The conceptualisation and measurement of sustained attention: understanding the role of motivation

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Abstract

Sustained attention can be defined as the ability of maintaining a focused state of mind for an extended period of time, and it is required in most daily activities. Its proneness to failures can, however, lead to dire consequences. Many have tried to understand which factors might counteract its fluctuations over time: motivation in particular is a natural area of interest, however, its effects on sustained attention are still not well understood. Existing findings are hindered by potential methodological confounds and a sparse theoretical background. With the general aim of examining the effects of motivation on sustained attention performance, the project firstly set out a theoretical basis by validating the most common operationalisations of the function through two factor analyses on popular computerised tasks. Secondly, it systematically tested the effects of multiple dimensions of motivation (extrinsic/intrinsic, trait/state) on behavioural performance. Finally, for the first time in the literature, it explored the motivational influence on behavioural periodicities, using spectral decomposition techniques. The results of a total of 8 studies (plus 1 application study) showed first that attentional lapses might represent the more robust task-general facet of sustained attention and is the recommended index for generalisable results. The findings of the effects of motivation were potentially paradoxical, in that higher intrinsic or reward-based extrinsic motivation led to worse performance, possibly because of context-related state variables. The only dimension of motivation that seemed to aid sustained attention was related to the intrinsic enjoyment of an activity. Furthermore, motivation did not interact with any aspects of behavioural oscillations. To conclude, the project provided useful recommendations to reconcile the various literature of sustained attention with robust behavioural indices. The present results also contributed to the understanding of motivation and sustained attention; however, further investigation is still required.

Acknowledgments

This whole ordeal would not have been possible without the people I have been so lucky to find along the way. First and foremost, I would like to sincerely thank my supervisors Quoc Vuong and Peter Gallagher for the constant support, advice and always inspiring conversations. I would also like to thank Beth Little, my university neighbour, colleague and friend. Our chats in good and hard times have always been fruitful. I hope my thanks also reach Becca for the help in collecting data, and to Lucy Robinson and Nicolaus Brosowsky for letting me use their data. Some miscellaneous thanks also go to Ben for our life-saving coffee breaks and attire advice, to Josh for our wholesome lunch breaks and to all the friends and colleagues who supported me. I am eternally in dept with the closest ones to me: my family, my friends and my partner Alia who kept me standing when alone I would not have been able to. Thank you.

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Covid impact statement

The project described in this document took place during the COVID-19 world pandemic and was significantly affected by it. The original project plan included multiple lab-based studies which comprised physiological data collection in addition to behaviour. Due to the lockdowns and the university policies, the project required complete redesign in a short period of time, focussing only on online data collection and available datasets.

The first empirical chapter which is centred on the validation of the operational definitions of sustained attention should have originally reported a laboratory-based study which employed a battery of tasks not only assessing sustained attention but also a wide range of cognitive domains. The study was in the pilot phase when the first lockdown started, and the time constraints and the online data collection resulted in a narrower scope. The study of motivation, on the other hand, was originally planned to be multimodal, comprising data recording utilising EEG and eye-tracking. The inclusion of EEG data would have also allowed to investigate oscillations in not only behaviour but also in its physiological counterparts. With data collection taking place online, only behaviour was accessible, and the design of the studies as well as the research questions had to be adapted. The resulting project was therefore built on newly collected behavioural data and existing datasets.

