment-to-moment task-relevant stimulus monitoring (“going through the motions”). This interpretation is also consistent with the view that anticipations are fundamental form of action slips and spoonerisms (cf. prolepsis; Douse, 1900; see also Norman, 1981) indicating mind-wandering or absent-mindedness (Reason, 1979, 1984; Reason & Mycielska, 1982). Finally, the distinct gap in the data points evident in Fig. 1 is clearly consistent with abrupt qualitative state changes.
A third potential index of mind-wandering in the SART task is the failure to respond to GO stimuli (i.e., omissions). Errors of omission are among the most common form of human error (Norman, 1981; Rasmussen, 1980; Reason, 1990, 1998). Errors of omission have been observed in the SART with both fixed and random inter-trial intervals and have been interpreted as a break from task engagement and thus reflective of lapsing attention (Johnson, Robertson, et al., 2007; Manly et al., 1999). This interpretation of omissions is supported by the finding that omissions tend to increase along with NOGO errors in the second half of the SART task when attentional engagement is thought to be low (Johnson, Robertson, et al., 2007). In addition, relative to controls, more omissions and NOGO errors have been observed for individuals with ADHD (Johnson, Robertson, et al., 2007; O’Connell, Bellgrove, Dockree, & Robertson, 2004) and patients with traumatic brain injury (Manly et al., 2003). Again, it is evident from Fig. 1 that there is a substantial gap in the upper portion of each record, even for the slowest responder, between the longest RTs and the end of each trial (at 1150 ms). Thus, transition from normal RTs to omissions appears to be as abrupt as that for anticipations, consistent with a qualitative change in state.

It is important to acknowledge that whether a given response latency is an anticipation or an omission is determined by the temporal parameters of the task. The argument for different states, however, hinges on whether there is a discontinuity between acceptable variations in response times for the task. In the model, an important executive function is to keep responding within task parameters. Hence, in State 1, variation is kept within acceptable ranges. Moreover, when performance approaches the limits of acceptable response speed or precision the data suggest that they are either brought back from that limit or they “pop out” of that range into extremely fast (automaticity) or very slow (in the limit – non-response). We therefore suggest that the three SART indices of mind-wandering described above (i.e., RT changes, anticipations, and omissions) are potentially valid indicators of the three states of attentional disengagement as described by the model.

Fig. 1. Three sample cases of reaction times for individual subjects over 225 SART trials including anticipations (RTs below 100 ms).
Applying the model in the context of the SART, speeding RTs indicate State 1. This pattern of alternating speeding and slowing would generate increased RT variability (Johnson, Kelly, et al., 2007). We therefore suggest that an appropriate index of State 1 is the coefficient of variability (CV = SD/Mean), a measure of variability independent of mean differences. We further propose that State 2 of attentional disengagement in the SART is manifest in anticipations of the SART stimuli. Anticipations occur when the focal semantic features of the stimulus (i.e., the value of the stimulus) are not fully processed and behavior (i.e., the key press) occurs automatically according to the rhythm of stimulus presentation. Finally, we suggest that omissions index State 3; namely, a cessation of responding within the temporal bounds of adequate task performance.

Task disengagement and bidirectionality

By task disengagement we mean the shifting of resources from on-line processing of task cues to off-line processing of materials not relevant to immediate task demands. Importantly, processing during task disengagement need not be entirely task irrelevant (Smallwood et al., 2004); merely irrelevant to concurrent task demands. Mind-wandering is often more than idle wool-gathering and may involve serious off-line problem solving (Kane et al., 2007; Singer, 1966, 1978). Indeed, because of the assumption of sufficient background competence and motivation, our model is compatible with the likelihood that much off-line processing is relevant to task performance and is, indeed, often precipitated by variations in task performance. Thus, even under optimal task conditions of competence and motivation, both successful and especially unsuccessful performance events, will induce off-line analysis of performance. This leads to the prediction that the performance – mind-wandering association is bidirectional.

It has been commonly noted that errors redirect attention back to the primary task at hand (Robertson et al., 1997; Sarason, Sarason, Keefe, Hates, & Shearin, 1986; Smallwood, Davies, et al., 2004; Smallwood, O’Connor, et al., 2004). Recent evidence suggests, however, that reflection on task performance accounts for substantial off-task processing, sometimes referred to as Task-Related Interference (Smallwood, Davies, et al., 2004; Smallwood et al., 2003). Smallwood and colleagues specifically report high levels of Task-Related Interference following errors (Smallwood, Davies, et al., 2004). Thus, although it may be the case that errors redirect attention back to the task, the redirection may often be in the form of off-line internal analysis, including evaluation of performance, itself a form of reactive mind-wandering, that may interfere with ongoing task performance. In the extreme, the bidirectional relation between mind-wandering and attention-related errors in performance can snowball with disastrous consequences in which off-line analysis leads to complete neglect of the task at hand (e.g. flying an aircraft or monitoring a nuclear facility, cf. Reason, 1979; Vincente, 2004).

Predictions

Following are general sets of predictions that emerge from a three-state bidirectional model of attentional disengagement when applied to SART performance.

Relations among SART indicators and general measures of mind-wandering: In general, the model predicts that RT CV, anticipations, and omissions will all be correlated with NOGO errors and, because they represent distinct states of mind-wandering, each of these measures will contribute independent variance to the prediction of NOGO errors. Thus, the first set of specific predictions concerns associations at the level of the individual differences between the proposed SART indicators of the states of disengagement (i.e., RT CV, anticipations, and omissions) and self-reported indices of everyday mind-wandering and attentional failure. The model predicts positive correlations among RT CV, anticipations, and omissions on GO trials as well as between each of these and SART errors, self-reported mind-wandering measured by the Mindful Awareness and Attention Scale – Lapses Only (MAAS-LO), and self-reported attentional failures measured by the Attention-Related Cognitive Errors (ARCES) scale. These predictions fundamentally assume stable individual differences in propensities for mind-wandering and the external validity of the SART measures.

