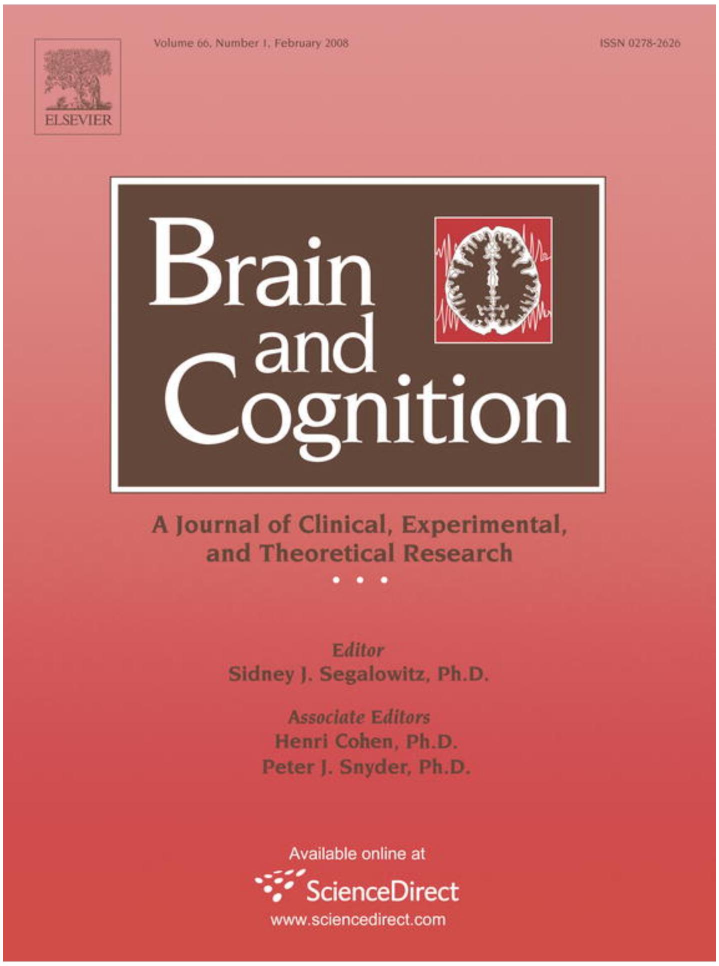
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Segmenting the stream of consciousness: The psychological correlates of temporal structures in the time series data of a continuous performance task

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Abstract

Using principal component analysis, we examined whether structural properties in the time series of response time would identify different mental states during a continuous performance task. We examined whether it was possible to identify regular patterns which were present in blocks classified as lacking controlled processing, either behaviourally (as a failure to withhold a response to a target) or subjectively (as an off task report at a thought probe). Principal component analysis identified three components present in response times accounting for 58.8% of the variance in the data. Of these components, the second largest factor showed two features that implied it was a marker for mind wande\ring. First, it was stronger under slow relative to fast stimulus presentation conditions, and so paralleled the distribution of mind wandering reports. Second, it was more powerful prior to behaviour markers of mind wandering (failures in response inhibition) and less powerful prior to reports of task focused thinking (on task reports). Taken together, the use of principal components analysis on response times seem a viable tool for differentiating different mental states and so could help identify the neural substrates which underpin mind wandering and other subjective states.

Keywords: Mind wandering; Attentional lapses; Task unrelated thought; Stimulus independent thought; Sustained attention and response time

1. Introduction

William James suggested that attention was "the sudden taking possession of the mind, in clear and vivid form of one of what seems several simultaneously possible objects or trains of thought" (James, 1890). While research has defined in detail the manner by which the waking brain is captured by external objects (Kanwisher & Wojciulik, 2000; Sabine & Ungerleider, 2000) our understanding of the temporal characteristics of how attention becomes captured by our own train of thought is less well understood. In this paper we consider whether structural patterns in the time-series data recorded during the performance of a continuous performance task act as an indirect marker for periods when attention has lapsed from the task.