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Abbreviations

ADHD: Attention Deficit/hyperactivity disorder

ANOVA: Analysis of Variance

ANTI-vea: Attentional Network Test for Interactions and Vigilance

AS: Starkstein Apathy Scale

CLOCK: Mackworth Clock test

COV: Coefficient of Variation

CPT: Continuous Performance Task

DAN: Dorsal Attention Network

DBP: Depressed Bipolar Disorder

DMN: Default Mode Network

EBP: Euthymic Bipolar Disorder

EEG: Electroencephalography

EFA: Exploratory Factor Analysis

FFT: Fast Fourier Transform

IIV: Intra-Individual Variability

IMI: Intrinsic Motivation Inventory

ISI: Inter-Stimulus-Interval

KMO: Kaiser Meyer Olkin index

MDD: Major Depression Disorder

MRT: Metronome Response Task

MTMM: Multitrait-Multimethod matrix

PSD: Power Spectral Density

PVT: Psychomotor Vigilance Test

RMSEA: Root Mean Square Error of Approximation

RMSR: Root mean Squared Residual

RRT: Rhythmic Reaction Times

RT: Reaction Times

SART: Sustained Attention to Response Task

SD: Standard Deviation

SDT: Signal Detection Theory

SESOI: Smallest Effect Sizes of Interest

tDCS: Transcranial Direct Current Stimulation

TFT: Traditionally Formatted Task

TOT: Time-On-Task

TOVA: Test of Variables of Attention

Chapter 1 - Introduction

The ability of sustaining attention is essential in everyday life. It sometimes entails focussing on a monotonous task for a prolonged period of time, for instance on driving, whilst remaining perceptive to potential risks and dangerous events. Some other times, with the example of an exam preparation, it requires the suppression of distractions and alternative activities for the benefit of the task at hand. Yet, sustaining attention can be difficult and prone to failures, with potentially grave consequences. A potential counteraction to failures of sustained attention is motivation, however, its role has not been properly understood. The literature has produced mixed findings regarding how different facets of the function are affected by motivation, which might be due to the vast variability of definitions, methods and approaches to sustained attention research. With the overarching aim of unfolding the influence of different facets of motivation on sustained attention, the project started with a validation of the empirical definitions of sustained attention. Once the methodological questions were settled, the project thoroughly examined the role of intrinsic and extrinsic motivation on an extended spectrum of behavioural variables.

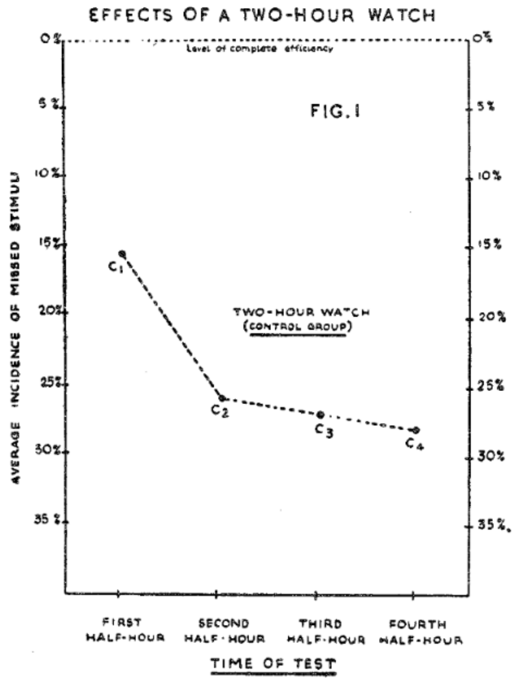
This chapter will provide an overview of the most relevant topics the project included. Firstly, a general overview of sustained attention will be provided examining how the psychological construct is defined and measured. This will lead to a first gap of the literature that will be examined throughout the project. Then, the chapter will provide an overview of motivation and potential mechanisms of interaction with sustained attention. This will be followed by an examination of the existing evidence, and potential limitations of the current understanding. Finally, it will introduce to a recent neurobiological hypothesis explaining oscillatory behaviour in sustained attention and how motivation might affect it.

1.1 Sustained attention: an overview

Sustained attention has been found critical in academic performance (Isbell et al., 2018) and in predicting grades and achievements (Steinmayr et al., 2010): its correct functioning is required for successful learning. Many other cognitive functions and psychological constructs are tightly related to sustained attention, among which are executive functions (Unsworth et al., 2010), and fluid intelligence and reasoning (Ren et al., 2013). With the transition from analogue to digital technologies, and the consequential advent of automation and advanced human-machine systems (see the well-known example of human-controlled lifts, turned to be automated in (Hancock, 2014) or the recent spread of self-driving vehicles), many operators have acquired a more supervisory role, in which monitoring for failures and problems represents the core activity. In the area of human factors research, sustaining attention has been proven to be fundamental for airport security staff in baggage screening (Meuter & Lacherez, 2016), surveillance of closed circuit television (CCTV) (Donald, 2019), train driving (Dorrian et al., 2007), driving on automated vehicles (Greenlee et al., 2018), long-distance flights (Naeeri et al., 2019), monitoring of nuclear power plants (Reinerman-Jones et al., 2016) and detection of potential terrorist threat (Hancock & Hart, 2002). In addition to that, in the healthcare system, maintaining a focussed attention is critical in many circumstances, for instance in intensive care nursing (Khanade & Sasangohar, 2017), in anaesthetists' work (Paget et al., 1981), or radiological monitoring (Phelps et al., 2018).

