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## **Response time fluctuations in the sustained attention to response task predict performance accuracy and meta-awareness of attentional states**

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## Abstract

Previous research suggests that response time (RT) patterns in the *Sustained Attention to Response Task* (SART) differentially predict different features of mind wandering but it is unknown how they relate to meta-awareness of attentional states. We applied principal component analysis to blocks of non-target (go) trials prior to target (no-go) trials and attentional state and meta-awareness probes in the SART and identified three distinct patterns that replicated those observed in previous research. A stable response rate was associated with superior target performance, whereas RT acceleration prior to targets was associated with poorer target performance. Self-reported attentional state was not significantly predicted by any of the pattern components. By contrast, meta-awareness was independently associated with two distinct RT fluctuation patterns with evidence that each pattern was specifically related to either meta-awareness of off-task or on-task states. These results suggest that mind wandering and meta-awareness of attentional states have distinct and overlapping imprints on RT patterns in the SART. We conclude by highlighting implications of these results for introspective methods and the measurement of mind wandering.

**Keywords:** attentional lapses; meta-awareness; mind wandering; sustained attention

Although we are often required to focus on tasks at hand, our thoughts very often drift away from the external world and are occupied by internal self-oriented content. *Mind wandering* refers to a state where attention is decoupled from the environment and directed towards task-unrelated thoughts (Qin et al., 2011; Smallwood & Schooler, 2015). Such states are very common in daily life with studies estimating that they occupy 30-50% of daily mentation in healthy individuals (Kane et al., 2007; Killingsworth & Gilbert, 2010; Marcusson-Clavertz et al., 2016; McVay et al., 2009).

Mind wandering is an elusive phenomenon whose research heavily relies on participants' introspection, a method that could include various confounds (Vinski & Watter, 2012). It is typically indexed during laboratory tasks by having participants classify the orientation of their thoughts (*on-task* or *off-task*) in the period preceding intermittent probes (Smallwood & Schooler, 2015). Despite the potential ambiguity of this introspective approach, mind wandering reports seem to be reasonably accurate and co-vary reliably with experimental conditions, parameters, and individual measures (McVay & Kane, 2009; Smallwood et al., 2003). Nevertheless, awareness of such states also fluctuates from aware (*tuning-out*) to unaware mind wandering (*zoning-out*) (Smallwood, McSpadden, et al., 2008). Even when participants are explicitly asked to monitor and report their attentional state, they may still be caught mind wandering without being aware of it (Schooler et al., 2004). Elucidating the features of meta-awareness has the potential to inform higher-order thought theories (Lau & Rosenthal, 2011) with direct implications for consciousness research.

Insofar as indexing subjective reports may confound the assessment of conscious states (Koch et al., 2016), identifying behavioural markers of mind wandering states in the absence of self-reports has considerable utility in consciousness research. Mind wandering research commonly employs sustained attention tasks, which are conducive to attentional lapses (Smilek et al., 2010). In the most widely used task in this literature (the *Sustained Attention to*

*Response Task* [SART]; (Robertson et al., 1997), participants respond to frequent non-targets (the digits 0-9, except 3 [go trials]) and withhold responses to infrequent targets (the digit 3 [no-go trials]) while also judging their attentional state (on-task vs. off-task) in response to intermittent probes. In line with the disruptive effects mind wandering has on performance, in this task, mind wandering (off-task) is associated with impaired signal detection (Smallwood et al., 2004), erroneous responses to targets (commission errors), misses to non-targets (omission errors), as well as increased response time (RT) variability (Cheyne et al., 2006, 2009)

Although these mind wandering effects are well documented, the foregoing measures neglect inter-trial dynamics (i.e., RT fluctuations) that may be more reflective of the underlying cognitive processes and provide a more robust indicator of attentional states. For example, acceleration in trials preceding a target error in the SART has been associated with “mindless responding” (Robertson et al., 1997) and the frequent rate of non-target trials in the SART creates a habitual “go” response. Therefore, along with slow RTs, markedly fast RTs may also reflect mindless responding and be associated with mind wandering states (Cheyne et al., 2009; McVay & Kane, 2009, 2012). Arguably, fast RTs in the SART may reflect not only inattention, but also anticipatory responses or a speed-accuracy trade-off. Consequently, examining the evolution of RT behaviour throughout a block of trials might be more informative than using the mean non-target RT.

One method for more rigorously investigating the characteristics of attentional states is to classify structural patterns in behavioural responses and match them to discrete states (Smallwood, McSpadden, et al., 2008). *Principal component analysis* (PCA) is a valuable tool for distinguishing structures in data on the basis of covariance between variables. Applying PCA to RT patterns in the SART, previous studies were able to differentially predict both target performance, a widely used behavioural proxy of mind wandering, and

mind wandering self-reports from RT components (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008). Smallwood, McSpadden, et al. (2008) applied PCA to RTs in the twelve (non-target) trials preceding targets or attentional state probes. They identified three distinct time series patterns (components): the first was characterized by a stable RT pattern throughout the series, with higher and lower scores reflecting slower and faster RTs than average; the second was characterized by linear RT changes, with positive and negative scores reflecting a steeper RT speedup or slowdown, respectively, prior to the end of the RT series; and the third reflecting quadratic RT changes with positive and negative scores reflecting slow-fast-slow and fast-slow-fast shifts, respectively. Slow oscillations in RTs may reflect transient fluctuations in attentional states. Component 2 had significantly higher values on runs preceding errors compared to baseline (i.e. all series ending in probes) and lower values on trials preceding on-task reports than baseline (i.e. all series ending with a target). Therefore, speeding up before the target positively predicted errors on the target, and slowing down predicted on-task reports. This suggests that component 2 may reflect a dynamic RT pattern that is suggestive of mind wandering. This component also covaried with a manipulation of stimulus presentation rate (i.e. it was higher in a slow than a fast presentation rate), which further corroborates its utility as a behavioural signature of mind wandering. These patterns were partially replicated in independent studies (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012). Importantly, Smallwood, McSpadden, et al. (2008) also found that zone-outs (mind wandering without awareness) were less likely than all other conditions to be preceded by component 1. This links a reduction in, or an absence of, meta-awareness during mind wandering to a lack of slow and careful responding, which is in line with studies showing that mind wandering has more disruptive effects when it occurs without awareness (Cowley, 2013).