The study of *mind wandering* (Antrobus, 1968; Mason et al., 2007; Singer, 1966; Smallwood & Schooler, 2006) uses thought probes to provide a subjective test of whether attention is currently directed to the task. This research has demonstrated that the maintenance of unconstrained mental activity comes at a cost; mind wandering impairs signal detection (Antrobus, 1968; Smallwood et al., 2004), prevents detailed encoding (Smallwood, McSpadden, & Schooler, in press) and impairs reading (Schooler, Reichle, & Halpern, 2005). Physiologically, mind wandering is accompanied by high autonomic arousal (Smallwood et al., 2004, in press) suggesting that these episodes may involve the focus of attention on future or past events in order to provide a more entertaining internal environment (Mason et al., 2007).

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A related domain, research on the *attentional lapse*, employs a similar strategy, although in this case the mental state is defined behaviourally by the response to a target. Research on attentional lapses, indexed by a response inhibition failure, has demonstrated that prior to signal detection failures response times are rapid and careless (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), EEG desynchronization within the alpha band is decreased (Dockree et al., 2004) and a late positive component centred over occipto-parietal and central sites is absent (Dockree et al., 2005). These failures to withhold a response are often attributed to a drifting focus of attention (Manly, Robertson, Galloway, & Hawkins, 1999, see also Smallwood et al., 2004).

Importantly, the same neural substrates are implicated by both subjective and behavioural measures of in-attention. For example, reports of mind wandering (Mason et al., 2007; McGuire, Paulesu, Frackowiak, & Frith, 1996) and ineffective responses to external events (Weissman, Roberts, & Woldroff, 2006) are preceded by activity in the default network (Raichle et al., 2001), suggesting that this neural system sub-serves task unrelated mental activity. Similarly, both self-reported failures in thought control (Mitchell et al., 2007) and failures in response inhibition (Hester, Foxe, Molholm, Shpaner, & Garavan, 2005) are followed by activation in the anterior cingulate, suggesting that the same conflict monitoring systems are engaged following the detection of both private and overt lapses in attentional control.

An alternative approach to the study of mental states is to determine structural regularities in objective data recorded under laboratory conditions. For example, slow oscillations in response time have been observed as participants perform signal detection tasks (Castellanos et al., 2005; Johnson et al., 2007) and are assumed to relate to failures in the normal controlled processing of the task. Similarly, intermittent activity in the default network activity has been detected during a passive sensory task (Grecius & Menon, 2004) suggesting that individuals were dividing their attention between the task and their private thoughts (see also Fox, Corbetta, Snyder, Vincent, & Raichle, 2005; Fransson, 2005). An alternative technique to understand the characteristics of private experience is, therefore, to identify structural regularities in the temporal sequence of either behavioural or physiological data and relate these changes to different mental states.

1.1. Current study

Mind wandering and related states of in-attention occur intermittently during a task (Smallwood & Schooler, 2006), and so if the structural patterns in behavioural or physiological measures relate to temporary lapse in the controlled processing of the current task they should manifest more strongly in blocks when mind wandering occurs. In this paper, we consider whether the intermittent presence of oscillation in response time is strongest in blocks in which participants provide both behavioural and subjective reports that they were off-task. Techniques such as Fourier transforms require extensive data sets to gain their temporal resolution, precluding their utility for identifying short temporal intervals. As an alternative, in this paper we use principal components analysis (PCA) to identify structural patterns in the time series of response time. PCA is a powerful tool for differentiating the component structure in data on the basis of similarities across cases in data set. In this study, the last 12 response times recorded before the end of each block constitute a single case, and, were analyzed using PCA to derive temporal structure present in the time series data. The relative power of each factor in each block can be used as a dependent measure to test the extent to which any given behaviour state relates to measures of different mental states. Should we identify a factor which contains descriptive evidence of oscillation, based on previous research (e.g. Castellanos et al., 2005; Johnson et al., 2007) it should be particularly powerful during blocks which end with either a behavioural (e.g. failure to withhold a response) or subjective indicator (off-task report) that the participant was mind wandering.

To this end, a sample of undergraduate students completed a sustained attention task in which they were presented with the digits between 0 and 9. Participants were asked to withhold a response to the digit 3 (target) and respond to all other stimuli (non-targets). Blocks were terminated by either a thought probe requiring a subjective account of the current mental state, or a target requiring response inhibition. Mind wandering was defined subjectively as an off task report at a thought probe, and behaviourally as a failure to withhold a response to a target.