The first instances of research in the area of sustained attention can be tracked to the 1920s with the studies of Henry Head, who used the name vigilance to indicate a "*state of high-grade physiological efficiency*" and a (psychological) "*state of intense readiness to respond to excitation*", highlighting the human ability of fast reactions and adapted responses (Head, 1923). However, the very first implementation of modern paradigms in studies of sustained attention and vigilance appeared during World War 2 with the psychologist Norman Mackworth, and his investigations of human perceptual efficiency in adverse working conditions and prolonged visual search. Specifically, he was interested in understanding why radar operators, especially towards the end of their shifts (between 1.5 to 2 hours) failed to detect submarines. To test this experimentally, he designed the Clock (test), a visual task in which, in a stylised clock, a pointer moved following a circle (composed by 100 positions). Each jump happened every second, with the rare possibility of skipping a position. Participants had to make a response every time the rare target event happened, throughout up to two-hours long sessions. He then made several fundamental observations: sustaining attention, as the capacity of detecting rarely occurring targets, is fallacious and prone to lapses, and performance is characterised by a *main* downward trend and *minor* trial-to-trial variations (i.e. lapses of attention) in signal detection efficiency (Mackworth, 1948). What Mackworth firstly noticed is now referred to as vigilance decrement, and represents the fundamental core of behavioural phenomena in sustained attention performance over time (Figure 1.1).

Figure 1.1
The original vigilance decrement found by Mackworth (1948). Performance showed a clear decrement in terms of missing target responses over the course of a 2-hours period. From (Mackworth, 1948).



1.2 A problem of definition (1)

Current research has attempted to explain the causes of the vigilance decrement through various theories and models, from multiple levels of analysis (Fortenbaugh et al., 2017). However, in the vast existing literature of almost a century of research, a significant issue exists: a standardised definition of sustained attention has yet to be derived. This has been evident since the original conceptualisations of the term. In fact, while Henry Head put the emphasis on the physiological aspect of his definition of vigilance in relation to the central nervous system, Mackworth focused more on the functional aspects of vigilance in the context of working conditions, an example of the applications of neuroscience to a real-world problem, ultimately putting the bases for a research area later called neuroergonomics (Hancock, 2019; Parasuraman et al., 2012).

In more current times, conceptualisations of sustained attention and vigilance can be found within broader taxonomies of the human attention systems. In the 2012 review of the seminal work by Posner and Petersen (Posner & Petersen, 1990), across the 3-way subsystems division of the attention system (alerting, orienting and executive control), vigilance can be found within the alerting subsystem. In this context, vigilance is closely related to the concepts of arousal and tonic alertness: slow variations of performance mostly due to neuromodulatory activity. In addition to that, top-down control of goal-maintenance, essential throughout vigilance tasks, can be seen within the executive control network (Petersen & Posner, 2012). In an alternative taxonomy by Chung and colleagues, the different forms of attention are categorised based on the types of information at hand: specifically, internal attention operates over internally generated information (like rules, strategies, memories, thoughts), while external attention works on sensory information. Within this framework vigilance can be identified as a modulatory-like property of general attention: the ability of sustaining the focus over time, after the selection of the relevant information. Importantly, in this context, attention and therefore vigilance are characterised by a limited capacity (Chun et al., 2011). Somewhat related to Posner's concept of alertness, in the research area of sleep-deprivation and arousal, vigilance is again considered as a physiological state without necessarily considering behavioural responsiveness, and mostly determined by tonic sleep-wake neuromodulatory activity (Oken et al., 2006). Research in vigilance and fatigue also appear to be significantly related (Eisert et al., 2016), especially regarding the focus on performance over time. While fatigue represents a complex multifaceted concept, studied by a wide variety of disciplines and of difficult definition per se, it can potentially be considered as the set of phenomena in performance deterioration over time. Vigilance (*decrement*) investigations could then just be a subset of fatigue research, where attention is employed. Thus, it is not surprising that theories and models of vigilance are used to explain fatigue, and vice versa (Pattyn et al., 2018).

From a purely psychological and behavioural perspective, vigilance and sustained attention are currently considered synonyms (Christensen & Joschko, 2001; Dillard et al., 2019; Neigel et al., 2020; Oken et al., 2006; Pattyn et al., 2018; Warm et al., 2009), however different laboratories, research groups or even publications have slightly different variations in their definitions. Two main conceptualisations can be found in the literature: coming from the historical research by Mackworth and more frequently found within the area of human factors - ergonomics, vigilance is usually defined as the ability of the observer to detect rare and transient signals over prolonged periods of time (Parasuraman et al., 1987; Parasuraman & Davies, 1977; Warm & Parasuraman, 2009); more common in clinical neuropsychology and sleep research, vigilance is related to moment-to-moment fluctuations of performance and responsiveness, rather than target detection or selection (Basner et al., 2013). Modifications in the scope can however still be found. Perspective is sometimes broader, as in considering vigilance or sustained attention as the continuous processing of information over time (Christensen & Joschko, 2001); in some other instances, definition can be more specific, including not only the focus on a particular stimulus, but the ability of excluding distractions (L. Shalev et al., 2011). Finally, empirical definitions can be given to guide comparisons across studies: for instance, Langner and Eickhoff (2013) considered sustained attention the function of stimulus processing for at least 10 second.