Although these RT patterns have the potential to serve as markers of discrete attentional states, the methodology used in the aforementioned paradigm may have involved an error-prone measure (McVay & Kane, 2012). The baseline which Smallwood, McSpadden, et al. (2008) used for each analysis contained all alternative blocks. For example, when analysing target accuracy, blocks preceding correct and incorrect trials were compared to all the blocks that ended in a thought probe (McVay & Kane, 2012). A further issue is that this analysis did not standardize RTs within participants and so between-participant differences may have impacted the observed results (McVay & Kane, 2012); for example, the results may suggest that mind wandering is more frequent or likely to occur for participants who display a tendency to speed up prior to probes. McVay and Kane (2012) circumvented this limitation by standardizing RTs within participants and optimising comparisons by contrasting incorrect and correct target responses and off-task and on-task reports. With this approach, they found similar results for target accuracy, but not subjective reports (meta-awareness was not measured). Specifically, component 1 had higher values for correct trials, suggesting that longer RTs correlate with better target performance, error trials had higher values on component 2 (as observed by Smallwood, McSpadden, et al., 2008) and lower values on component 3, suggesting that shorter RTs at the beginning and especially at the end of the series are associated with errors on the target. Analysis of thought probes showed that only component 1 predicted subjective reports; on-task reports were accompanied by higher component 1 values suggesting that slower responding across the series predicts on-task reports. One potential confound in this study is that blocks always ended with a target trial that in some cases (60%) would be followed by a probe. In turn, RT series from the same pools of trials were used to predict both behavioural and subjective markers, which may inflate associations between the two. For example, inserting a thought probe after a target

trial could confound subjective reports by leading participants to match their reports with their perceived performance.

In this study, we attempted to conceptually replicate and expand upon previous research on the behavioural response patterns of mind wandering and meta-awareness. As in previous studies (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008), we decomposed RT patterns during the SART using PCA in order to identify the structural patterns of behavioural and subjective mind wandering. We deviated from the methodology of previous studies, which relied on binary judgments for these two probe questions, in order to more robustly capture intra-individual differences in attentional states and meta-awareness thereof, as done in other research (Christoff et al., 2009). Using mixed-effects models (McVay & Kane, 2012), we further extended this approach to meta-awareness judgments to determine whether meta-awareness of attentional states can be predicted from RT patterns and whether such patterns overlap or not with those associated with behavioural and self-report indices of mind wandering.

## Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study (Simmons et al., 2012).

### *Participants*

74 healthy controls (48 females, age range: 18-48,  $M_{Age}=24.5$ ,  $SD=7.1$ ; years of education (post-secondary school):  $M_{Yoe}=3.6$ ,  $SD=2.3$ ), participated in this study in accordance with local ethical approval and were compensated £7 per hour. This sample corresponds to that of a previous independent study that was run concurrently (Terhune & Hedman, 2017). Our original aim was to collect 84 participants on the basis of an *a priori* statistical power analysis



with the aim to be able to detect correlations in the range of  $r=.30$  ( $\alpha=.05$ , two-tailed, power=.80) within a specific period in the academic year. Data collection ceased early because of the academic calendar, resulting in a sample size of 74, which enabled us to detect correlations  $\geq .32$  (sensitivity analysis:  $\alpha=.05$ , two-tailed, power=.80). The data were not examined until collection was completed so as to avoid optional stopping.

### *Materials & Procedure*

*Sustained Attention to Response Task (SART)* (Robertson et al., 1997). The SART is a sustained attention task that has been widely used in the study of mind wandering (Christoff et al., 2009; Marcusson-Clavertz et al., 2016; Smallwood et al., 2004; Smilek et al., 2010). In this study, trials consisted of an inter-stimulus interval (blank grey screen; 2000ms) followed by a digit (0-9; Arial font, white) against a grey background (500ms). Participants were instructed to respond to frequent non-targets (0-9, except 3) and withhold responses to infrequent targets (3). During completion of the task, participants were presented with thought probes at pseudorandom intervals that indexed attentional state (attentional state probe: “Where was your attention focused just before the probe?”) and meta-awareness of attentional states (meta-awareness probe: “How aware were you of where your attention was focused?”) (see Christoff et al., 2009). Participants were presented with these probes in a sequential manner. The first probe required participants to indicate whether their attention was directed towards the task or something unrelated to the task. The second probe asked participants whether or not they were aware of the focus of their attention (i.e. towards the task or something else) (Christoff et al., 2009). Participants responded to both probes using 6-point Likert scales (mind wandering probe: “completely on-task” to “completely off-task”; meta-awareness probe: “completely aware” to “completely unaware”). The task was completed on a PC with Windows 7 and a rotatable DELL LED display in the horizontal

position (1920x1200 pixels, 56x36cm) from a 70 cm distance. The experimenter made sure that participants understood the probe scales prior to completing the task. Participants responded by pressing a single button on a Cedrus response pad (Cedrus Corporation, San Pedro, CA) for non-targets and responded to probes by pressing one of 6 buttons on the response pad. After a practice block with 33 non-targets, 3 targets, and 4 sets of probe questions (presented in random order), participants completed 460 trials including 440 non-targets, 20 targets, and 20 sets of probe questions. Trials were broken into 5 types of blocks. Two of the blocks consisted of 9 non-targets and either a target or a probe (each block presented 8 times). Two consisted of 19 non-targets and either a target or probe (each block presented 4 times). Lastly, there was one block with 18 non-targets, one target, and one probe (each block presented 8 times). The trials were randomized (with no constraint on position of probes or targets) within each block and the order of blocks was also randomized.