As a manipulation we change two task parameters known to effect mind wandering. Previous research has confirmed that slow presentations encourage mind wandering (Antrobus, 1968) and increase activation of the purported neural substrate (McKiernan, D'Angelo, Kaufman, & Binder, 2006) so as a manipulation, participants were either allocated to a fast (1 stimulus every 1250 ms) or a slow presentation condition (1 stimulus every 2500 ms). As mind wandering reports increase with time on task (Smallwood, Obonsawin, & Reid, 2003; Teasdale, Lloyd, Proctor, & Baddeley, 1993) we used a block design with relatively long target blocks (approximately 30 or 45 s long). The longer blocks were interspersed with shorter blocks (12.5 s) ensured that in order to perform the task correctly participants were required to sustain attention throughout the course of all blocks.

There is a growing body of evidence that we sometimes switch attention from the task without recognizing we are doing so (Smallwood & Schooler, 2006). For example, while reading *War and Peace* participants were caught mind wandering 13% of the time when probed despite being asked to self report these events as soon as they recognised it (Schooler et al., 2005). In addition, behavioural lapses during signal detection often remain uncorrected (Rabbit, 2002). Neuroimaging evidence validates the notion that errors often remain unrecognized; despite the fact that all response inhibition errors engaged the anterior cingulate, only those errors which were reported by the participants additionally engaged bi-lateral, pre-frontal and parietal areas (Hester et al., 2005). In this study, therefore, participants were additionally required to report their awareness of being on or off-task at the thought probes, using a published methodology (Smallwood et al., in press) in order to explore whether awareness of mind wandering relates to any of the structural properties of response time.

1.2. Experimental aims

The extent to which we observe a temporal pattern which accurately reflects periods of mind wandering will depend on how closely it maps onto what previous research suggests about these experiences. According to Castellanos et al. (2005) and Johnson et al. (2007) it should involve a pattern of slow oscillations in response times. In addition, a marker for mind wandering should be more powerful under circumstances which promote these experiences (Short blocks > Long Blocks, Fast Blocks > Slow Blocks). Finally, a maker for off-task episodes should be more powerful under conditions when performance on the subsequent markers implies that the mind was wandering (Correct > Errors, On Task > Off-task).

2. Method

2.1. Participants

A total of 23 (4 males) undergraduate students (age range 19–22) participated in this experiment. All participants either received course credits or a payment of $10 CAD for participation in this study. Eleven participants completed the task in the slow stimulus presentation condition.

2.2. Materials

2.2.1. Stimuli

Stimuli for this experiment were numeric digits, 0–9, the target stimuli was nominated as the digit '3'. Participants were allocated using a counterbalanced design to either a fast stimulus presentation rate (1250 ms) or a slow stimulus presentation rate (2500 ms). The slower rate of stimulus presentation (2500 ms) is consistent with rates employed previously (Smallwood et al., 2004, in press; Smallwood, Fishman, & Schooler, 2007) while the faster rate of stimulus presentation (1250 ms) is closer to that employed by other research teams (Robertson et al., 1997). In both conditions stimulus duration was 1250 ms.

Targets and thought probes were presented using a quasi random sampling procedure. At the outset of any given block, stimuli were presented in a random order until the target digit ('3') was presented. Following presentation of the filler target, the procedure entered a loop which randomly selected either a short (10 s), moderate (30 s) or a long (50 s) block length. During these blocks non target stimuli were presented in a random order. At the end of these blocks the computer either presented a thought probe or a target. To increase the power of thought probes, these events occurred following 60% of blocks, with targets being presented on the remaining 40%. Participants completed a total of 48 blocks and duration of testing was approximately 40 min.

2.2.2. Thought probes

During the thought probe, participants were asked to report whether they were (i) on-task, (ii) off-task and aware of this fact (*Tune Out*) or (iii) off-task and unaware that they are off-task (*Zone Out*) using a previously published methodology (Smallwood et al., in press). To help the participants make this judgment, we provided subjects with booklet containing definitions of mind-wandering with and without awareness. *Zone Outs*, defined as mind-wandering without awareness, were described to the participants as reflecting a situation when the occurrence of the probe reminds them that their attention was off-task. *Tune Outs*, defined as mind-wandering with awareness, were described to participants as reflecting a situation when they had been aware for some time before the probe occurred that their attention was off-task. Participants responded at the probe using the first letter of the experience (t, z or o).

