Timecourses showing mind wandering and heuristic strategies interact complexly to affect SART performance rapidly

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INTRODUCTION: Go/no-go tasks (such as the sustained attention to response task, SART) may elicit two lingering effects arising from (a) mind wandering and (b) the mental strategy adopted. AIM: To determine the onset rate of these effects and whether the effects are additive or interact in a complex way. METHODS: An online experiment (~20 minutes) with 78 volunteers who experienced 6 experimental blocks of SART with go-percentages of 100%, 87%, 75%, 50%, 25% and 6% in a randomized order (inter-trial interval = 5.2s). Each block was followed by mind wandering thought probes and rating scales. Analysis was done with linear mixed effects models, non-parametric group tests, and cumulative distribution probability graphs. RESULTS: Mind wandering accelerated reaction time when accompanying haste, but it slowed reaction time when accompanying inhibitory passivity. In both cases it increased error-making. Reaction times reflected new strategies within 30 seconds. CONCLUSIONS: Mind wandering can both accelerate or decelerate performance depending on the context and its effective strategy; it typically co-opts parallel mental resources.

CCS Concepts: • **Applied computing** → **Psychology**; • **Human-centered computing** → **Laboratory experiments**; **User studies**.

Additional Key Words and Phrases: mental strategy, mind wandering, attentional resources, effort, SART

ACM Reference Format:
Omar Elkelani, Sara I. Ribeiro-Ali, Carina E. I. Westling, and Harry J. Witchel. 2024. Timecourses showing mind wandering and heuristic strategies interact complexly to affect SART performance rapidly. In *Proceedings of European Conference on Cognitive Ergonomics (ECCE '24).* ACM, New York, NY, USA, 11 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

1.1 Mind Wandering states

Mind wandering (MW) is defined as mental state where "attention drifts from its current train of thought (often an external task) to mental content generated by the individual rather than the environment" [19]. MW is important for human factors and applied psychology because many studies have shown it has links to medical errors and increased risk of major accidents such as when driving [17, 28]. In the laboratory, MW is also associated with decline in performance on many tasks which require sustained cognitive effort [6, 10]. It is also a mystery as to how there are not more apparent

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errors occurring, given that up to 50% of the attentional states in healthy awake adults is reported (using experience sampling in daily life) as MW [4], and MW is considered by some as the “default mental state” [3, 23].

The causes and mechanisms for mind wandering have been sought in part to reduce the risk of accidents and errors. Interestingly, Smallwood et al. illustrated that the conditions that induce medical errors (e.g. working long hours, stress and fatigue, repetitive tasks, etc.) were also inducers of mind wandering [17]. There is a long-standing controversy over whether MW is a failure in executive monitoring [6], which would involve co-opting a subset of parallel mental resources [22], versus MW resulting from exhaustion of attentional resources [11, 25], which would involve attentional resources cycling serially between the main task and mind wandering [27]. The exhaustion of resources model has been characterised as "perceptual decoupling" [9]. The executive failure is sometimes seen as a choice due to insufficient effort and motivation; the choice is between two strategies [26]: a careful strategy (*encode-and-check*) and a hasty strategy (*encode-and-click*) that leaves out the final double-checking step. This choice would be the basis of the well-known speed-accuracy trade-off, in which reaction times and error rates are inversely related [10]. If such a choice is made, it may explain the basis of the dichotomy between intentional mind wandering (IMW) [13], where low motivation or boredom drives attentional focus to a heuristic (mental shortcut) that allows MW, versus unintentional MW (UMW), where the person’s attention is overwhelmed by the task or distractions, so attentional focus is withdrawn from the task and picked up by MW.