### *Analysis*

We first separated non-target RT data into series comprising the 10 trials prior to targets and probes. We selected 10 trials for each RT series based on the data structure and on the basis of previous research that successfully identified RT components using RT series of 12 non-target trials (Marcusson-Clavertz et al., 2012; Smallwood, McSpadden, et al., 2008). We excluded RT series that had more than one error and those with errors at either edge (-10 or -1 positions). Single non-target errors in the remaining series were interpolated using the two respective adjacent trials. We next standardized RTs within participants using a z-score transformation (using each participant's mean RT) as in McVay and Kane (2012), in order to eliminate between-participant variability. Based on the foregoing criteria, four participants' data were excluded for having too few suitable RT series (<5). This resulted in 1223 RT series for the remaining 70 participants (series range: 7-24,  $M=17.5$ ,  $SD=4.1$ ). The series

range for target trials was 2-15 ( $M=8.7$ ,  $SD=2.7$ ) and for probe trials 3-14 ( $M=8.7$ ,  $SD=2.5$ ). These RT series were next included in a PCA, with each series entered as a separate case. As in previous studies (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008), a three-component solution was pre-specified and factor rotation was not employed. Post-PCA data are available here: <https://osf.io/3hncu/>. Next, the series were separated based on the outcome variable with 612 series that preceded a target trial and 611 series that preceded attentional state reports. The component scores were next included as predictors in analyses with three primary outcome variables: target accuracy (0=incorrect response [commission error], 1=correct withholding), attentional state (1-6 [higher scores reflect off-task states]), and meta-awareness of attentional state (1-6 [higher scores reflect reduced awareness of attentional state]) in mixed-effects models with component scores included as fixed effects and ID (participant) as a random effect. We additionally conducted a further exploratory analysis using the same approach separately for meta-awareness judgments in on-task and off-task states.<sup>1</sup> Finally, we repeated the primary analyses including only participants with 5 or more RT series for both target- and probe-level analyses (see Supplemental Materials).

## Results

### *Data summary*

All analyses were conducted on the sample of 70 participants (see Analysis). As can be seen in Table 1, participants made commission errors on 44% of target trials and omission errors on 7% of non-target trials. Anticipations (non-target responses faster than 100ms) were very infrequent (<1%). On average, participants tended to report being on-task slightly more often (attentional state probe judgments: 1-3) and being aware of their attentional state (meta-

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<sup>1</sup> We would like to thank anonymous reviewers for suggesting this analysis.

awareness probe judgments: 1-3). A number of the variables were significantly inter-correlated and these relationships were comparable to those previously reported (Cheyne et al., 2006, 2009; Marcusson-Clavertz et al., 2012). Within-participant ranges ( $\Delta_{\text{report}}$ : maximum-minimum) for attentional state and meta-awareness reports covered the full range of possible difference scores (0-5; mind wandering:  $M=2.81$ ,  $SD=1.24$ ; meta-awareness:  $M=2.61$ ,  $SD=1.23$ ). Similarly, at the sample level, mean report scores covered the full range for attentional state reports<sup>2</sup> (1-6;  $M=2.91$ ,  $SD=1.10$ ), and nearly the full range for meta-awareness reports (1-4.9;  $M=2.50$ ,  $SD=0.90$ ). These range values indicate that participants appeared to be using the full range of responses.

Table 1

*Descriptive statistics and correlation matrix for research variables (N=70).*

Variable	<i>M (SD)</i>	CV	As	CEs	OEs	ASP	MP
Non-target RT (ms)	313 (30)	-.13	-.26*	-.45***	-.44***	.10	.05
Non-target coefficient of variation (CV)	0.18 (0.03)		.53***	.38**	.13	.19	.13
Non-target anticipations (As) (%)	0.2 (0.8)			.28*	.14	-.003	.12
Target commission errors (CEs) (%)	44 (19)				-.20	.19	.17
Non-target omission errors (OEs) (%)	7 (8)					.14	.09
Attentional state probe response (ASP)	2.86 (0.96)						.60***
Meta-awareness probe response (MP)	2.46 (0.81)						

*Note.* Higher scores on the attentional state probe response indicate off-task states. Higher scores on the meta-awareness probe response indicate lower awareness of attentional state.

\*  $p < .05$

\*\*  $p < .01$

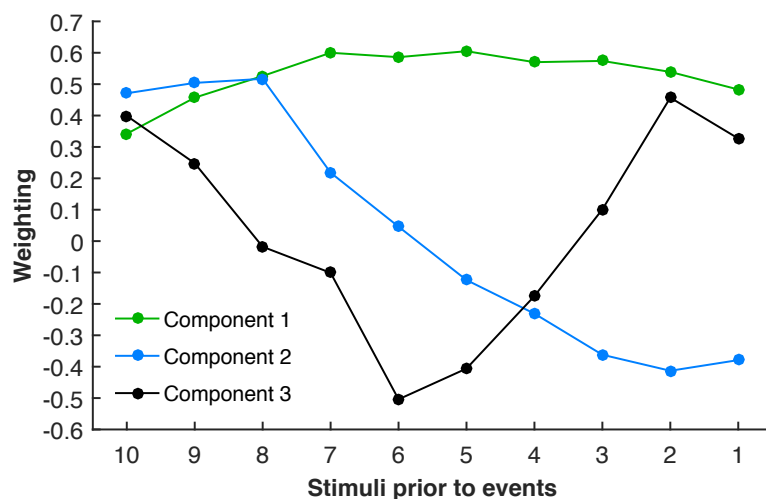
\*\*\*  $p < .001$

<sup>2</sup> These means differ slightly from those reported in Table 1. The former correspond to trials that were included in the mixed-effects models whereas the latter correspond to all trials.