We note that some of these predictions are counterintuitive from an inhibition perspective, given that anticipation would seem to index strong disinhibition whereas omissions would appear to reflect complete inhibition. According to the model, however, anticipations and omissions represent successive states in attentional disengagement related to task performance/nonperformance and hence should be positively mutually associated and both should be positively associated with commission errors on NOGO trials. In our earlier analyses (Cheyne et al., 2006), we found, consistent with previous and subsequent research, that overall RTs were significantly and robustly negatively associated with NOGO errors (r = -.64, p < .001). Previously, however, RTs included the anticipations discussed above and, as argued above. For the present study, we therefore calculated RT and RT CV only for trials with RTs above 200 ms and counted as anticipations all RTs less than 100 ms. The very few ambiguous RTs (i.e., between 100 and 200 ms) were ignored.
In our earlier research, we reported that a self-report measure of mind-wandering propensity, the Mindful Awareness of Attention Scale (MAAS) was significantly associated with SART GO RTs and accounted for the association between the self-report scale of Attention-Related Cognitive Errors (ARCES) and RTs (Cheyne et al., 2006).

On the other hand, the ARCES contributed unique variance to the prediction of SART NOGO Errors. This pattern of results was consistent with the hypothesis that the MAAS and SART RT speeding directly reflect mind-wandering, whereas ARCES and SART NOGO errors are cognitive performance consequences of mind-wandering. We therefore predicted that a slightly revised scale, focusing on lapses only, the MAAS-LO (Carriere et al., 2008) and the ARCES would be significantly correlated with RT CV, as well as with anticipations and omissions but that the MAAS-LO would account for the association of the ARCES with each of these measures.

Temporal relations and transitions between states: A critical aspect of the three-state model of attentional disengagement is the hypothesis that the three states are sequentially related. Hence, speeding of RT should occur on trials immediately prior to anticipations and omission as well as following anticipations. Second, the probability of anticipations and omissions should increase on trials just before and after anticipations and anticipations.

Bidirectionality of mind-wandering and NOGO errors: The model states that mind-wandering and the resulting inattention to the task leads to errors and to reflection on those errors, consequently directing attentional resources away from current task conditions. Thus, the bidirectional aspect of the model predicts that all performance tests (NOGO trials in the SART), successful as well as unsuccessful, will lead to reflection on task performance and hence provide occasions for mind-wandering. To assess these predictions, we examined RT changes, anticipations, and omissions following as well as preceding both correct and incorrect NOGO trials. We predict that, in the context of the SART, all indicators of mind-wandering (RT variability, anticipations, and omissions) will serve as both precursors and consequences of both successful and unsuccessful task performance.

The bidirectional model leads to one further prediction. If performance tests (i.e., NOGO trials) lead to increased mind-wandering then closely spaced NOGO trials should also lead to increased probability of errors, especially following a recent NOGO error.

Method

Participants

Subjects were selected from among prior respondents to a WWW survey on sleep paralysis (see Cheyne et al., 2006). The final selection of participants who completed the full study included 349 females, 155 males (N = 504). Participants ranged from adolescence to senescence, with a mean age of 32.23 (SD = 11.23). Blank or incomplete submissions were removed from analysis and any instances of multiple submissions from the same participant were removed. Similarly, results from participants who failed to complete all 225 trials of the SART, or responded in opposite manner to that in which they were instructed (i.e., key press provided only when the target appeared), were removed from the data set. Of an original 717 participants, total of 213 participant responses were removed in this manner.

Measures

RT CVs were calculated for all response latencies over 200 ms. RTs less than 100 ms were coded as anticipations. If no response was made during a GO trial this was recorded as an omission. Responses to the NOGO stimulus (“3”) were coded as NOGO errors and successful withholding of responses as NOGO successes. The self-report measures included the 12-item ARCES and the 13-item revised Mindful Awareness of Attention with Lapses Only (MAAS-LO; see Carriere et al., 2008).

The SART procedure, as described by Robertson et al. (1997), involves 225 single digits, 25 each from 1 to 9, presented for 250 ms and followed by an encircled X mask for 900 ms, for a total digit-to-digit duration of 1150 ms. Participants were instructed to respond via a key press to each digit, unless that digit is a 3. The digits are randomly distributed, as are the font sizes of all 225 trials, with equal representation of 48, 72, 94, 100, and 120 point size Symbol font in white against a black background. The SART was recreated in Macromedia Flash MX 2004 according to these specifications, in order to allow on-line presentation of the SART with the rest of the questionnaires. 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 x 800) display, used for scale development, stimulus height varied from 8.74 mm (34 px) to 21.33 mm.
Procedures

Participants received an informational e-mail regarding the study, including a link to the study website and a pre-assigned personal identification number. Upon visiting the study website, participants received further instructions regarding the purposes of the study and were given the opportunity to participate by completing, in random and undisclosed order, the ARCES, MFS, and MAAS. Participants completed the three measures in a single session, followed by the SART, at the end of which they were given a feedback page thanking them for their participation and providing further information about the purposes of the study and links to a website with additional information on sleep paralysis.

Lag analyses

Lag RTs were calculated as follows. For each NOGO trial, separately for correct and incorrect responses, the RTs for the four preceding trials and the four trials following the NOGO trial were tabulated. RTs were then averaged within each lag. The same procedure was repeated for four trials preceding and four trials following anticipations and omissions. Lag probabilities for anticipations and omissions were calculated as follows. For each NOGO trial the four preceding and the four following trials were analyzed separately for correct and incorrect responses. Probabilities for a given trial type were generated by taking the number of occurrences of that type at a given lag, divided by the total number of trials counted at that lag (in most cases this was equal to the number of errors considered, except when an error occurred within four trials of the beginning or end of the experiment). These analyses were performed using a command line tool written in C.

To ensure that our measures of RTs, anticipations and omissions before and after NOGO errors did not overlap, it was necessary to exclude some trials and participants from the analyses. Hence, sample sizes vary slightly from measure to measure and between comparisons within measures and are reflected in the changing degrees of freedom of the F-tests. For RT, for example, we recorded as missing data trials preceding or following NOGO errors that included omissions, anticipations, or other NOGO trials. Missing data also arose in cases in which RT was not available because the end or beginning of the session occurred within four trials of the target NOGO trial. For anticipations and omissions, conditional probabilities for mutual transitions could be calculated only for individuals committing anticipations or omissions.