1.2 Sustained Attention to Response Task (SART)

The SART has used in to assess retained executive function and the ability to maintain sustained attention. In the traditional SART, there are numeric stimuli (e.g. digits 1 -9), which prompt a response from the participant. This is either a ‘Go’-stimulus (any digit 1 to 9 except 3) that requires the participant to press a button as soon as possible, or a ‘No-Go’-stimulus (a 3), when the participant must inhibit their responses. Traditionally in the SART, because researchers were more interested in response inhibition, *no-go*-stimuli were called ’target stimuli’ and *go*-stimuli were called ’nontarget stimuli’. After a block of trials, the individual is questioned, using a thought probe, on whether they were on task or experiencing task-unrelated thoughts, also known as mind wandering. Many researchers have used and adapted the SART to suit their respective aims; one example is the manipulation of *go*-percentage (GP), the proportion of *Go*-stimuli to total (*Go* and *No-Go*) stimuli [26]. The SART measures performance by reaction time (RT0) and by errors. Several mind-wandering studies have used the SART to demonstrate that commission errors (pressing inappropriately instead of refraining) increase during mind wandering, which may suggest the executive failure to inhibit the default *go*-response [2, 14]. Our team has recently demonstrated that go/no-go tasks can elicit both mind wandering **and** strategic changes, and that these linger briefly after the task stops [5]. The aim of this study is to determine the onset rate of the effects of mind wandering and strategic changes, and to estimate whether these effects are additive or interact in a complex way.

2 METHODS

2.1 Participants

We recruited 78 healthy online participants through the *Prolific.co* online platform. Compensation of £3.50 was offered for the 20 minutes it takes to complete the experiment. Ethical approval for the study was provided by the Brighton and Sussex Medical School Research Governance and Ethics Committee (ERA/BSMS1645/6/3). All the tasks were conducted under the Declaration of Helsinki for informed consent.

2.2 Protocol for Online Experiment

Gorilla.sc provided the platform for building the experiment (https://app.gorilla.sc). This is a platform that uses a simple GUI and spreadsheets to create experiments based in HTML and JavaScript that run locally on the participant's computer, and then their computer uploads the results (including accurate reaction times) to the platform's central server [1]. Participants were recruited through *Prolific* and redirected to gorilla.sc to complete the task and subsequently sent back to *Prolific* to be compensated. On *Prolific* we set the inclusion criteria as: any participant with fluent English, located in the United Kingdom, with a stable Wi-Fi connection and to be performed from a laptop or desktop (not on a mobile device). We excluded any participants who did not complete all the trials. We designed the experiment to last ~18-20 minutes. The introduction included: ethical information, consent, 4 questions from a very brief personality questionnaire [8], task instructions, a reaction time test and a SART practice task. The first block and set of thought probes, which they completed, were discarded from our data to account for becoming accustomed to the task. Then they completed the main task; A sequence of six 90-second SART blocks consisting of 16 trials (screens with stimuli) with different go-percentages (GP, the proportion of go-stimuli in that block to total stimuli in that block; GP06, GP25, GP50, GP75 GP87, GP100). The order in which the different GP blocks appeared was randomised so every participant completed every block once. Upon task completion the participants were redirected back to *Prolific* with a completion code to redeem their compensation.

2.3 Task Structure

During the instructions we embedded two different practice tasks. The first of which, we asked the participant to press the right arrow key as soon as any digit appeared on the screen. The purpose of this trial was to obtain the raw reaction times, as well as familiarising the participant to the subsequent tasks. The next task during the instructions section was a simulation of the main task but with feedback. Pressing the right arrow key when a "3" is shown is counted as a commission error, not pressing the right arrow key when digits "1,2,4-9" are shown are recorded as an omission error. The participants were advised that they should strive to maintain accuracy as well as speed simultaneously. See the online supplement for the full instructions. **** We adapted the SART to show digits (1-9) in the centre of the screen over a white background. We used a variety of fonts and positions to avert single-pixel heuristics (focusing on one spot on the screen as opposed to a true reaction to the digit shown). The task involved first, an inter-trial fixation screen (a cross within a circle symbol) for 5.2 seconds, followed by a visual stimulus (digits 1-9) for 1 second, where the participant must respond appropriately; this process is repeated for 16 trials. Traditionally, the inter-trial interval in SART is 1.1s; our rationale for using the 5.2 seconds interval is that it induces MW faster, allowing an overall shorter number of trials per block to elicit sufficient MW to analyse. Upon completing the 16 trials (1 block), the participant was shown a pair of mind wandering thought probes regarding the previous block. Here the participants first report their overall attentional state (MW or OT), whether it was intentional or unintentional if MW, and then they rate the previous task from 1 -9 on difficulty, effort, caution. The participant would then immediately move onto the next block until the experiment's end.