### *Principal Components Analysis*

The three components cumulatively accounted for 51.63% of the total variance in non-target RTs (see Figure 1). Component 1 accounted for 29% of the variance in RTs (eigenvalue [EV] =2.85), component 2 accounted for 13% (EV=1.31), and component 3 accounted for 10% variance (EV=1.01). As can be seen in Figure 1, component 1 was characterized by stable RTs across the trials with reliably positive loadings across trials indicating that different series diverged from participant's average response rate to non-targets. By contrast, component 2 had positive loadings at the beginning of the series followed by increasing negative loadings nearer to the end of the series, reflecting linear RT changes. Finally, component 3 was characterized by oscillations between fast and slow RTs across the series, reflecting quadratic RT changes. Cumulatively, these data corroborate the PCA results of previous studies (Marcusson-Clavertz et al., 2012, McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008) and suggest the presence of distinct RT patterns in the processing of non-target stimuli.

PCA derived loadings indicate the degree to which each series corresponds to the pattern expressed by the respective component. Positive scores for component 1 depict series with slower RTs than participants' average and negative scores depict series with faster than average RTs. For component 2, positive scores depict acceleration towards the end of the series whereas negative scores depict deceleration. Finally, positive scores for component 3 depict series that started slow and fluctuated from faster to slow towards the end, whereas negative scores indicate a fluctuation from fast to slow and back to fast responding at the end of the series.



*Figure 1.* Weightings of components identified by RTs to non-targets in the 10 non-target trials prior to targets or probes.

#### *Using RT components to predict different features of mind wandering*

We sought to determine whether the 3 components were predictive of three measures related to mind wandering: target accuracy, attentional state, and meta-awareness of attentional state. In the mixed-effects logistic regression model of target accuracy, a behavioural index of mind wandering, components 1 and 2, but not 3, were significant predictors of target accuracy (Table 2). Component 1 positively correlated with accuracy, whereas component 2 negatively correlated with accuracy (Figure 2). These data suggest that participants performed better on the target when keeping a steady slower rate (reflected by positive scores on component 1) or decelerated towards the end of the block (reflected by negative scores on component 2). These effects remained stable after excluding participants with few trials (see Supplemental Materials). These results partially replicate previous findings regarding response patterns and target accuracy (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008) and suggest that poor response inhibition on the target is linked to acceleration in response times on the preceding trials.

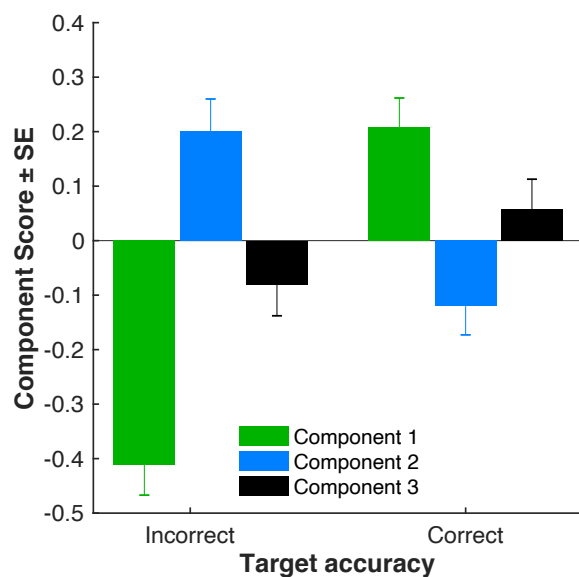


Figure 2. Component scores by target accuracy ( $N_{\text{series}}=612$ ).

Table 2

*Inferential statistics for the mixed-effects model in the prediction of accuracy on the target*  
( $N_{\text{series}}=612$ ).

Component	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>	OR [95% CI]
1	.73	.10	7.15	<.001	2.07 [1.70, 2.52]
2	-.35	.10	3.61	<.001	0.71 [0.58, 0.85]
3	.13	.10	1.38	.17	1.14 [0.95, 1.37]

In contrast with the analysis of target accuracy, the RT components did not significantly predict attentional states, as indexed by self-report probes (Table 3). These results remained non-significant after excluding participants with few trials (see Supplemental Materials). Component 2 was previously found to be negatively associated with on-task self-reports (Smallwood, McSpadden, et al., 2008), but this was not replicated in our analysis. By contrast, McVay and Kane (2012) reported that component 1 loadings were positively associated with on-task reports. Insofar as we observed a negative association between

component 1 loadings and off-task reports, our results are consistent in direction with their finding although the corresponding effect in our data did not achieve significance. These discrepancies suggest that self-reported attentional state is not reliably related to PCA-derived RT patterns in the SART with variations across studies potentially attributable to methodological and analytic differences.<sup>3</sup>

Table 3

*Inferential statistics for the mixed-effects models in the prediction of attentional state probe responses.*