2.3. Procedure

Upon arrival, participants were greeted by a research assistant and seated in a comfortable chair in front of a computer screen. The experimenter outlined the experimental procedure and invited each participant to read and sign an informed consent sheet. Ethical approval was obtained from Department's Ethics committee prior to testing.

Participants were informed that their task was to detect targets (the digit '3') from a series of stimuli (the digits '0–9') presented sequentially on a computer screen. The instructions were to respond by pushing the spacebar whenever the non-target stimuli appeared on the screen and to inhibit responding whenever the target stimulus was on the screen. Before beginning the task, participants completed a short practice block of this task which included thought probes. During the testing procedure, participants were approximately 1 m from the computer screen and no restrictions were made on the participants' movement. Participants were asked to put equal emphasis on performing the task both quickly and accurately.

3. Results

3.1. Principal components analysis

Our first step was to conduct PCA on the response time series data to identify structural patterns in which occurred

Table 1
Proportion of variance explained by the three factors identified using principal component analysis

Component	Initial Eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative (%)	Total	% of variance	Cumulative (%)
1	4.817	40.146	40.146	4.817	40.146	40.146
2	1.198	9.981	50.127	1.198	9.981	50.127
3	1.043	8.691	58.818	1.043	8.691	58.818
4	.977	8.143	66.961			
5	.753	6.278	73.239			
6	.608	5.067	78.306			
7	.567	4.729	83.035			
8	.503	4.192	87.226			
9	.439	3.655	90.882			
10	.414	3.448	94.330			
11	.346	2.880	97.210			
12	.335	2.790	100.000			

Extraction method: principal component analysis.

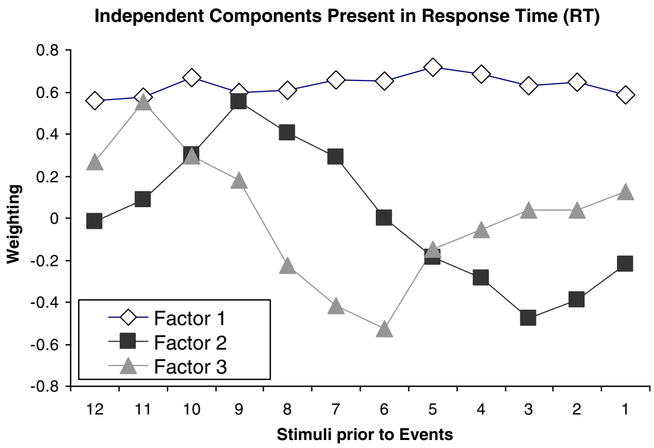

Fig. 1. Graphical representation of the three independent components identified in response time.

intermittently during the performance of the task. A requirement of PCA is that each case contains the same number of data points. In order to maximise block length we only considered blocks that were either moderate or long in length as these both shared a 30 s window which was free from targets. Additionally, the two stimulus presentation conditions varied in terms of the number of events which occurred in this period. In order to compare the presence of the same factors across conditions, we averaged each second stimulus in the fast stimulus presentation condition thus equating the number of data points (12).

Each block was entered as a separate case, and was described by the last 12 response times recorded prior to a task critical event (thought probe or target) were entered sequentially. This analysis was therefore 'blind' to the nature of the block (target or probe), presentation condition (fast or slow) and subsequent report of mental state. Factors were selected using principal component analysis on the basis of Eigen values greater than 1. No factor rotation was employed. After blocks with missing response times were excluded a total of 230 blocks preceded a target and 374 occurred before a thought probe.