2.4 Statistical analysis

The data recorded by gorilla.sc were imported into Matlab with purpose made scripts that also analysed the blocks. We always excluded the reaction time for first trial for any block. The following is a list of criteria of data exclusion for statistical analysis:

- Blocks with median reaction time > 1 second.
- Thought probe response times > 15 seconds.
- Any block where the net error rate > 30%.
- If more than 30% of responses are < 0.15 s (impossibly fast).
- Participants with two or more blocks meeting any of these criteria

We used Matlab to perform the statistical tests (including: Wilcoxon rank sum (Mann Whitney U) tests and linear mixed effects models (LMEs)) and to generate the graphs shown in the results section. Bias was calculated as follows [20]:

$$Bias = -0.5 \times \log \frac{(1 - FalseAlarmRate) \times (1 - HitRate)}{HitRate \times FalseAlarmRate} \tag{1}$$

where:

$$HitRate = \frac{0.5 + NumGoTrials - NumOmissionErrors}{1 + NumGoTrials} \tag{2}$$

and

$$FalseAlarmRate = \frac{0.5 + NumCommissionErrors}{1 + NumNoGoTrials} \tag{3}$$

3 RESULTS

3.1 Data Summary

Seven blocks were excluded due to having too many errors (out of 468 blocks). For the remaining 461 blocks, 303 blocks (65.72%) were on-task, 158 blocks (34.27%) were MW. This can be further split into 22 blocks IMW (4.77%) and 136 blocks UMW (29.5%). The total number of trials was 7,376. From these 3,843 were "*go*-stimuli" and 3533 were "*no-go* stimuli". There were 255 commission errors (7.2%) and 31 omission errors (0.81%) making a combined error rate of 8.01% per trial.

3.2 Mind Wandering, Go-Percentage and Errors

We expected that lower go-percentages would encourage intentional MW, and also that errors would be linked to MW due to the reduced attentional resources. Figure 1A and 1B show how much different go-percentages elicited MW, grouped by whether that block included any error (commission or omission). As seen in 1A, when not making errors there is a trend toward maximum on-task attention at GP = 50%, but this was not significant, nor were the differences

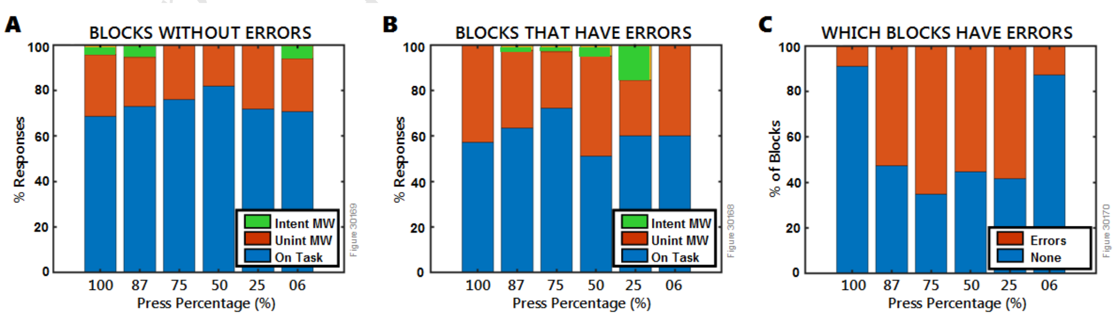

Fig. 1. Mind wandering rates change with go-percentage and are linked to errors. Panel A: How mind wandering is affected by go-percentage in those blocks where no errors were made. Panel B: How mind wandering is affected by go-percentage in those blocks where at least one error was made. Panel C: Percentage of blocks that have at least one error (commission or omission) grouped go-percentage.