Component	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Attentional states ( $N_{\text{series}}=611$ )				
1	-.07	.05	1.45	.15
2	-.03	.05	0.61	.54
3	-.01	.05	0.19	.85
Meta-awareness of attentional states ( $N_{\text{series}}=611$ )				
1	-.03	.05	0.59	.56
2	-.12	.04	2.66	.008
3	-.09	.04	2.01	.045
Meta-awareness of on-task states ( $n_{\text{series}}=413$ )				
1	-.05	.05	1.17	.244
2	-.11	.05	2.36	.019
3	-.01	.05	0.32	.749
Meta-awareness of off-task states ( $n_{\text{series}}=198$ )				
1	-.06	.09	0.60	.551
2	-.08	.09	0.91	.362
3	-.15	.09	1.67	.097

The analysis of meta-awareness probes, for which higher scores reflect reduced awareness of attentional state, revealed partially overlapping effects with the analysis of target accuracy (Table 3). In particular, component 1 did not significantly predict meta-awareness judgments, whereas components 2 and 3 were both significant negative predictors.

<sup>3</sup> We conducted the analysis treating the variable as binary but the RT components were again not significant predictors of the reports ( $ps>.3$ ).



After excluding participants with few trials, the component 2 effect remained stable whereas the component 3 effect declined slightly in magnitude and became non-significant (see Supplemental Materials). This approach is potentially limited insofar as we collapsed across on-task and off-task judgments, which are likely to have different features. In order to remedy this, we repeated the analysis on meta-awareness judgments separately for on-task and off-task states. The results revealed a suggestive double dissociation such that Component 2 was the only significant (negative) predictor of meta-awareness of on-task states and was not a significant predictor of meta-awareness of off-task states. By contrast, Component 3 displayed a weak trend as a negative predictor of meta-awareness of off-task states, but not of on-task states. Previous research (Smallwood, McSpadden, et al., 2008) suggested a link between lower scores on Component 1 and unaware mind wandering (relative to on-task and aware mind wandering), but our findings do not replicate this result, potentially due to differences in the contrast used. Rather, in our data, *reduced* awareness of on-task states was independently associated with a tendency to change from fast to slow responding prior to the target (reflected by negative scores on component 2) whereas *reduced* awareness of off-task states was weakly associated with a quadratic RT trend characterized by oscillations between fast and slow responses ending in fast responses prior to the probe (component 3).

## Discussion

In this study, we applied PCA to RT time series in a sustained attention task in order to identify structural patterns that may reflect discrete cognitive processes. The three identified components offer a depiction of the principal behavioural states underlying performance on the SART. Two of the components were able to independently predict target performance accuracy, often used as a proxy measure of mind wandering (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, 2011; Smallwood, McSpadden, et al., 2008), but

none could significantly predict self-reported attentional states. Similarly, two components (with one overlapping to those above) independently predicted meta-awareness of attentional states. Specifically, the component associated with accuracy on the target was also associated with reduced awareness of on-task states, whereas reduced awareness of off-task states was weakly associated with lower values on the third component. These data suggest that sustained attention performance and meta-awareness of attentional states are associated with partially overlapping dynamical RT patterns.

This study sought to expand upon previous research on the behavioural signatures of mind wandering and meta-awareness of attentional states. Our PCA replicated previously observed patterns underlying RT series in the SART and the utility of these patterns in predicting behavioural indices of mind wandering (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008). In particular, our data demonstrate that participants were more accurate on targets when they exhibited longer RTs, either by keeping a steady slower rate throughout the series (component 1) or by decelerating prior to the target (component 2). Both of these effects were statistically significant, or suggestive, in Marcusson-Clavertz et al.'s (2012) and McVay and Kane's (2012) studies and numerically present in Smallwood, McSpadden, et al.'s (2008) study, although only the difference between incorrect performance and baseline was statistically significant for component 2 (Smallwood, McSpadden, et al., 2008). Similar to Smallwood, McSpadden, et al. (2008) and Marcusson-Clavertz et al. (2012), but in opposition to McVay and Kane (2012), component 3 did not predict target accuracy. One possible explanation for the latter discrepancy is the larger number of trials (and large sample size) in McVay and Kane's (2012) study, which may have afforded greater sensitivity. Indeed, the effect was in the same direction in our study, suggesting that our non-significant result might have been underpowered. Taken together, these results suggest that a pattern of consistently slow responses is associated with

target accuracy, as also shown in other research on mind wandering (Head & Helton, 2013; Seli et al., 2012, 2013). Further research is needed to clarify the role of quadratic RT patterns prior to target accuracy.

The predictive utility of the three RT components did not generalize to self-reported mind wandering. In particular, none of the components significantly predicted attentional state. These results are inconsistent with previous findings using this approach. For example, McVay and Kane (2012) found that slow and steady responding (component 1) was predictive of on-task reports whereas Smallwood, McSpadden, et al. (2008) observed that deceleration towards the end of the series (component 2) was associated with on-task reports (Marcusson-Clavertz et al. [2012] did not measure self-reported mind wandering). These inter-study discrepancies plausibly derive from methodological differences. Our study used a continuous measure of mind wandering whereas previous studies employed dichotomous measures; thus, the foregoing results may reflect RT dynamics related to categorical states of mind wandering that could not be captured by our continuous measure, which may have indexed more the *intensity* of mind wandering *per se*. Notably, another potentially significant difference is that Smallwood, McSpadden, et al. (2008) compared RT series preceding off-task and on-task reports and targets, the latter of which plausibly included a mixture of on- and off-task states, thereby introducing noise into the contrast of these different attentional states. They specifically found that on-task reports were associated with lower scores on component 2 than baseline (all series ending with a target), whereas no significant differences were observed between on-task and mind wandering reports. Their study also included more variable inter-trial intervals (1250-2500ms) than the present study (2000ms) although it's unclear why this might give rise to these discrepant results. McVay and Kane's (2012) results might have been influenced by their design, in which probes were always preceded by a target. Insofar as positive loadings for component 1 were predictive of both target accuracy