For the sake of clarity and completeness, in this project sustained attention and vigilance are considered synonyms and intended as the ability to maintain a focussed attention and to remain responsive to stimuli for a prolonged period of time (Warm et al., 2008).

1.3 Theoretical frameworks

In the attempt of understanding the mechanisms underlying sustained attention performance, and specifically the phenomena of vigilance decrements, more than 70 years of research have produced multiple explanatory theories (Esterman & Rothlein, 2019). Each theory relies on the assumption that sustained attention performance is influenced by multiple factors, either external or internal to the individual. Among the extensive number of existing theories, the focus will be on the overload, underload and attentional allocation accounts, together with relevant research on factors affecting performance.

Among these factors, motivation consistently plays a relevant role which will be discussed in detail in section 1.6.

1.3.1 Overload account

The resource-depletion hypothesis, the leading overload theory, explains sustained attention performance over time assuming that information processing resources are limited and that the continuous effort required in vigilance tasks (or real-world environments) overloads the available resources, resulting in poorer performance (Grier et al., 2003; Smit et al., 2004). This account attempts to explain the vigilance decrement following the main assumptions that vigilance tasks are taxing and cognitively demanding, and that they are subjectively perceived as frustrating and stressful (Helton & Russell, 2017; Warm et al., 2008). Experimentally, the sense of effort induced by these tasks has been investigated with two main approaches: the effects task parameters have on performance, and the effects of tasks on subjectively perceived effort. Since the origin of the theory, multiple types of vigilance tasks with variations in parameters and modalities have been employed to test the effects on performance (Teichner, 1974). The first systematic categorisation can be tracked in the work of Parasuraman and Warm, in the venerable *taxonomy*, where vigilance tasks are divided following four dimensions: signal type; event rate; sensory modality; source complexity. Worse performance was found associated with high event-rate, successive discrimination tasks, and complex signals (Caggiano & Parasuraman, 2004; Parasuraman et al., 1987). Further investigations on the effects of task parameters on sustained attention performance have substantially replicated this seminal evidence, providing evidence that increasing task workload and thus cognitive demands requires more attentional resources, and ultimately induces worse performance (Helton & Russell, 2013; Smit et al., 2004; Tiwari et al., 2009). Evidence of a cognitively demanding nature in vigilance tasks comes also from investigations of subjective perceptions of effort, where high levels of self-reported workload, stress, disengagement and boredom have been extensively found post vigilance tasks (Dillard et al., 2013; Finomore et al., 2016; Matthews, 2016; Scerbo, 2001).

1.3.2 Underload account

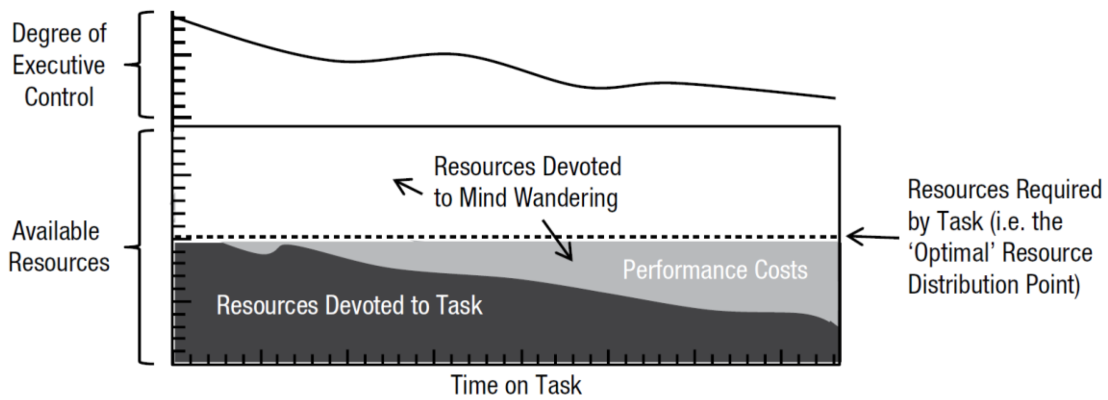
Originating from the same observation that vigilance tasks are repetitive, boring, and lengthy, underload accounts explain the vigilance decrement as the result of understimulation and underarousal, thus considering (as opposed to overload accounts) these tasks undemanding. The mindlessness theory posits that the repetitive nature of sustained attention tasks fails in maintaining the attentional focus, resulting in automatic responses (Robertson et al., 1997). More specifically, this withdrawal of attentional resources is caused by failures in the executive attention system, which is increasingly more vulnerable to task-irrelevant factors (Manly et al., 1999). While this account does not specify where exactly attentional resources would be directed to, the mind-wandering theory states that given the underarousing nature of vigilance tasks, the mind tends to be directed towards task-unrelated-thoughts (TUT), thus causing the decrement in performance (Seli et al., 2016; Smallwood & Schooler, 2006). Support for underload accounts comes from evidence that increasing task variability can stabilise the vigilance decrement (Thomson, Smilek, et al., 2015), but mostly from subjective reports of increased mind-wandering and TUTs across periods of watch in vigilance tasks (Körber et al., 2015; McVay & Kane, 2012; Seli, Cheyne, et al., 2013).The underload framework relies on the assumption that vigilance and sustained attention tasks are by nature underarousing (Thomson, Besner, et al., 2015). Therefore, manipulations of task engagement should theoretically be able to reduce the decrement in performance. Even though the topic is currently heavily discussed (Neigel et al., 2020), evidence exists that engaging the individual through physical interaction is able, in part, to lessen the vigilance decrement (Pop et al., 2012). Influences of task engagement on mind wandering and performance are also investigated through task-induced energetic arousal. While physiological arousal per se seems to be related to vigilance performance by affecting attention control via the classic U-shaped Yerkes Dodson curve (Lenartowicz et al., 2013), task engagement, operationalised as energetic arousal tracked by pupillometry, was able to predict self-reported mind wandering and performance decrements (Unsworth & Robison, 2018).