in IMW or UMW between the different GPs (LMEs, P > 0.1 for all). Among those blocks where the participants did commit at least one error, there was no difference in on-task states or unintentional MW states among the different GPs (LMEs, P > 0.2, GP = 87% reference). However, the increase in IMW when GP = 25% is significant (LME, t = 2.95, P = 0.0037); 7 out of 13 of the IMW blocks that had errors occurred when GP = 25%. Furthermore, as can be seen comparing panel A to panel B, claiming to be mind wandering was significantly linked to having made an error (LME, t = 4.46, P = 1×10^{-5}). Although this could imply that mind wandering increases the risk of making errors, the reverse could also be true, that making an error makes one more likely to report later that you were mind wandering. Panel C shows that avoiding errors was much more common at GP = 100% and 6%, suggesting that these versions of the task may encourage heuristics.

3.3 Error Rates and Bias

Because there are so few errors in the 100% and 6% blocks, we checked the commission and omission error rates *per trial* for each go-percentage (Figure 2). We found that commission error rates were indeed very low at 6%, and it was, of course, impossible to make a commission error at GP = 100%. Although the probability of having any errors in block was similar between GP = 25% to 87% (Figure 1C), the commission error rate consistently went down as the go-percentage decreased (Figure 2A). Compared to GP = 87%, an LME showed that GP = 75% lowered the risk per trial by 10% (t = -3.47, P = 5.8×10^{-4}), GP = 50% by 21% (t = -7.1), GP = 25% by 25% (t = -8.9), and GP = 6% by 31% (t = -10.9). Furthermore, being on-task lowered the risk per trial by 4.9% (t = -2.1, P = 0.035).

This pattern may imply that the risk of making commission errors was part of a strategy of inhibiting responding when there is less to respond to, so we checked whether the pattern of omission errors was concordant with this strategy (Figure 2B). Although omission errors were 10× more rare than commission errors, the same pattern could also be seen, especially in the large number of omission errors in GP = 6% (LME, 5.6% more common, t = 3.3, P = 0.001). Being on-task also reduced the risk of omission errors per trial (LME, 2.8%, t = -2.6, P = 0.011). It would appear that the opposing correlations between go-percentage versus commission and omission errors may be part of a strategic pattern.

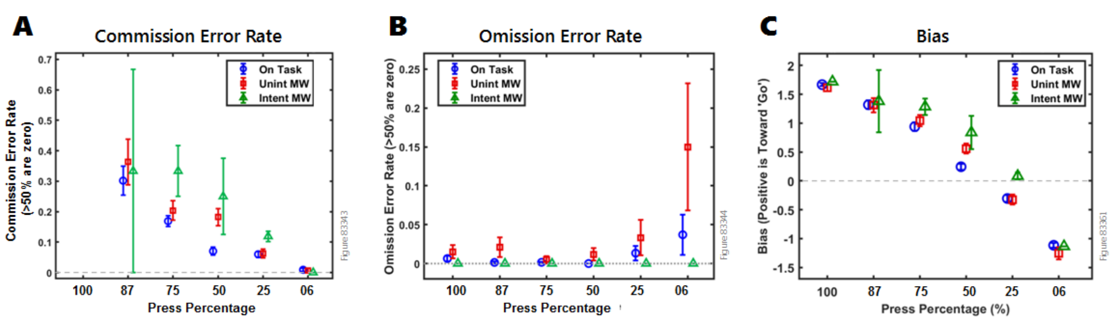

Fig. 2. The effect of go-percentage and mind wandering on error per trial rates. Panel A: Effects of go-percentage and attentional focus on commission error rate (per trial). Note that it is impossible to make a commission error in the 100% version. Colour code: blue squares = on task, red circles = unintentional mind wandering, and green triangles = intentional mind wandering is green on top. Panel B: Effects of go-percentage and attentional focus on omission error rate (per trial). Panel C: The effect of go-percentage and mind wandering on response bias (see methods for calculation). Response bias relates to whether the participant decided "go" or "no-go"; this relates to the go-percentage (if they were compliant) and also to any errors they made. It hints at any heuristics they might been using.