and on-task reports in their study, it follows that component 1 might have predicted the latter by virtue of a tendency for participants to infer that they were on-task if they correctly withheld a response on the preceding target. Subjective reports of attentional state are probably estimated through an admixture of participants' *attentional state* monitoring and *performance* monitoring, that is, such reports might reflect states of mind wandering and/or a retrospective attempt to explain one's behavioural performance. For example, (Macdonald et al., 2011) found that confidence in perceptual decisions was positively correlated with attentional state reports, in that when participants were more confident about their decisions they also tended to report being more focused on the task. Individuals regularly evaluate their performance and use this information to adjust performance over time (Weissman et al., 2006). Therefore, attentional state reports in McVay and Kane's (2012) study may have been confounded by awareness and/or evaluation of task performance. The present results are not limited by this confound. Nevertheless, as described above, it is possible that our failure to observe associations between RT components and self-reports may be due to the inclusion of fewer trials, and in particular fewer non-target trials than McVay and Kane's (2012) study. Similarly, our failure to replicate the specific association between Component 1 and on-task reports (McVay & Kane, 2012) may be attributable to our smaller sample size as the observed effect in our study was in the same direction as in their study. Despite the methodological differences across these studies, prediction of target accuracy was reliable whereas subjective reports have not been consistently associated with a specific RT component across studies. Further research is clearly required to more definitively investigate this relationship.

An analysis of meta-awareness reports suggests a partially overlapping association with the RT dynamics linked to behavioural mind wandering. Unlike in a previous study (Smallwood, McSpadden, et al., 2008), Component 1, the tendency to display stable response

rates, did not significantly predict meta-awareness. One possible reason for this is that Smallwood, McSpadden, et al. (2008) treated subjective reports as categorical variables whereas our analysis involved pseudo-linear scales of meta-awareness of attentional state (1-6). In addition, their effect reflected a difference between zone-outs and all other trials combined (neither Marcusson-Clavertz et al. [2012] nor McVay and Kane [2012] measured meta-awareness in their studies). This discrepancy might also be due to the fact that Smallwood, McSpadden, et al. (2008) were specifically measuring meta-awareness of mind wandering whereas our measure pertained to meta-awareness of attentional states. Our results showed that Components 2 and 3 were significant predictors of meta-awareness, suggesting that two distinct RT patterns were independently associated with a tendency for reduced awareness of attentional states. To further interrogate this result, we further subdivided trials according to the corresponding attentional state report. This revealed that a shift from a faster to a slower response rate (Component 2) was associated with poorer meta-awareness of on-task states, whereas a sharper quadratic shift from a fast to a slow to again a fast response rate (Component 3) was weakly associated with reduced meta-awareness of off-task states. Interpretation of the latter result should be qualified by the fact that the component 3 effects were either marginally significant or only suggestive and thus might not be reliable. Nevertheless, these results potentially suggest two discrete behavioural patterns associated with meta-awareness of attentional states. In the first, a participant is less aware of the direction of their attention and starts to respond more slowly near the end of the block, potentially reflecting reduced task engagement, adoption of a useful strategy, or implicit learning regarding the relative probability of an imminent target, which in turn facilitates superior target accuracy. This suggests that meta-awareness of on-task states is not required for strong performance in the SART and in turn that performance on the target is not an optimal indicator that one is aware of being on task. The second pattern, by contrast, seems to

reflect a sequence of zoning out coupled with a continuation of fast responding, which is consistent with the inverse tendency to slow down in anticipation of the end of the block when meta-awareness is present. Overall, the results further show that the independent RT components have distinct predictive utility and that attentional state, as indexed by behavioural performance, and awareness thereof are reflected distinctively in RT dynamics.

The present results should be considered against the limitations of this study. The PCA approach used here does not consider errors on non-target trials, which may contain rich information for mapping behavioural performance to attentional states. Identifying a behavioural marker of different attentional states is crucial, yet it seems that RT patterns vary greatly across individuals as well as within. Therefore, even though dimension reduction provides great insight into RT patterns and performance, this approach might be strengthened by coupling the analysis of such patterns with analysis of concurrent pupillometric (Franklin et al., 2013; Konishi et al., 2017) or electroencephalographic measures of attentional states (Baird et al., 2014; Braboszcz & Delorme, 2011; Kam et al., 2011; Smallwood, Beach, et al., 2008). A second limitation of this study is the use of the SART. Performance on the SART seems to primarily correlate with mind wandering during cognitively-demanding tasks, as indexed by experience sampling, and thus the present results may not generalize beyond such contexts (Marcusson-Clavertz et al., 2016). Moreover, in the SART, self-report probes are always preceded by stimulus trials, including sometimes by targets (McVay & Kane, 2012), and errors in this task are relatively easy to gauge (McAvinue et al., 2005). The need to seek explanations and interpret our experience is an integral human trait, offering great sense of comfort by providing a sense of consistency and continuity in the world (Gazzaniga, 1985). If participants become aware that they are performing poorly and then are probed to judge their attentional state, a natural inference would be that their poor performance was due to mind wandering (see also Macdonald et al., 2011). Accordingly, mind wandering in the SART,

where performance can be easily and continuously evaluated, might be misidentified as a *cause* of poor performance instead of an *effect* of performance monitoring (Head & Helton, 2016). A similar potential limitation of this study was that meta-awareness probes were always preceded by attentional state probes, which may have led to the latter influencing the former. The fact that RT dynamics predicted meta-awareness probe responses, but not attentional state reports, renders this unlikely. Future research should therefore seek to explore the relationship between performance monitoring and subjective reports of attentional state and meta-awareness and develop novel tasks that would circumvent the potential confounding influence of performance monitoring in the assessment of mind wandering.