Given the statistical power of the large sample size and the multiple repeated measures the lower-bound degrees-of-freedom were used for all repeated-measures analyses, leading to further variations in degrees of freedom across tests.

Results and discussion

Associations among indicators and consequences of mind-wandering

We began by testing our prediction that the three target variables (RT CVs, anticipations, and omissions on GO trials) as measures of states of mind-wandering generalize beyond the SART. Hence, by hypothesis, each of the SART indices will be correlated with one another, with NOGO Errors, and with self-reported mind-wandering measured by the MAAS-LO and self-reported attentional failures measured by the ARCES. The correlations among each of these measures are shown in Table 1.

Table 1

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<tr>
<th></th>
<th>RT CV</th>
<th>Anticipations</th>
<th>Omissions</th>
<th>NOGO errors</th>
<th>MAAS-LO</th>
<th>ARCES</th>
</tr>
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<tbody>
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<td>RT CV</td>
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<td>0.70</td>
<td>0.62</td>
<td>0.50</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>Anticipations</td>
<td>(0.12)</td>
<td>3.13</td>
<td>0.53</td>
<td>0.52</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Omissions</td>
<td>(0.76)</td>
<td>5.79</td>
<td>3.40</td>
<td>0.42</td>
<td>0.19</td>
<td>0.13</td>
</tr>
<tr>
<td>NOGO errors</td>
<td></td>
<td>(5.83)</td>
<td>(10.89)</td>
<td>0.31</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>MAAS-LO</td>
<td></td>
<td></td>
<td></td>
<td>54.76</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>ARCES</td>
<td></td>
<td></td>
<td></td>
<td>(12.05)</td>
<td>49.40</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in Table 1, the three SART indicators (RT CV, anticipations, and omissions) were significantly and strongly correlated with one another. Also as predicted, RT CV, anticipations, and omissions were each robustly correlated with NOGO.
Errors. These correlations corroborate the interpretation of, and the model predictions for, RT CV, anticipations and omissions as indices of mind-wandering in the SART task. Also consistent with predictions, RT CV, anticipations, and omissions were significantly correlated with self-reported mind-wandering as measured by the MAAS-LO and with self-reported action slips assessed by the ARCES. Moreover, extending our previous findings (Cheyne et al., 2006) that the association of the MAAS-LO with the RTs completely accounted for association of the ARCES and RT, a series of regression analyses, replicated this result for RT CV, anticipations, and omissions. The ARCES contributed no additional significant predictive power for any of these variables beyond that of the MAAS-LO, though, also consistent with previous analyses, it did for NOGO errors, $\beta = .13, t = 2.02, p < .04$. This finding is consistent with the conclusion that anticipations and omissions, like SART RTs, are best interpreted as direct indices of mind-wandering.

A further prediction arising from the three-state model is that different states of mind-wandering make independent contributions to cognitive errors and action slips. Consistent with this prediction, a multiple regression analysis with NOGO errors as the dependent variable, yielded significant coefficients for RT CV, anticipations, and omissions (see Table 2). Anticipations made slightly stronger contributions than the other two variables and omissions made slightly weaker contributions to the prediction of SART errors. The latter finding may reflect a peculiarity of omissions in the SART task. Because the critical feature of successful task performance requires the withholding of a response, omissions will occasionally lead to spuriously successful NOGO trials, attenuating the general positive association of omissions with NOGO errors. It is predicted that omission will provide even better prediction for a variant of the SART that requires an alternative positive response (rather than none).

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td><strong>Multiple regression predicting NOGO errors with RT CV, anticipations, and omissions.</strong></td>
</tr>
<tr>
<td>Dependent variable: NOGO errors</td>
</tr>
<tr>
<td>RT CV</td>
</tr>
<tr>
<td>Anticipations</td>
</tr>
<tr>
<td>Omissions</td>
</tr>
<tr>
<td>$R^2 = .32, F(3,500) = 77.74, p &lt; .001$</td>
</tr>
</tbody>
</table>

*Temporal associations among the SART indicators of mind-wandering RTs and anticipation:* RTs for the four trials (lags) immediately preceding and following anticipations were analyzed (Fig. 2). The data were analyzed in a 2 (pre-anticipations vs. post-anticipations) by 4 (lag) repeated-measures ANOVA for individuals making anticipations. This analysis yielded significant temporal order and lag effects, which were superseded by a significant temporal order by lag interaction, $F(1,162) = 23.42, p < .001, \eta^2 = .31$. This interaction was disambiguated by analyses of the lag effects for pre- and post-anticipation RTs. RTs preceding anticipations showed a robust significant linear decrease, $F(1,162) = 110.17, p < .001, \eta^2 = .39$, and a smaller quadratic component, $F(1,162) = 47.88, p < .001, \eta^2 = .22$. RTs following anticipations appeared to show a near mirror-image linear decline, although RT speed was significantly faster immediately prior to, than following, anticipations, $t(197) = 9.44, p < .001$ (see Fig. 2).
Anticipations and omissions: To assess the sequential associations of anticipations and omissions, the conditional probabilities of anticipations for the four trials immediately preceding and following omissions and the conditional probabilities of omissions preceding and following anticipations were analyzed in a 2 (anticipation vs. omission) by 2 (pre vs. post) by 4 (lag) repeated-measures ANOVA for individuals making anticipations (see Fig. 3). This analysis yielded significant temporal order and lag effects, which were superseded by a significant temporal order by lag interaction, $F(1,207) = 49.68, p < .001, \eta^2 = .19$ (see Fig. 3). The interaction was disambiguated by analyses of the lag effects for pre- and post-anticipations and omissions combined. Preceding conditional probabilities showed a robust significant linear increase with a marked inflection between $t – 2$ and $t – 1$, well above the mean baseline, yielding significant linear $F(1,210) = 62.36, p < .001, \eta^2 = .23$, quadratic, $F(1,210) = 32.69, p < .001, \eta^2 = .13$, and cubic, $F(1,210) = 10.48, p < .001, \eta^2 = .05$, effects. Probabilities following anticipations and omissions showed the expected near mirror-image pattern, with virtually identical results, including linear, $F(1,208) = 62.90, p < .001, \eta^2 = .23$, quadratic, $F(1,172) = 27.56, p < .001, \eta^2 = .12$, and cubic, $F(1,208) = 9.49, p < .001, \eta^2 = .04$, effects. Trials immediately preceding ($t – 1$) and following ($t + 1$) anticipations and omissions were, significantly above the overall baseline probabilities.