One way to integrate the commission and omission error rates is to look at response bias (see methods). For example, at a GP of 50%, before the stimulus digit appears, the *go* and *no-go* stimuli would be equally likely; thus, participants would not rationally benefit from using heuristics due to the unpredictability of the task. Figure 2 panel C shows the participants' response bias for each go-percentage. Zero on the Y-axis means that there was no bias; participants were equally likely to respond (*go*) or inhibit their response (*no-go*). A positive response bias means participants were more inclined towards pressing (regardless of whether the stimulus displayed was the number 3) and a negative bias suggests participants were less inclined to press and more inhibited. As expected, the greatest bias to respond was for GP = 100%, and the strongest bias toward inhibiting responses occurs at GP = 6%; as a rule, participants are more biased toward responding than toward inhibiting for each go-percentage (e.g. the bias at GP = 50% is greater than zero for all attentional states). What is noticeable is that intentional mind wandering tends to bias responses toward *go* in the mid-range GPs (75%, 50%, and 25%, Wilcoxon rank sum P = 0.152, 0.060, 0.023); these are not all significant because the N number for IMW was so low. Furthermore, unintentional MW clearly biases toward *go* at GP = 50% (P = 0.0035, rank sum) compared to on-task.

3.4 Timecourses of Mean Reaction Times

In figure 3, the mean cohort reaction time (ms) is plotted for each go-percentage (except for GP=6%) for each trial number, in order of trial appearance. For the initial 1st to 3rd trials, the mean reaction time for all GPs decreases; participants become faster at responding to the digit appearing on their screen, and there are no differences between the reaction times at the various GPs. This was tested using separate linear mixed effects models for each trial number, with the GP (fixed effect) tested against GP = 100% (reference value). For all GPs at these early trial numbers, there was no significant difference in the mean reaction time between GP of 25%, 50%, 75% and 87% compared to 100% (LMEs t < 1.9, p > 0.05 for all). At the 4th and 5th trials, the reaction time for GP = 100% continues to decrease; however, for all other GPs after trial 4, mean reaction times increase as trial number becomes higher. At trial 4, in comparison to GP = 100%, at GP = 25% mean RT0 is already significantly higher ($t = 4.3$, $P = 3 \times 10^{-5}$), and at trial 5, GP = 50% is also already

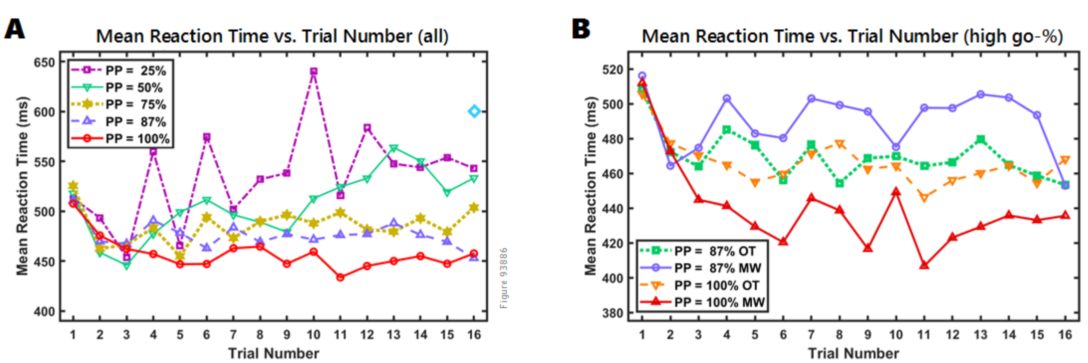

Fig. 3. Timecourses of how reaction time (for "go" trials only) changed by trial number for each of the go-percentages; as with other order effects, these changes reflect either learning, boredom, or heuristics. Panel A shows the mean reaction time for all participants for the first trial, the second trial, etc., grouped according to the go-percentage. The cyan diamond (upper fright) is the average reaction time when GP = 6%. Note that "no-go" trials do not have a reaction time, so participants can drop out and back in with different trial numbers, hence the high variability for the low go-percentages. Panel B shows the timecourses grouped by attentional focus (on-task versus mind wandering) for 100% and 87%.