PCA identified three factors which accounted for 58.8% of the total variance present in the data. The exact proportion explained by each of these factors is presented in Table 1, while the time course to which these patterns relate is represented graphically in Fig. 1. Factor One (White Diamonds) describes a behavioural pattern in which participants maintain a consistent slow response rate to the non-target stimulus throughout the block. Factor Two (Black Squares) describes a pattern of behaviour in which response time oscillates from a relatively slow rate towards a faster rate directly prior to the end of the block. Finally Factor Three (Grey Triangles) also shows evidence of fluctuations between rapid and slow response time, although in this behaviour state participants appear to have reached a local minimum earlier and so have been decelerating for longer by the time the block ends. These three factors reflect the dominant 'behaviour states' which manifest during the performance of this task.

4. Effects of block length and stimulus presentation rate on the structural patterns in response time

Having identified the factors in the response time data, we next consider whether these 'behaviour states' are sensitive to either of the manipulations of task environment (Stimulus Presentation Rate or Block Length). We used multivariate ANOVA to assess this question on a trial by trial basis. The three factor scores for each trial were entered as separate dependent variables. To control for the possible effects of fatigue we weighted least squares by the block number (1–48).[1] This analysis indicated that Factor Two was sensitive to stimulus presentation rate [$F(1,600) = 4.63$, $p < .05$, MSE = 23.4, Partial Eta Squared = .01]. Factor Two was relatively more prominent

[1] To account for the possible role of individual differences, we repeated the analysis with the individual Subject ID included as a covariate. This reanalysis yielded the identical pattern of relations observed in the analysis we present in the body of the text. We, therefore, only report the basic analysis in the text.

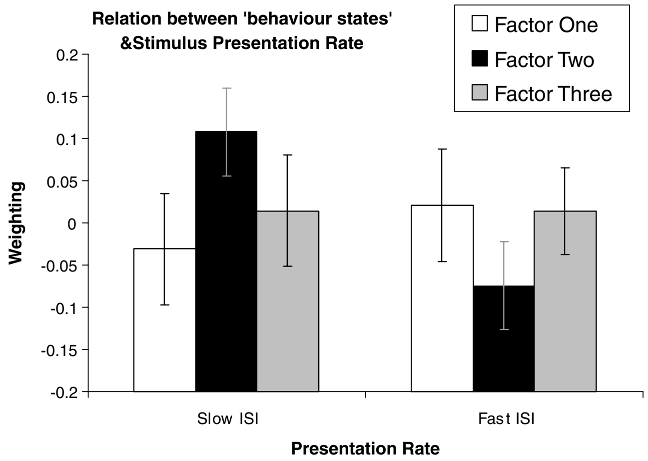

Fig. 2. Relation between behaviour states and rate of stimulus presentation. Analysis indicated that Factor Two (black bars) was more prominent in the slow than the fast stimulus presentation condition. Error bars describe the standard error of the mean.

in the Slow than in the Fast condition (Fig. 2). No effects of block length nor were the subsequent interactions reliable [$p = \text{ns}$].

We next consider the frequency of explicit measures of mental states across the different task environments. On average participants reported being on task 38% of the time (SE = 1), off-task and aware 31% (SE = 1) and off-task unaware at the remaining 32% of probes (SE = 1). Using the same analytic strategy, ANOVA indicated fewer examples of on task reports were made in the slow condition [mean = 30%, SE = 2] than in the fast condition [37% (SE = 2), $F(1,669) = 3.7$, $p = .05$, MSE = 5.4, Partial Eta Squared = .01]. An effect of block length was also reliable [$F(2,665) = 4.01$, $p < .005$, MSE = 5.4, Partial Eta Squared = .01] indicating that more on task reports were made at the short blocks [4 s, mean = 41%, SE = 4] than at either Moderate [30 s, mean = 29%, SE = 4, post hoc LSD test, $p < 0.01$] or Long [55 s, mean = 31% SE = 4, post hoc LSD test, $p = 0.05$]. No difference in the proportion of off-task episodes with or without awareness was observed across fast and slow conditions [$p = \text{ns}$]. Response inhibition failures were made on 39% of occasions (SE = 3) in the Slow condition, and 45% (SE = 3) of occasions in the Fast condition. This difference was non-significant [$p = \text{ns}$].