In summary, we replicated previously extracted patterns underlying RT series in the SART and found evidence for their utility in representing patterns of behavioural performance on the SART (Marcusson-Clavertz et al., 2012; McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008). However, our results are discrepant with those of previous studies, particularly in the prediction of self-reported mind wandering (McVay & Kane, 2012; Smallwood, McSpadden, et al., 2008), but may be attributed to methodological and analytic differences. There is now emerging consensus that measuring subjective reports may cause interferences in the experience these measures are trying to index, and in turn may confound findings with processes that are introduced by the experiment itself (see Koch et al., 2016). Studies on subjective experience need to identify behavioural measures that can capture such phenomena experimentally. Identifying methods that can apprehend conscious states and their meta-representations via behaviour would allow future research to use measures that do not require participants to monitor their experience. Still, these data suggest that behavioural performance and subjective attentional state reports can be dissociated through the analysis of RT series and thus these features of SART performance should not be equated. We expanded upon previous research by further showing that RT series components

had partially overlapping utility in the prediction of behavioural performance and meta-awareness of attentional states, suggesting potentially distinct modes of reduced awareness of attentional states.

## References

- Baird, B., Smallwood, J., Lutz, A., & Schooler, J. W. (2014). The Decoupled Mind: Mind-wandering Disrupts Cortical Phase-locking to Perceptual Events. *Journal of Cognitive Neuroscience*, *26*(11), 2596–2607. [https://doi.org/10.1162/jocn\\_a\\_00656](https://doi.org/10.1162/jocn_a_00656)
- Braboszcz, C., & Delorme, A. (2011). Lost in thoughts: Neural markers of low alertness during mind wandering. *NeuroImage*, *54*(4), 3040–3047. <https://doi.org/10.1016/j.neuroimage.2010.10.008>
- Cheyne, J. A., Solman, G. J. F., Carriere, J. S. A., & Smilek, D. (2009). Anatomy of an error: A bidirectional state model of task engagement/disengagement and attention-related errors. *Cognition*, *111*(1), 98–113. <https://doi.org/10.1016/j.cognition.2008.12.009>
- Cheyne, J. A., Carriere, J. S., & Smilek, D. (2006). Absent-mindedness: Lapses of conscious awareness and everyday cognitive failures. *Consciousness and Cognition*, *15*(3), 578–592. <https://doi.org/10.1016/j.concog.2005.11.009>
- Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(21), 8719–8724. <https://doi.org/10.1073/pnas.0900234106>
- Cowley, J. A. (2013). Off Task Thinking Types and Performance Decrements During Simulated Automobile Driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *57*(1), 1214–1218. <https://doi.org/10.1177/1541931213571270>



- Franklin, M. S., Broadway, J. M., Mrazek, M. D., Smallwood, J., & Schooler, J. W. (2013). Window to the Wandering Mind: Pupillometry of Spontaneous Thought While Reading. *Quarterly Journal of Experimental Psychology*, *66*(12), 2289–2294. <https://doi.org/10.1080/17470218.2013.858170>
- Gazzaniga, M. S. (1985). *The social brain: Discovering the networks of the mind*. Basic Books.
- Head, J., & Helton, W. S. (2013). Perceptual decoupling or motor decoupling? *Consciousness and Cognition*, *22*(3), 913–919. <https://doi.org/10.1016/j.concog.2013.06.003>
- Head, J., & Helton, W. S. (2016). The troubling science of neurophenomenology. *Experimental Brain Research*, 1–5. <https://doi.org/10.1007/s00221-016-4623-7>
- Kam, J. W. Y., Dao, E., Farley, J., Fitzpatrick, K., Smallwood, J., Schooler, J. W., & Handy, T. C. (2011). Slow Fluctuations in Attentional Control of Sensory Cortex. *Journal of Cognitive Neuroscience*, *23*(2), 460–470. <https://doi.org/10.1162/jocn.2010.21443>
- Kane, M. J., Brown, L. H., McVay, J. C., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). For Whom the Mind Wanders, and When. *Psychological Science*, *18*(7), 614–621. <https://doi.org/10.1111/j.1467-9280.2007.01948.x>
- Killingsworth, M. A., & Gilbert, D. T. (2010). A wandering mind is an unhappy mind. *Science*, *330*(6006), 932. <https://doi.org/10.1126/science.1192439>
- Koch, C., Massimini, M., Boly, M., & Tononi, G. (2016). Neural correlates of consciousness: Progress and problems. *Nature Reviews Neuroscience*, *17*(5), 307–321. <https://doi.org/10.1038/nrn.2016.22>
- Konishi, M., Brown, K., Battaglini, L., & Smallwood, J. (2017). When attention wanders: Pupillometric signatures of fluctuations in external attention. *Cognition*, *168*, 16–26. <https://doi.org/10.1016/J.COGNITION.2017.06.006>