1.3.3 Attentional allocation accounts

The opportunity cost model (Kurzban et al., 2013) was formulated in the attempt of explaining the wider phenomena of mental effort and fatigue, and can be potentially applied in the context of sustained attention. It assumes that the resources at the disposal of executive control are limited, and thus the number of tasks that one undertakes is to be prioritised. Choosing one task however carries an *opportunity cost*, the value and potential benefits of the "*next-best alternative to the current choice*" (Kurzban et al., 2013). The sensations of mental effort and fatigue are therefore caused by the subjective perception of these costs (Kurzban, 2016). Vigilance decrement is explained by the over time learning of benefits and costs of the task at hand and of the potential alternatives. With time-on-task, costs of the vigilance task increase, as well as benefits of alternative tasks (e.g., mind-wandering), inducing attentional re-allocation and thus performance decrements. Combining multiple elements from the both overload and underload accounts, the resource-control theory of mind wandering (Thomson, Besner, et al., 2015) attempts to explain the full behavioural phenomena in vigilance research. It relies on a few assumptions: information processing resources are limited but do not wane over time; mind-wandering is the state to which the individual naturally tends; in order to maintain effective performance in a task and to prevent

Figure 1.2

Visual representation of the resource control theory. At the beginning of the task an optimal amount of resources are directed to task-relevant processes. With time-on-task, the executive control fails to maintain the correct devotion of resources, resulting in higher performance costs and mind-wandering. From (Thomson et al., 2015)



task-unrelated activities and thoughts, executive control actively directs cognitive resources; time-on-task causes a reduction in executive control (Figure 1.2). These two models of sustained attention can be considered complementary in the explanation of the vigilance decrement: failures in the allocation of resources by the executive system may be caused by the gradual increase of subjective costs in completing the task, resulting in increased mind-wandering (Thomson, Besner, et al., 2015).

1.4 Measuring sustained attention

The heterogeneity of definitions and models in the literature of sustained attention is directly reflected to a variety of methods of assessment of the functions.

1.4.1 Sustained attention tasks

1.4.1.1 Traditional vigilance tasks

Replicating the main features of the original Mackworth Clock test (Mackworth, 1948) described above, traditional vigilance tasks have been extensively used to study human performance over time. Sometimes called Traditionally Formatted Tasks (TFT) (Carter et al., 2013), they require participants to make a response at the presentation of targets, among distractors. They are characterised by a long duration (usually more than 30 minutes), and a very low target probability (between 5% to 20%) and event rate (usually of at least 1.5 seconds) (Parasuraman & Davies, 1977; Parasuraman & Mouloua, 1987; Teichner, 1974). Stimuli can be either visual or auditory (Paus et al., 1997). However, it is not rare in human factors research to replicate the same structure in a real-world situation like simulated unmanned aerial flights (Dillard et al., 2019; Funke et al., 2017), driving automated vehicles (Greenlee et al., 2018), or military sentry duties (McBride et al., 2007). Although applications of the original design are still found in current research (Haubert et al., 2018; Martel et al., 2014; Reteig et al., 2019), the slow pacing, low event-rate, and especially the extensive duration make the implementation of these tasks potentially inconvenient in neuropsychological investigations (e.g. in developmental disorders or brain damage) or imaging studies. To address this problem, shorter versions of the traditional tasks have been created, with overall increased event-rate (less than 1 second) and of duration lasting between 8 to 12 minutes (e.g. the Abbreviated Vigilance Task (Helton & Russell, 2011; Temple et al., 2000)). The central outcome variable for these tasks is performance accuracy of correct detections, usually measured through Signal Detection Theory metrics (sensitivity and response bias (Parasuraman et al., 1987)). Typical of overload accounts, TFTs reflect one of the two main conceptualisations of sustained attention, which highlights the ability of detecting rare and transient targets.