Fig. 2. Mean SART RTs (with SEs) for four trials preceding and four trials following anticipations.

Fig. 3. Mean conditional probabilities of anticipations/omissions (with SEs) for four trials preceding and four trials following omissions/anticipations.
**RTs and omissions:** To assess the temporal association of RTs and omissions, the RTs for the four trials immediately preceding and following omissions were analyzed in a 2 (pre vs. post) by 4 (lag) repeated-measures ANOVA for individuals making anticipations (Fig. 4). This analysis yielded significant order and lag effects, which were superseded by a significant order by lag interaction, $F(1,205) = 22.31, p < .001, \eta^2 = .25$. This interaction was disambiguated by analyses of the sequential lag effects for pre- and post-omission RTs. Preceding RTs showed a robust significant increase leading up to $t_0$, well above the mean baseline, yielding significant linear $F(1,220) = 62.36, p < .001, \eta^2 = .23$, and quadratic, $F(1,210) = 31.69, p < .001$, effects. Conversely, there was a significant decrease following $t_0$, yielding significant linear, $F(1,208) = 62.90, p < .001, \eta^2 = .23$, and quadratic, $F(1,208) = 27.56, p < .001, \eta^2 = .12$, effects. The deviation from linearity in both cases is clearly evident at $t – 1$ and $t + 1$. There was substantial slowing of RTs on the trial immediately before an omission. Hence, extremely slow RTs are harbingers of omissions. Had our inter-stimulus interval been shorter, the pre-omission RTS responses would have themselves been omissions. Ultimately, omissions are simply very long response times that exceed the available time for the task. Nonetheless, it clear that there is an abrupt transition from moderately slower RTs in the normal range to very long RTs. This result and the post-omission speeding of RTs are consistent with abrupt transitions between states.

![Fig. 4. Mean SART RTs (with SEs) for four trials preceding and four trials following omissions.](image)

**Bidirectionality of mind-wandering and attentional errors**

The final set of predictions that we tested concerned the bidirectionality of mind-wandering and task challenges such as attentional errors. Specifically, we predicted that each of the SART indicators of mind-wandering should both precede and follow NOGO trials, particularly those involving errors. To evaluate these bidirectional relations, we assessed RTs, anticipations, and omissions on four trials (lags) before and four trials (lags) after correct and incorrect NOGO trials.

**RTs preceding and following NOGO trials:** The data were analyzed in a 2 (correct vs. incorrect) by 2 (pre- vs. post-NOGO trial) by 4 (lag) repeated-measures ANOVA. All effects were highly significant, including the three-way interaction, $F(1,481) = 36.18, p < .001, \eta^2 = .07$ (see Fig. 5). This interaction was disambiguated by a series of analyses of the lag effects for correct and incorrect responses, pre- and post-NOGO trials. RTs preceding successful NOGO trials, were all significantly above baseline and characterized by increasing RTs, with significant linear, $F(1,494) = 111.70, p < .001, \eta^2 = .18$, and quadratic components, $F(1,481) = 16.12, p < .001, \eta^2 = .03$. Conversely, RTs preceding error NOGO trials were all below baseline RTs and decreased prior to a NOGO error, with significant linear, $F(1,492) = 6.68, p < .01, \eta^2 = .01$, and cubic components, $F(1,492) = 12.12, p < .001, \eta^2 = .02$. RTs following successful NOGO trials, dropped markedly below baseline and then rapidly recovered, yielding significant linear, $F(1,498) = 126.42, p < .001, \eta^2 = .20$, quadratic, $F(1,481) = 75.74, p < .001, \eta^2 = .13$, and cubic components, $F(1,481) = 13.54, p < .001, \eta^2 = .03$. In contrast, RTs following error NOGO trials increased to baseline levels and then resumed...
significantly below baseline and not different from preceding RTs yielding significant quadratic, $F(1,497) = 23.08, p < .001, \eta^2 = .04$, and cubic components, $F(1,497) = 7.55, p < .001, \eta^2 = .02$. The mean RT for NOGO errors is also shown in Fig. 5. The mean NOGO error RT is significantly faster than mean RTs for any lag.

**Anticipations preceding and following NOGO trials:** A 2 (correct vs. incorrect) by 2 (pre9 vs. post9NOGO trial) by 4 (lag) repeated-measures ANOVA of anticipations yielded a significant two-way accuracy by temporal order interaction, $F(1,494) = 14.84, p < .001, \eta^2 = .03$ (see Fig. 6). The likelihood of an anticipation following an error was greater than for the other three conditions, $p < .001$. The finding that anticipations were not significantly more likely preceding errors than correct NOGO trials was somewhat counter-intuitive, especially given that anticipations during a NOGO trial create an automatic error. Nonetheless, the increased probability of anticipations following errors is consistent with the bidirectional model.

**Omissions preceding and following NOGO trials:** 2 (correct vs. incorrect) by 2 (temporal order: pre9NOGO trial vs. post9NOGO trial) by 4 (lag) repeated-measures ANOVA for omissions yielded a significant three-way interaction, $F(1,494) = 21.51, p < .001, \eta^2 = .04$ (see Fig. 7). A series of lag analyses for pre-error trials, but not pre-success trials yielded a marginal cubic effect, $F(1,481) = 7.70, p < .006, \eta^2 = .02$. There was a significant increase in omissions in the trial immediately preceding an error. Omissions following a success decreased and then returned to near baseline, producing a significant quadratic effect, $F(1,481) = 8.33, p < .001, \eta^2 = .02$. Omissions following an error increased then declined, yielding significant linear, $F(1,481) =$
The results for omissions following a NOGO error are perhaps the most striking of all, particularly at t + 1. Not only are RTs lengthened, and anticipations increased, but omissions are markedly increased, with incomplete recovery over the four post-error trials (see Fig. 7).