5. Consequences of structural patterns

Our next analysis considers whether the structural patterns in response times act as an indirect marker for mental states. Towards this end we examined whether any factors were predictive of either the subjective reports made at the thought probes, or, the whether the participants was able to withhold a response to the subsequent target. As our randomization regime meant that blocks were terminated by either a target or a thought probe, the total bin of all alternative blocks acted as a baseline measure. So when comparing the ability of participants to withhold a response, we entered the overall factor patterns derived from the blocks which were terminated by thought probes as a baseline.

5.1. Behavioural performance

Multivariate ANOVA was employed with the least squares weighted by trial number as before. We included three independent factors: Block Length, Stimulus Presentation Rate and Error status. Error Status contained three levels: Baseline, Correct and Incorrect. In addition to indicating the effect of Stimulus Presentation rate observed before, this analysis indicated that Factor Two varied with error status [$F(2,592) = 5.68$, $p < 0.005$, MSE = 23.1 Partial Eta Squared = .02]. Post hoc LSD tests indicated that Error blocks weighted higher on Factor Two than did Baseline blocks [$p < .005$, see Fig. 3, upper panel]. No additional main effects or subsequent interactions were reliable [all p-values = ns].

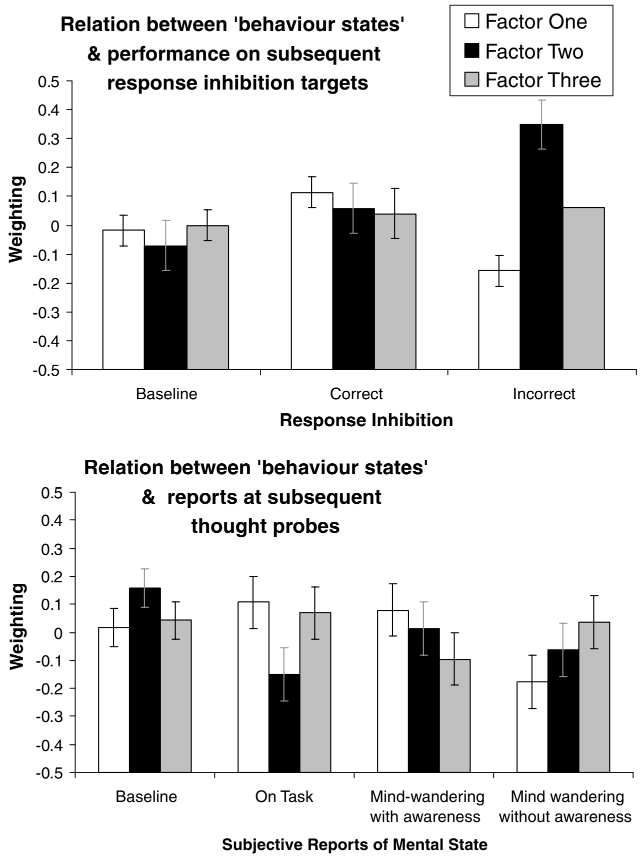

Fig. 3. Comparison of the relative weighting of the three behaviour states prior to behavioural (upper panel) and subjective descriptions of mental state (lower panel). In the case of behavioural performance, poor response inhibition followed periods showing greater evidence of Factor Two (black bars) than was present in the baseline condition ($p < .005$). Similarly, subjective reports of task focus followed periods in which Factor Two (black bars) was less present in behaviour ($p < .005$). Error bars describe the standard error of the mean.

5.2. Subjective reports

Multivariate ANOVA using the same constraints as described above indicated both a marginal main effect of Stimulus Presentation for Factor Two and a reliable main effect of reported experience on the same factor [$F(3,588) = 2.7$, $p < .05$, MSE = 23.3 Partial Eta Squared = .02]. Post hoc LSD tests indicated that On Task reports weighted less on Factor Two than did the Baseline condition [$p < .005$, see Fig. 3, lower panel]. Additionally, when Zone Outs were compared to all other experiences, analysis indicated that mind wandering without awareness were less likely to be preceded by Factor One [$F(1,604) = 4.63$, $p < .05$, Partial Eta Squared = .01].