1.4.1.2 Continuous performance tasks

Continuous Performance Tasks (CPT) were born to investigate clinical populations and diagnose brain-damage (Rosvold et al., 1956). Similar to traditional vigilance tasks, they typically require participants to maintain their focus of attention on a continuous presentation of stimuli, and to produce a response only for targets. Many versions of CPTs exist, with different types of stimuli (letters, numbers, shapes, images) and multiple modalities (Keilp et al., 1997; Riccio et al., 2002; Rosenberg et al., 2013; Tekok-Kilic et al., 2001). Prototypical of modern CPTs, the Conners' Continuous Performance Test-II (Conners & Staff, 2009) is a 14-minute long computerised task in which letters are presented on the screen at various interstimulus intervals (1, 2 and 4 seconds), where 10% of the stimuli are targets which require participants to withhold the response (X). In contrast to TFTs, participants need to make a response to the majority of stimuli (non-targets) and withhold to rare stimuli (targets). Because of this, they are usually referred to as high GO, low NO-GO task, while traditional vigilance tasks can be identified with low GO, high NO-GO tasks. Thanks to this design it is possible to acquire significantly more data compared to TFTs, in a shorter duration of time. The Sustained Attention to Response Test (SART) (Robertson et al., 1997) is a similar alternative with a 5-minute duration and digits as stimuli, in the original implementation. Again, participants need to make a response in 90% of trials, corresponding to non-targets, and withhold in 10% of the time. A recent introduction is the gradual onset Continuous Performance Task (grad-CPT) (Rosenberg et al., 2013). Similar in design to other SART-like CPTs, it implements smooth transitions between stimuli to prevent exogenous activations of attention. Another CPT variant is the Test of Variables of Attention (TOVA), developed and frequently used for neuropsychological assessment (mostly ADHD) (Greenberg, 2011).

Interestingly, it shows features of both traditional vigilance tasks and modern CPTs: while the overall duration is 23 minutes, the first half has a low GO, high NO-GO design, while in the second half the design is inverted (high GO, low NO-GO). In these tasks sustained attention performance is usually indexed by errors of commissions, trials in which the participant fails to withhold the response. Furthermore, compared to TFT, the continuous acquisition of data allows for a detailed investigation of not only performance accuracy, but reaction times (RTs), both in overall trend and consistency over time.

1.4.1.3 Reaction times tasks

While CPTs and TFTs are mostly focused on performance indexes and overall trend in reaction times, there exists a different type of tasks which targets specifically moment-to-moment fluctuations of responsiveness and alertness. The Psychomotor Vigilance Test (PVT) is arguably the most widely implemented task in sleep-loss research (Basner & Dinges, 2011; Dinges & Powell, 1985). It is a simple 10-minutes long computerised task, during which participants are asked to press a button anytime a counter starts at random intervals (between 2 and 10 seconds). Rather than assessing sustained attention by performance accuracy, RT trend over time and variability are the core variables measured. From a different approach, the Metronome Response Task (MRT) taps into the same behavioural consistency in responsiveness (Seli, Cheyne, et al., 2013). In this task, participants are instructed to press a button in synchrony with a continuous rhythmic presentation of a tone (every 1.3 seconds). Performance indexes are abandoned, focusing entirely on reaction time variability over time. Similarly, the simple Tapping Task (Kucyi et al., 2017) requires participants to tap a button rhythmically for 8 minutes (every 0.6 seconds), following a cueing 10 seconds of metronome presented at the beginning. CPTs and especially these RT tasks are mostly implemented to test underload accounts, and explain the second main definition of sustained attention, focused on moment-to-moment fluctuations over time.

1.4.2 Behavioural measures

Although there is vast heterogeneity in the behavioural tasks used to measure sustained attention, they share two primary outcome variables: response accuracy and reaction time (RT). Approaches in the analysis of these variables either focus on overall indexes of task performance based on these two variables, or in investigating their dynamics over time. Most interestingly, time-on-task effects reveal the vigilance decrement, the most ubiquitous outcome variable to behaviourally measure sustained attention.