significantly raised (t = 3.5, P = 6×10^{-4}). Ultimately, the reaction times start to significantly diverge towards the final blocks (trials 15 and 16), especially for the lower GPs of 6%, 25% and 50% (LMEs, t > 4.0, P < 1×10^{-4}, for all)

Figure 3B shows how the timecourse changes depend mind wandering, and how the effects of mind wandering depend critically on the go-percentage. For on-task blocks, GP = 100% (orange downward pointing triangles) and GP = 87% (green squares) have almost the same timecourse; this is not surprising, as these two versions of the task are similar in rate of pressing and in arousal. However, for mind wandering, GP = 100% (red upward triangles) accelerates the responses, as if one was using a mental strategy that skipped a mental checking step. By contrast, for MW at GP = 87% (purple circles), the responses are slowed and get slower, as if the occasional surprising *no-go* stimuli caused the participant to slow down their entire approach.

3.5 Distributions of Reaction Times

Cumulative distribution functions (CDFs) show the distribution of a variable for different participants as the probability (expressed as a fraction) that the data point would fall at that value or less. Figure 4 shows the distributions of the mean reaction times using cumulative distribution graphs (each data point is one block from one participant). As shown, this produces a diagonal curve with the data point where the y-axis = 1 being the slowest mean reaction time (value read on the x-axis) for that go-percentage. Panel A shows how the participants performed when on-task, and panel B shows how the participants performed when mind wandering. In the CDF graphs, curves positioned to the left and upward indicate faster responses, whereas curves that are downward and to the right are slower. The parallel line pattern seen