6. Discussion

In this study, we used PCA to demonstrate the presence of three structural patterns within the time series of response times as participants performed a signal detection task. These factors provide a statistical description of the dominant behaviour states which manifest during the performance of the task. Of these patterns, the second factor, presented in black in Fig. 1 seems in descriptive terms, to reflect the oscillations in response time which have previously been interpreted as an absence of controlled processing of the task (e.g. Castellanos et al., 2005; Johnson et al., 2007). In addition to this descriptive similarity, our data presents three empirical findings consistent with the claim that when this behavioural pattern manifests when the attention of the participant is off task. First, our manipulation of presentation rate increased both reports of mind wandering and the presence of Factor Two implying that the two measures relate to the same underlying mental state. Second, Factor Two was absent from blocks in which participants reported being on task relative to baseline blocks (see Fig. 2, lower panel). Third, Factor Two was higher in blocks in which individuals failed to withhold a response than in baseline blocks (see Fig. 2, upper panel). Similar to the convergence of behavioural and subjective indicators for mind wandering outlined in the introduction, we can have confidence that the oscillations in response time identified by Factor Two provide an indirect marker for the presence of task irrelevant mental activity.

Analysis also identified that an absence of awareness of mind wandering (Zone Out) was associated with an absence of slow and careful responding (Factor One, see Fig. 2), although this relation was not significant in the omnibus ANOVA. The fact that Zone Outs show less evidence of careful processing in the response time series is consistent with findings that these mental states are predictive of response inhibition failures (Smallwood et al., in press) and are associated with worse text comprehension (see Smallwood et al., 2007 for a review). It is possible that the relatively weak relation between Zone Outs and the factors was due to the fact that response times are too indirect a measure of cognitive function to speak directly to the nature of awareness. Possibly extending this analysis to more sensitive measures of cognitive function such as ERP or fMRI could shed light on the importance of awareness of off-task episodes in sustained attention.

Our data did not identify a greater presence for our marker of mind wandering in the Long Blocks than Moderate Blocks, although it is important to note that this pattern is consistent with the frequency of explicit indications of mental state which did not vary across this interval either. One possible reason is that the temporal intervals we chose for this manipulation are too crude to reveal the sequence of mental states; a more fine grained approach could be applicable to this question in the future. Alternatively, the onset of mind wandering in any given block could be subject to individual differences—an issue which could prove important in determining the sequence with which mental states unfold in a task. Not withstanding these issues, the triangulation between the effects of the rate of presentation, and the relative association with moment to moment behavioural and subjective measures of mind wandering provides strong evidence that Factor Two represents the structural manifestation of mind wandering in this task.

7. Conclusion

Using PCA we successfully determined a number of structural regularities in the time series of response times during a continuous performance task which reflect the dominant modes within which the task was performed. The presence of one of these behaviour states, Factor Two (i) responded to manipulations of presentation rate in a comparable manner to verbal reports of off-task thinking, (ii) was present in performance in the period prior to a behavioural lapse and (iii) absent prior to a report of task focused thinking. As such this factor seems a strong candidate for an indirect marker for the capture of attention by our own thoughts as alluded to more then a century ago by William James.

One advantage of the research outlined in this paper is that it has the potential to identify periods of off-task mental activity based on statistical principles rather than by binning data based on responses to probes or targets. Presumably, not all behavioural lapses involve mind wandering, and the recording of subjective information in the scanner has been questioned (Mason et al., 2007) and so a tool for delineating different mental states is of interest to the neuroscience community at large. As response times provide a simple one dimensional metric, deriving the temporal structure which relates to different mental states is a trivial task compared to the same task in multi-dimensional data sets provided by data imaging tools such as fMRI or EEG. One possibility, therefore, is to use the structures detected in the time series of response times as a template upon which to map more complex measures of brain function – this boot-strapping procedure could help simplify the task of mapping private states of attention in the waking brain. Moreover, the identification of these response time patterns is made on a statistical basis and so can take place without the need for thought probes. It seems, for example, a relatively straight-forward prediction that in certain populations that areas of the default network could show stronger BOLD activity in blocks when response times show patterns of fluctuation than when responses are slow and consistent. In the future, the use of structural properties of behavioural data as a template for more detailed measures of cortical function could provide an invaluable asset in parsing more complex data sets, and so help elucidate the temporal grammar of mental states.

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