1.4.2.1 Performance accuracy

In traditional vigilance research, performance accuracy in correct detection is the main variable analysed. Correct rejections, hits, misses and false alarms are used to compute the classical Signal Detection Theory (SDT) metrics of perceptual sensitivity, response bias and decision criterion (Parasuraman et al., 1987). In many CPTs, given the high imbalance between targets and non-targets, SDT is not suitable for implementation. Performance is then assessed through correct omissions (correct inhibition of responses to target stimuli), commission errors (incorrect response to target), omission errors (missed response to non-target). An alternative is using hit rate (percentage of targets detected) (Matthews et al., 2017). This approach, focused entirely on overall performance measures, allows for simple comparisons across conditions, and is typically found in neuropsychological and clinical research (e.g. in ADHD investigations (K. A. Johnson, Robertson, et al., 2007), or disability (Swanson, 1981)), in sleep research (Fronczek et al., 2006; Gobin et al., 2015; Horne et al., 1983), in brain stimulation (Esterman, Thai, et al., 2017), psychophysics (Rothlein et al., 2018) as well as individual differences (Shaw et al., 2010).

1.4.2.2 Reaction times

RT analyses usually rely on central tendency measures and variability of correct responses. In the context of sustained attention research, mean RT is used in a similar fashion as overall performance measures, typically in comparing conditions (e.g. stimulus modalities (Seli, Cheyne, Barton, et al., 2012), or in sleep research (Lim & Dinges, 2008; Whitney & Hinson, 2010)). Variability in reaction times, on the other hand, yields information on consistency in responsiveness. On the individual-level, intraindividual variability (IIV) is a useful index (Jensen, 1992; Moss et al., 2016) commonly obtained through simple standard deviation (SD) or coefficient of variation

(CoV, ratio between individual standard deviation and mean RT (Carriere et al., 2010; Flehmig et al., 2007)), and interpreted as moment-to-moment fluctuations and lapses of attention (Seli, Cheyne, & Smilek, 2012). In RT-based tasks like the PVT, a quantification of attentional lapses is given by the number of trials with RT > 0.5 seconds (Basner et al., 2011; Luna et al., 2018). An increasingly more common approach, introduced to address the issue that empirical reaction times do not usually follow a Gaussian curve (Ratcliff, 1978) violating the usage of summary statistics, is distributional analysis. It entails fitting alternative curves (such as Ex-Gaussian, Gamma, Weibull) to RT data and then using distribution parameters in place of mean and standard deviation (Balota & Yap, 2011; Luce, 1986; Moss et al., 2016; Unsworth et al., 2010). Moment-to-moment fluctuations in RT can also be analysed by the application of the Fast Fourier Transform, which allows for a detail characterisation of fluctuations across multiple time-scales (Castellanos et al., 2005; K. A. Johnson et al., 2008; Riaz et al., 2016).

1.4.2.3 Vigilance decrement

From the very roots of research in sustained attention, the fundamental aspects analyses have focused on are the dynamics of performance with time-on-task. Sustained attention is characterised by deteriorations over time, both in terms of performance accuracy, as well as reaction speed, the so called vigilance decrement (Mackworth, 1948; Parasuraman et al., 1987; Warm et al., 2008). In addition to that, especially in recent times, evidence has shown that performance fluctuates over time and that these fluctuations are affected by time-on-task (M. S. Clayton et al., 2015; Esterman et al., 2013). To investigate the vigilance decrement, the essential requirement is to divide the whole task performance by time or by trials into bins. Then, analyses across bins can be done to test time-on-task effects. Arguably, the most common method is to carry an analysis of variance (ANOVA) on performance accuracy, mean reaction times or intraindividual variability depending on the specific paradigm implemented (Haubert et al., 2018; Reteig et al., 2019; Unsworth et al., 2010; C. Wang et al., 2014). A finer grain analysis of RT trend over time (although possible on performance measures as well, but between blocks similar to ANOVAs), consists in fitting mixed effects models (an extension of traditional linear models) to the data, and using the slope as a measure of the decrement (slower RTs) over time (Löffler et al., 2018; Robison & Brewer, 2019; Unsworth & Robison, 2016). To examine moment-to-moment fluctuations of attentional stability on a detailed level, an alternative approach is computing the variance-time-course, normalising RTs on a trial-level, and then smoothing the resulting curve (Esterman, Poole, et al., 2017; Rosenberg et al., 2013).