Interval length and errors: The final prediction concerns the effect of mind-wandering induced by NOGO trials.

The previous results reveal increases in the indices of mind-wandering. Therefore, error trials following soon after a NOGO trial should show increased error rates. This hypothesis was tested by assessing the association of length of interval between NOGO trials with probability of an error at the end of the interval (i.e., the proportion of subjects making an error after varying interval lengths). The bidirectional hypothesis suggests, however, that the effect should be especially strong for short intervals and hence this relation should show significant non-linear components. Separate linear and quadratic regression analyses were conducted regressing probability of NOGO errors following a correct prior NOGO trial, P(E|C), and NOGO errors following an incorrect prior NOGO trial, P(E|E). Analysis of successful prior challenges reveals independent linear and quadratic effects, linear: \( \beta = .76, t = 6.53, p < .001 \); quadratic: \( \beta = .33, t = 2.82, p < .010 \). The overall model generated a robust effect of \( R^2 = .72, F(1,22) = 26.45, p < .001 \). The \( R^2 \) change produced by adding the quadratic component was also significant, \( R^2_{\text{change}} = .11, F(1,21) = 7.97, p < .010 \). Analysis of unsuccessful prior challenges also revealed independent linear and quadratic effects, linear: \( \beta = .76, t = 7.08, p < .001 \); quadratic: \( \beta = .26, t = 2.28, p < .033 \). The overall model generated a substantial effect of \( R^2 = .80, F(1,22) = 26.45, p < .001 \). The \( R^2 \) change produced by adding the quadratic component was also significant, \( R^2_{\text{change}} = .07, F(1,21) = 5.18, p < .033 \).

The function for errors following shorter intervals appears somewhat steeper than that following correct withholds. To assess the effect the difference in the linear component for correct and incorrect trials a SEM model was constructed in which the linear components for Interval length and both P(E|C) and P(E|E) were constrained to be equal. The results of the analysis of this model were compared to those of an unconstrained (saturated) model in which all parameters were free to vary. This comparison resulted in a significantly poorer fitting model, \( \chi^2(1) = 11.81, p < .001 \). Hence, the linear component of the association of interval length and P(E|C) and P(E|E) differ significantly. The linear component was significantly stronger for P(E|E) that P(E|C). In contrast, a parallel analysis constraining the quadratic components to equality yielded a well fitting model, \( \chi^2(1) = 0.02, p = .90 \). Hence, the quadratic component of the associations of interval length and P(E|C) and P(E|E) did not differ significantly.

Summary: The present results are generally consistent with the hypothesis that the three indices of mind-wandering are associated with errors on NOGO trials, and two of these indices (RT speeding and omissions) preceded errors at a rate significantly above baseline. Errors, in turn, lead to faster RTs and increased probabilities of both anticipations and omissions. Successful trials are less likely than errors to lead to mind-wandering as indicated by a brief, one-trial speeding of RTs, a brief, one-trial increase in anticipations, but no evidence of an increase in omissions. Errors lead, in contrast, to a sustained increase in

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anticipations and an especially dramatic increase in omissions. The results generally support the conclusion that the relation
between mind-wandering and attentional errors on NOGO trials is bidirectional.

In addition, consistent with the model, many of the transitions between indices appear to be rather abrupt. Thus, an abrupt
increase in RT presaged the occurrence of an omission, but this occurred at t – 1, as reflected in a significant deviation from
linearity in the trials preceding an omission. The transition between anticipations and omissions was similarly qualitative.

General discussion

We have described and tested a three-state bidirectional model of attentional engagement/disengagement. According to this
model, and consistent with the evidence presented, attentional disengagement during a sustained attention task can be described
as three distinct states of mind-wandering. Indices of these three states are positively associated with one another, with NOGO
errors, and with self-reported measures of mind-wandering and attention-related cognitive errors in everyday settings and tasks in
theoretically consistent patterns. The relations between SART and self-report measures suggest that the SART measures
generalize beyond the SART task and provide potentially useful individual difference behavioral measures of mind-wandering.

We also found evidence that indices of these states precede and follow one another as well as NOGO errors at above chance
levels. Particularly striking is the fact that anticipations and omissions, which represent opposite extremes of RT, are positively
correlated with one another across individuals, are sequentially associated in time and, although also positively correlated with
variation within the normal range of RT (RT CV), and are associated with NOGO errors independently of such variation and one
another. One alternative possibility is that anticipations reflect very late responses that carry over to the next trial. This is
consistent with the positive associations found both across individuals and over time (trials). It is, however, not consistent with
the finding of independent associations of each with NOGO errors. Moreover, although the carry-over interpretation is consistent
with the strong transition from omissions to anticipations (i.e., that an anticipation is the much delayed response to the previous
trial, which would have been an omission), it is clearly inconsistent with the significantly stronger likelihood of transition from
anticipation to omission (see Fig. 3).