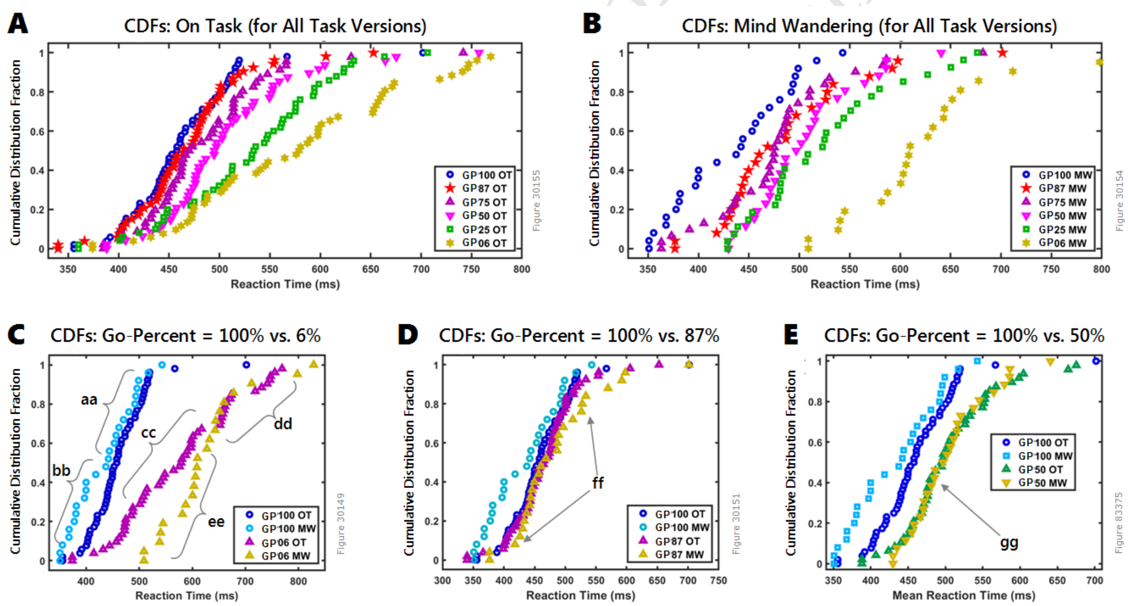

Fig. 4. Cumulative Distribution Fractions showing the distribution of mean reaction times (RT0 for each block). Panel A: Mean reaction times for on-task (OT) blocks only, grouped by go-percentage. Panel B: Mean reaction times for mind wandering (MW) blocks only, grouped by go-percentage. Panel C: Mean reaction times for go-percentages 100% and 6%, also grouped by attentional focus. Panel D: Mean reaction times for go-percentage 87% grouped by attentional focus, showing the 100% data from panel C for comparison. Panel E: Mean reaction times for go-percentage 50% grouped by attentional focus, showing the 100% data from panel C for comparison.

in panel B (MW) indicates that lower go-percentages may cause a consistent delay among all the participants, and this may signify a serial mental effect, such as an extra step before or after initial perception. By contrast, the branching pattern in panel A (on-task) indicates that some participants were strongly delayed (e.g. gold stars at upper right, GP = 6%) whereas other participants experiencing the same go-percentage were able to compensate (e.g. via motivation or mental discipline) and perform almost as well as they could on faster versions (e.g. gold stars at lower left).

In figure 4 panel C, we can see the opposing effects that MW has on SART reaction times (RT0). The RT0 when GP = 100%-MW is the fastest as it falls furthest to the left (cyan circles, symbol bb), whereas the GP = 6%-MW was slowest (gold triangles), as all participants were slower than 500ms, hence, the curve appears far to the right. The GP = 100%-MW (cyan circles) and GP = 6%-MW (gold triangles) cohorts are parallel and do not overlap; as both are mind wandering, this again indicates at least one factor other than attentional focus is influencing the change in RT0 for all participants. For both GP100-OT (dark blue circles) and GP06 OT (purple triangles) cohorts, there is a split from their respective MW cohorts (compare cc to ee on panel C). The graphs show that there is a subgroup of the GP06-OT cohort which conforms to the same curve as the GP06 MW (see overlapping gold and purple triangles at dd) but then branches off where a portion of the GP06-OT cohort seem to respond with faster mean RT0 values (cc) compared to GP06-MW (dd, purple triangles). The inverse of the same phenomenon is evident within the GP100 cohort; here GP100-OT follows the GP100-MW curve initially (see section aa, panel C) and then branches off and has slower RT0 values (bb, dark blue circles). It can be assumed that when the trends overlap significantly, it indicates a common strategy used between the groups producing the same effect for at least a portion of the distribution.

Panel D of figure 4 shows that the on-task reactions at GP = 87% (purple triangles) are identical to GP100-OT (dark blue circles), and that the only a small subset of participants were slower than this for GP87-MW (ff, gold triangles). In panel E of figure 4, our data shows unequivocally that at GP = 50%, MW and OT demonstrated almost identical distribution curves (see how gold downward triangles overlay precisely over green upward triangles, section gg, figure 4E), which therefore hints that they may be using the same response strategy despite differing in reported attentional focus. This data highlights the 3 strategies which can be categorised as: “truncated” - fast with a hasty heuristic (bb, light blue squares), “considered” (gg, gold and green triangles in panel E) - a middle speed that represents perceptive yet cautious due to uncertainty, and “passive” (ee in panel E) – slow with an inhibitory heuristic. This use of heuristic strategies matches what we saw with the bias analysis (figure 2C).