- Lau, H., & Rosenthal, D. (2011). Empirical support for higher-order theories of conscious awareness. *Trends in Cognitive Sciences, 15*(8), 365–373.  
<https://doi.org/10.1016/j.tics.2011.05.009>
- Macdonald, J. S. P., Mathan, S., & Yeung, N. (2011). Trial-by-trial variations in subjective attentional state are reflected in ongoing prestimulus EEG alpha oscillations. *Frontiers in Psychology, 2*, 82. <https://doi.org/10.3389/fpsyg.2011.00082>
- Marcusson-Clavertz, D., Cardeña, E., & Terhune, D. B. (2016). Daydreaming style moderates the relation between working memory and mind wandering: Integrating two hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(3), 451–464. <https://doi.org/10.1037/xlm0000180>
- Marcusson-Clavertz, D., Terhune, D. B., & Cardeña, E. (2012). Individual differences and state effects on mind-wandering: Hypnotizability, dissociation, and sensory homogenization. *Consciousness and Cognition, 21*(3), 1097–1108.  
<https://doi.org/10.1016/j.concog.2012.04.002>
- McAvinue, L., O’Keeffe, F., McMackin, D., & Robertson, I. (2005). Impaired sustained attention and error awareness in traumatic brain injury: Implications for insight. *Neuropsychological Rehabilitation, 15*(5), 569–587.  
<https://doi.org/10.1080/09602010443000119>
- McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(1), 196–204.  
<https://doi.org/10.1037/a0014104>
- McVay, J. C., & Kane, M. J. (2012). Drifting from slow to “d’oh!”: Working memory capacity and mind wandering predict extreme reaction times and executive control

- errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38(3), 525–549. <https://doi.org/10.1037/a0025896>
- McVay, J. C., Kane, M. J., & Kwapil, T. R. (2009). Tracking the train of thought from the laboratory into everyday life: An experience-sampling study of mind wandering across controlled and ecological contexts. *Psychonomic Bulletin & Review*, 16(5), 857–863. <https://doi.org/10.3758/PBR.16.5.857>
- Qin, J., Perdoni, C., & He, B. (2011). Dissociation of subjectively reported and behaviorally indexed mind wandering by EEG rhythmic activity. *PloS One*, 6(9), e23124. <https://doi.org/10.1371/journal.pone.0023124>
- Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). 'Oops!': Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, 35(6), 747–758. [https://doi.org/10.1016/S0028-3932\(97\)00015-8](https://doi.org/10.1016/S0028-3932(97)00015-8)
- Schooler, J. W., Reichle, E. D., & Halpern, D. V. (2004). Zoning Out while Reading: Evidence for Dissociations between Experience and Metaconsciousness. In *Thinking and seeing: Visual metacognition in adults and children* (pp. 203–226). MIT Press.
- Seli, P., Cheyne, J. A., & Smilek, D. (2012). Attention failures versus misplaced diligence: Separating attention lapses from speed–accuracy trade-offs. *Consciousness and Cognition*, 21(1), 277–291. <https://doi.org/10.1016/j.concog.2011.09.017>
- Seli, P., Jonker, T. R., Solman, G. J. F., Cheyne, J. A., & Smilek, D. (2013). A methodological note on evaluating performance in a sustained-attention-to-response task. *Behavior Research Methods*, 45(2), 355–363. <https://doi.org/10.3758/s13428-012-0266-1>
- Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2012). A 21 Word Solution. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2160588>

- Smallwood, J. (2011). The footprints of a wandering mind: Further examination of the time course of an attentional lapse. *Cognitive Neuroscience*, 2(2), 91–97.  
<https://doi.org/10.1080/17588928.2010.537746>
- Smallwood, J., Beach, E., Schooler, J. W., & Handy, T. C. (2008). Going AWOL in the Brain: Mind Wandering Reduces Cortical Analysis of External Events. *Journal of Cognitive Neuroscience*, 20(3), 458–469. <https://doi.org/10.1162/jocn.2008.20037>
- Smallwood, J., Davies, J. B., Heim, D., Finnigan, F., Sudberry, M., O'Connor, R., & Obonsawin, M. (2004). Subjective experience and the attentional lapse: Task engagement and disengagement during sustained attention. *Consciousness and Cognition*, 13(4), 657–690. <https://doi.org/10.1016/j.concog.2004.06.003>
- Smallwood, J. M., Baracaia, S. F., Lowe, M., & Obonsawin, M. (2003). Task unrelated thought whilst encoding information. *Consciousness and Cognition*, 12(3), 452–484. [https://doi.org/10.1016/S1053-8100\(03\)00018-7](https://doi.org/10.1016/S1053-8100(03)00018-7)
- Smallwood, J., McSpadden, M., Luus, B., & Schooler, J. (2008). Segmenting the stream of consciousness: The psychological correlates of temporal structures in the time series data of a continuous performance task. *Brain and Cognition*, 66(1), 50–56. <https://doi.org/10.1016/j.bandc.2007.05.004>
- Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology*, 66(1), 487–518. <https://doi.org/10.1146/annurev-psych-010814-015331>
- Smilek, D., Carriere, J. S. A., & Cheyne, J. A. (2010). Failures of sustained attention in life, lab, and brain: Ecological validity of the SART. *Neuropsychologia*, 48(9), 2564–2570. <https://doi.org/10.1016/j.neuropsychologia.2010.05.002>
- Terhune, D. B., & Hedman, L. R. A. (2017). Metacognition of agency is reduced in high hypnotic suggestibility. *Cognition*, 168, 176–181. <https://doi.org/10.1016/j.cognition.2017.06.026>

Vinski, M. T., & Watter, S. (2012). Priming honesty reduces subjective bias in self-report measures of mind wandering. *Consciousness and Cognition*, *21*(1), 451–455.

<https://doi.org/10.1016/J.CONCOG.2011.11.001>

Weissman, D. H., Roberts, K. C., Visscher, K. M., & Woldorff, M. G. (2006). The neural bases of momentary lapses in attention. *Nature Neuroscience*, *9*(7), 971–978.

<https://doi.org/10.1038/mn1727>