The results for the lag analysis of RTs preceding NOGO errors were consistent with prior findings and interpretations of the
attentional implications of speeding of SART GO RTs. This pattern is particularly consistent with the interpretation of SART RT
change directly reflecting attentional task disengagement. The present results also add the finding that longer RTs, within the
normal range, prior to a NOGO trial are associated with an increasing probability of a successful withholding, suggesting that
changing RTs within the normal range reflect both increases and decreases in attentional engagement in the task. In addition,
although mean NOGO error RTs were faster than RTs at any lag they were still within normal RT range and appear to reflect a
linear trend of increasing State 1 task disengagement prior to, and during, an error. Nonetheless, the most significant task events
for the SART are errors on NOGO trials. These appear to produce substantial task interference as indexed by increased
anticipations and omissions following errors. This interference appears to persist for several trials (Figs. 7 and 8). Persisting
interference is further indexed by the mutual and self-sequencing of anticipations and omissions (Fig. 3) as well as the effects of
NOGO trial interval length. Moreover, although the immediate effect on RT was actually greater for successful NOGO trials, the
effect on RT was more protracted following an error (Fig. 5). Thus, RT results are also consistent with the hypothesis that errors
may lead to longer off-task rumination than successful performance.
In the trial immediately following a NOGO error there was a significant slowing of RTs. This would appear to be consistent with the hypothesis of increased caution and on-task attentional engagement (Manly et al., 1999; Robertson et al., 1997). Alternatively, however, and consistent with the foregoing arguments, this one-trial effect may reflect a brief disruptive reaction to the error, that is, a task-relevant distraction. Interestingly, in the trial immediately following a successful NOGO trial, there was a significant and substantial speeding of RT. Indeed, this was the only trial around a NOGO trial in which RTs associated with correct response were faster than those associated with an error. This may also reflect a brief distraction from the task as subjects evaluate their performance.

Catastrophic mind-wandering: There were extremely abrupt transitions in response times indexing state transitions, anticipations and omissions, following lesser degrees of acceleration and deceleration of RTs. That is, abrupt state transitions to anticipations and omissions were presaged in the immediately preceding trials by smaller deviations in the same direction. Thus, the precipitous drop in RTs (~=350 ms) that defined anticipations were signaled by smaller but significant speeding of RT (Fig. 2). Conversely, slowing in RT signaled an upcoming omission, which, in the context of the present task, entailed a dramatic single trial mean change of over 500 ms (Fig. 3). Such abrupt shifts provide corroboration for the claim of qualitatively different states. The pattern of findings is also consistent with the existence of an underlying process with a transitional period of quantitative changes (speeding and slowing of task-relevant responses within task parameters) and a reduction of on-line attentional processing followed by an abrupt collapse of on-task processing. According to the model, in the case of anticipations, the collapse represents a cessation of task analysis and, in the case of omissions, a failure of response preparation.

Bidirectionality: We found considerable evidence for bidirectionality between mind-wandering and attention-related errors. All three indicator variables occurred as reactions to errors (Figs. 6–8). Anticipations and omissions were particularly sensitive to errors, suggesting that NOGO trials and particularly errors on NOGO trials constitute important occasions for reactive mind-wandering. In all cases, it seems possible that reactive mind-wandering reflects attempts to reengage with the task, but which, paradoxically, at least briefly adversely affect ongoing performance.

Bidirectionality may be relevant to a recent distinction, similar that proposed in the present paper, between sustained and transient aspects of control processing (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, Barch, Gray, Molfese, & Snyder, 2001; Braver, Reynolds, & Donaldson, 2003; Burgund, Lugar, Miezin, & Peterson, 2003; Cohen, Botvinick, & Carter, 2000; Donaldson, Peterson, Ollinger, & Buckner, 2001; MacDonald, Cohen, Stenger, & Carter, 2000; Miller & Cohen, 2001; Mitchell et al., 2007; Velanova et al., 2003; Visscher et al., 2003). A sustained or tonic mode of attention involves monitoring of task conditions and behavioral performance and has been associated with prefrontal activity. The second, transient mode, is an occurrent form of attention, reactively engaged by behavioral and cognitive (cf. Mitchell et al., 2007) conflicts and has been associated neurologically with anterior cingulate cortex activity (Carter et al., 1998; Cohen et al., 2000). Sustained and transient control processes work in tandem.

The first process engages in active, ongoing monitoring of task conditions and engages a reactive process when outcomes
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The present findings also shed light on a recently reported a principled components analysis of SART RTs in blocks between critical events (NOGO trials or thought probes) (Smallwood, McSpadden, Luus, & Schooler, 2008). The first of three components extracted appeared to be a conventional “size” factor and, as such, likely reflects consistency in individual differences in mean RT across trials, possibly reflecting individual differences in Stage 1 propensities. There appear to have been differences in this component between correct and incorrect trials as well as between mind-wandering with and without awareness (Smallwood et al., 2008, Fig. 1). The second and third components appeared to be more bipolar and contrasted trials following one critical event and, particularly the second component, those preceding the next critical event. That is, early RTs appeared to be mutually positively correlated with one another, as are those of late trials, whereas early and late trials are negatively correlated. Thus, individuals who show reactive mind-wandering appear to have a different pattern of RTs prior to the next critical event from those of less reactive individuals. If this interpretation is correct, the bidirectional aspect of the present model predicts that this component should be stronger in blocks terminated by an error. Consistent with this, error blocks produced higher weightings on the second component than did baseline blocks. Moreover, correct blocks appear to generate intermediate weights on Factor 2, also consistent with present model.

A paradox observed, explained, and generalized: The increased probability of errors following very short intervals following prior NOGO trials, especially unsuccessful NOGO trials, may seem at odds with prior research indicating that tasks with long intervals or slow presentation rates increase error rates (Antrobus, 1968; Smallwood et al., 2003, 2004; Teasdale et al., 1993; but see Smallwood et al., 2008). There is an important difference however, between tasks with long intervals providing many mind-wandering opportunities, and episodes of repeated challenges interspersed among long periods of inactivity. Thus, combining the present results with previous findings, we hypothesize that situations most conducive to mind-wandering are those with long periods of inactivity (random or periodic mind-wandering) interspersed with bouts of distracting critical events (reactive mind-wandering). Such situations are not uncommon in reading and driving tasks, both of which may have long “fallow” periods interspersed with critical events (passages critical for future understanding of text, encountering construction zones or accident scenes). In addition, real-world catastrophes often entail series of closely spaced cumulative errors, which would likely compound the reactive effects suggested by our bidirectional model (Three Mile Island, Bhopal, Chernobyl: see Reason, 1990, Appendix).