4 DISCUSSION

It would appear that our participants jump to conclusions very quickly. We and others [5, 26] have previously shown that go/no-go tasks with different go-percentages elicit delays that are related to strategies (instead of just mind wandering). In the current study we demonstrated that these delays were the result of mental heuristics, that the heuristics seem to involve response bias, and that these biases develop very quickly – in under 30 seconds. The rapid biases develop despite the participants’ not receiving any information to tip them off as to the regularity or go-percentage of the block. Furthermore, we show that there are at least three different kinds of strategies: (a) a normal (compliant) strategy that involves perception and uncertainty (Wilson et al.’s *encode-and-check*), (b) a very fast strategy (Wilson et al.’s *encode-and-click*), and (c) a very slow strategy that appears when there are mostly *no-go*-stimuli. Finally, we showed that mind wandering predisposes participants to different strategies depending on the go-percentage: when GP = 100%, mind wandering encourages (among some participants) a hasty (*encode-and-click*) strategy (Figure 4C, bb), whereas when GP = 6%, mind wandering encourages a very slow strategy (dd and ee). This adds further evidence that mind wandering disables excess parallel resources [22], which would allow for some modest mental multi-tasking with only occasional ill effects, as justified below.

It has been presumed that mind wandering co-opts some attentional resources, thus leading to performance decrement [14, 18]. Mind wandering has consistently been linked to serious error-making in psychological tasks that make persistent demands (the context regulation hypothesis [19]), but the effects of mind wandering on response speed (such as reaction time) is either inconsistent or dependent on the precise type of mind wandering [12]. Although it may seem obvious that mind wandering does not disable all other activity, so it might work by co-opting a subset of attentional resources in a parallel way (so-called executive failure, [6]), some researchers have proposed that mind wandering **decouples** mental activity from perception [9, 14], leading to a proposal that mind wandering causes serial delays in thinking [27]. This model would work by having attention/perception on a duty cycle where it is bouncing back and forth between the main task and mind wandering; if the cycles were quick, then the reaction time delay would be a random fraction of the duty cycle (e.g. 50%), depending on when (randomly) in the off-task part of the duty cycle the stimulus is presented. Previously Smallwood et al. [15] found that mind wandering could slow down go/no-go responses (see their figure 1, successive) from ~500ms (on task) to ~570ms; in that experiment, the inter-trial interval was medium (approximately 3.5 seconds) and the go-percentage was high (80%). In a later experiment, Smallwood et al. [16] demonstrated that go-percentage reversed the effect of mind wandering on the reaction time (see their figure 1B), such that zoning out (MW without awareness) sped up reaction time (~470ms) compared to on-task (~530ms) when the go-percentage was high (80%). But when the go-percentage was medium (60%, i.e. more stimuli required inhibition), then the reaction time for mind wandering was normal for that task (~530ms), but for on-task the reaction time was slowed (~570ms). So MW still sped up the response. In Wilson et al.'s experiment [26], participants were pre-warned of the upcoming change in go-percentage; in our study, the changes were left unspoken.

The main limitation in this study is that there is no objective method of measuring mental state due to the nature of it being an entirely subjective experience [24]. Therefore, all data in this field is reliant on self-reported outcomes via the use of thought probes, despite the repeated reservations of many authors in this field [13, 21].

4.1 Conclusions

This study shows that participants adopt strategies based on jumping to conclusions within 30 seconds. These rapid decisions occur despite the fact that participants are given clear instructions to balance both errors and speed (as in GP = 50%), and despite the fact that the most passive tasks (i.e. versions high in no-go trials) are in a context with other tasks that are quite active. Extrapolating these strategic changes to the medical workplace, people can jump to conclusions without any prompting surprisingly quickly. Mind wandering can both accelerate or decelerate performance depending on the context and its effective strategy

The data also suggests that – for these simple tasks in the context of a short, online psychology experiment – mind wandering co-opts resources working in parallel, such that it supports the executive failure model [6] rather than the perceptual decoupling model [9]. While some researchers have engaged with this controversy using dual tasks to split attention, a future experiment that has been less investigated would be to ask participants to subjectively assess their own mental processing. For example, we have previously shown that intentional mind wandering is a low effort state [7]. Perhaps participants may be aware of their parallel processing and double-checking.

ACKNOWLEDGMENTS

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Received 18 April 2024; revised 99 March 9999; accepted 99 June 9999