The patterns of RTs, anticipations, and omissions could arise through a combination of at least three factors: (1) exogenous task and non-task events (2) endogenous rhythmic attentional oscillations (see below), and (3) explicit strategic modifications of attention based on expectations. Thus, it is possible that the high rate of errors found for closely spaced NOGO trials might reflect a lowered expectation of another NOGO trial immediately following preceding NOGO trials. Perhaps, subjects strategically relax vigilance following NOGO trials and only gradually increase on-task attention as the expectation of a NOGO trial grows over succeeding trials. Studies underway attempt to assess this possibility by manipulating the probability of NOGO trials at different trial intervals. Preliminary results suggest that the function presented in Fig. 8 is independent of such manipulations.

Future studies: further predictions from the three-state model

In what follows we consider further potential correlates, causes, and effects of the three states of attentional disengagement at behavioral, phenomenological, physiological, cognitive, and neural levels.

The influence of endogenous attentional rhythms: The linear trends found in almost all analyses likely reflect increasing inattention across trials preceding NOGO errors. In a number of cases for all attentional indices, however, there were also frequent quadratic and cubic trends. These latter results may reflect unstable, fluctuating attentional engagement throughout the task, suggesting that task engagement is an unstable and constantly fluctuating set of states. A further possibility that should be acknowledged is that the state transitions may be affected by an underlying periodicity of attentional states or arousal, or underlying neural oscillator driving manual responses, or indirectly affecting attention (Gilden & Hancock, 2007; Johnson, Kelly, et al., 2007; Smallwood et al., 2008). Smallwood and colleagues, for example, using a principal components analysis, report systematic fluctuations in RTs leading up to SART errors or probe-detected mind-wandering.

The increasing RTs prior to successful NOGO trials may suggest the possibility of an explicit strategy of allocating attentional resources to the task as time passes and the expectation of a NOGO trial increases. Speeding following errors, conversely, might reflect a decreased expectation of an imminent NOGO trial, though this would not explain the differential speeding following correct and incorrect trials. The present results do not provide direct evidence for anti-correlated endogenous oscillations such as
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Near-misses: During SART performance subjects sometime report perceived incipient movements as muscle tension in the arm or they may detect small hand or finger movements too small to be conventionally recorded as overt responses (i.e., key presses). These are potentially informative behavioral cues that could be recorded electromyographically (EMG) and potentially related to changes in the lateralized readiness potential, such as those reported for nontarget trials (Smallwood et al., 2008), and possibly indexing incipient attention-related errors. According to the model, State 1 of mind-wandering consists of brief and partial processing of stimulus meaning of the sort likely to lead to near-misses. Thus, being presented with a NOGO trial while in State 1 of mind-wandering should lead to muscle activity in the arm as if the subject were about to respond, but with sometimes successful inhibition of the overt response (a near miss). In State 2 of mind-wandering task monitoring is no longer effective. Accordingly, we predict that being presented with a NOGO trial while in State 2 will lead to a larger ERN response relative to State 1 and that this will more often lead to an overt commission error. Finally, because State 3 of mind-wandering is characterized by a complete failure to engage to task response system, we predict that presenting a NOGO trial during State 3 of mind-wandering will be associated with no EMG response. In addition, when detected by subjects in State 1, near miss cues should also lead to off-line ruminations about performance in the same way as overt errors. Such ruminations could be assessed by probes (e.g., Smallwood et al., 2004) designed to detect awareness of near-misses following speeding, anticipations, and omissions. Smallwood and colleagues (2007) also suggest the possibility of using probes separated by different intervals to assess the timing and duration of state transitions as well as the comparison of self-caught and probe-caught mind-wandering as potential indices of early and late (e.g., States 1 and 2) mind-wandering.

GSR: The galvanic skin response (GSR) has been fairly consistently associated with SART performance (O’Connell et al., 2007; Smallwood et al., 2004). Also, for example, and consistent with our finding of behavioral responsiveness to both successful and unsuccessful NOGO trials, O’Connell and colleagues reported GSR to both errors and successful withholds on NOGO trials (O’Connell et al., 2007). Also consistent with the model, GSR was slightly greater to errors than to successful withholds. Finally, across subjects, SART error detection rates and GSR were significantly correlated. Thus, GSR appears to index task-related mind-wandering following NOGO trials. This suggests that GSR will be differentially related to indices of the three mind-wandering states following both success and error, but especially following error, on NOGO trials.

ERP: Several predictions also follow from the three-state model regarding brain activity (as measured by event-related potentials – ERP). Error processing has long been thought to involve two separate mechanisms, one for error detection and another for error correction (Rabbitt, 1966). Error negativity (ERN) appears to be related to implicit detection (but not necessarily conscious awareness) of error, whereas late error positivity (Pe) appears to be related to the (conscious) evaluation of response strategies in response to error awareness (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1990; O’Connell et al., 2007). Smallwood and colleagues (2008) also report a reduction in P300 prior to errors and off-task reports. We hypothesized above that the post-error changes in RTs and increases in the probability of anticipations and omissions likely also reflect a cognitive response to error in the form of off-line processing (i.e., task-relevant mind-wandering). Hence, we predict that, whereas ERN will be associated with errors generally, only late error positivity (Pe) will be specifically associated with RT change, anticipations, and omissions that follow an error on NOGO trials.

Memory effects: The available evidence suggests that mind-wandering also has detrimental effects on recall of environmental- and task-relevant events (Smallwood et al., 2006). More specifically, mind-wandering is associated with a decrease in recall (explicit memory) relative to familiarity (implicit memory) (Smallwood et al., 2003, 2004). Recall should decline as mind-wandering moves from State 1 to 3. We also predict an increasing shift from explicit to implicit remembering. It is an interesting possibility that both explicit and implicit recall will be reduced during state 3.

Special populations: Attentional deficits are a common feature of debilitating psychiatric and neurological pathology (Sonuga-Barke & Castellanos, 2007). One of the central characteristics of the three-state model is that it can be used to describe qualitative differences in attentional disengagement across individuals. That is, the model makes specific predictions regarding how attentional disengagement is affected by various attention-related disorders such as traumatic brain injury (TBI), attention deficit hyperactive disorder (ADHD), and anxiety disorders such as obsessive compulsive disorder (OCD). ADHD individuals often have much more variable RTs (Klein, Wendling, Huettner, Ruder, & Peper, 2006) and have been reported to have, occasionally, extremely long RTs (Hervey et al., 2006). The interpretation of such findings has been hampered by the absence of
a coherent theory to integrate such findings (Castellanos et al., 2005). The present model provides a principled explanation for these findings in terms of different states of mind-wandering related to the degree of decoupling of attention from task. Future studies employing the indices proposed here may well contribute to a theoretically grounded understanding of the nature of ADHD attentional deficits.

With regard to TBI, the available evidence suggests that TBI patients perform very poorly on the SART and, in addition, show poor error detection (Hart, Giovannetti, Montgomery, & Schwartz, 1998; McAvinue, O’Keeffe, McMackin, & Robertson, 2005; Stemmer, Segalowitz, Witzke, & Schonle, 2004). Moreover, GSR in response to NOGO errors is significantly reduced in TBI participants relative to controls even with awareness of errors (O’Keeffe et al., 2004). Given that TBI patients seem less responsive to attention-related errors, we expect that they will have less incentive for off-task rumination and should show weaker behavioral reactions to unsuccessful NOGO trials. That is, TBI patients should be less likely to engage in post-error ruminations, which should decrease their post-error RT speeding, anticipations, and omissions relative to normal controls. Thus, compared to normal controls, the bidirectional relations between mind-wandering and attention-related errors should be reduced for TBI patients.

In contrast, individuals with anxiety disorders, depression or OCD might experience exaggerated bidirectional relations between mind-wandering and attention-related errors. Anxious individuals will likely be more attentive to their errors and will tend to ruminate on them following errors. Farrin and colleagues report that depressed individuals may respond “catastrophically” to errors producing an enhanced sense of failure (Farrin, Hull, Unwin, Wykes, & David, 2003). It is also possible that this is because such exaggerated reactions to error produce greater rumination on performance (cf. task-related interference; e.g., Smallwood, Davies, et al., 2004). This would be especially disafflicting in that individuals would have a subjective sense of increased task effort associated with increasingly poorer performance. This should result in greater post-error RT speeding, anticipations, and omissions in anxious individuals compared to normal controls. The associated task-related mind-wandering then leads to more attention-related errors, which will lead to more task-related ruminations, ultimately leading to a snowball effect. Similar predictions can be made for individuals suffering from sub-clinical levels of performance anxiety.

Real-world tasks: Although we have empirically assessed the three-state model in the context of the SART, our reference to real-world mind-wandering situations in the exposition of the model reflects our conviction that the model applies beyond the SART task to many everyday continuous performance tasks such as reading and driving. An important aspect of our model is its ability to make concrete predictions about attentional disengagement in these real-world tasks. For example, in the context of reading, the model makes specific predictions about readers’ eye movements and their phenomenology as they progress through states of task disengagement. In particular, we predict that entering State 1 disengagement during reading will be accompanied by sporadic increases in the speed of eye movements and reduced memory for content. There may also be more regression saccades (re-reading) as readers catch themselves mind-wandering and attempt to get back on task. In State 2, readers’ eyes will be moving from word to word in a very stereotyped fashion reflecting a lack of processing of textual meaning and, hence, if stopped and tested at such times, readers will have very little to no memory of the content. Finally, in State 3, readers will stop moving their eyes altogether or look away and stare completely engaged in internal processing.

Similar predictions from the three-state model can be made with regard to driving performance. In State 1 of mind-wandering, a driver will be intermittently less responsive to the focal moment-to-moment demands of the immediate driving situation but be periodically aware that at times he/she is fully engaged in driving. In State 2, drivers’ responses will be more automatic and triggered only by generic cues present in the environment. In this state, one might, for example, intend to take a new route only to find oneself automatically following a habitual, highly familiar route. In State 3, the driver will become unresponsive to the driving environment. If briefly falling into State 3 while driving, an individual might completely fail to brake in response to external cues (e.g., inadvertently running a red light). Moreover, following from the bidirectionality predictions of the model, when the driver commits an error (e.g., begins to drive off of the road); awareness of the error might lead to more mind-wandering in the form of rumination about inattention and driving performance potentially generating another bout of mind-wandering.

Concluding comments

Our major goals have been to present a model of attentional engagement/disengagement consistent with existing data on mind-wandering and sustained attention, to present new data to assess directly a number of predictions from the model, and to suggest novel predictions to guide future research. As noted in our introductory remarks indices employed in the present study were selected based on our task analysis of the SART and that detailed task analyses will be required for the application of the model to different tasks and contexts. At an applied level, the three-state model of attentional disengagement also points to possible means to prevent, or at least limit, the progression of attentional disengagement. Given signatures for each state, for
example, we could use these as triggers to provide extrinsic cues to alert subjects to the onset of mind-wandering during attentionally demanding tasks. Previous research has reported that providing even non-contingent, non-predictive, content-free “cues-to-attend” (Fassbender et al., 2006) reduces SART errors in both healthy subjects and stroke patients (Manly et al., 2004). Based on the present model, similar extrinsic cues provided contingently on RT changes, anticipations, and omissions should be even more effective at improving performance of subjects, and especially individuals with marked deficits in sustained attention (e.g., ADD and TBI). Indeed, it is possible that cueing based on either decreasing or increasing RTs, anticipations, and omissions might selectively reduce inattentional states as well as errors. Use of fading techniques in which cues become more subtle and even subliminal might effectively “wean” people from the cues as they become sensitized to the onset of mind-wandering states, and be less likely to engage in reactive mind-wandering. It would also be of interest to consider potentially more general effects of such training on an individual’s sense of self efficacy and self control, as well as possible changes in affect. Future investigations of these possibilities should contribute to the further development of the current model of attention disengagement with the ultimate goal of developing techniques to reduce the debilitating effects and consequences of failures of sustained attention and attention-related errors in the real world during attentionally demanding tasks.

References