1.5 A problem of definition (2)

Following on section 1.2, it should now be clear to the reader that the methodology to measure sustained attention is particularly rich of alternative approaches. This variability stemmed from the fact that, although "*Everybody knows what attention is*" (James, 1890), the experience individuals have of sustained attention is purely subjective and a standardised, objective definition is yet to be formulated and is currently a topic of debate (Fraulini et al., 2017; Thomson et al., 2016). Sustained attention is in fact a latent psychological construct, "*assumed to be reflected in test performance*" (Cronbach & Meehl, 1955): an intangible construct, not directly measurable, but only observable through behaviour. Operationalising means defining a latent construct through a set of "*concrete operations*" (Stevens, 1935) that can be empirically reproduced. In Psychology these operations usually include a procedure (e.g., long experimental sessions), a task (e.g., the SART) and an outcome variable (e.g., number of correct responses). The resulting conception through methodology, although fundamental to build empirical knowledge (Bergmann & Spence, 1941), introduces three dimensions dependant on the subjectivity and the needs of the researcher: procedure, task, variable.

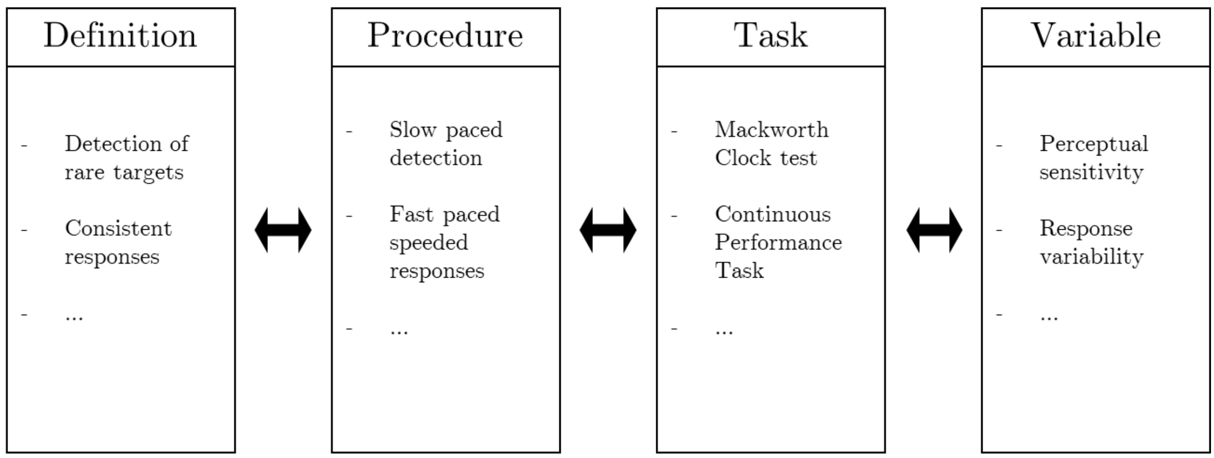
For instance, in his previously mentioned seminal research, Mackworth (1948) was interested to understand the ideal amount of time after which attention would wane and participant's performance would be impacted in the applied setting of airborne radar operators. He therefore designed a test in which participants would look at a pointer moving in 1-second steps around a clock figure. At times, the pointer would skip a step (i.e., jumping at 2 seconds) and participants were instructed to press a button whenever they detected the unusual target movement. This test, which he called

Clock test, would then last for 2-hours to recreate the difficult requirements of a radar operator. He would then quantify performance by looking at the proportion of missed targets over time. As another example, Robertson and colleagues (1997) measured sustained attention using the Sustained Attention to Response Task (SART), which displayed a random number for each trial in fast presentations, lasting less than 5 minutes. Participants were required to produce a response for each number except for the number 3, which appeared very rarely. The task was designed to investigate the phenomenon of slipping attention, and the outcome variable was the number of failures of inhibition (participants making a response for the number 3).

These examples, among many found in the literature, exemplify how depending on the intentions of the researcher, different methods can be ideated to measure the construct of interest. To these methods, or operations, corresponds the respective operationalisation of the construct. This subjectivity, however, introduces a problem of *translation validity* (Slife et al., 2016), a subset of construct validity: how close is the operational definition to the original psychological construct in its sets of operations? And more importantly, how comparable are different interpretations of the concept's meaning and the resulting operationalisations formulated to measure it? Different operationalisation should, in fact, be reconducted to the starting construct of interest (Figure 1.3) indicating a task-general construct. However, instead of being appropriately verified, it is usually, wrongly, assumed. The assumption is immediately contested by the possibility, frequently found in the literature, of using the same methods to operationalise different constructs, such as using the CPT to measure impulsivity (Behforooz et al., 2017), inhibition (Overtoom et al., 1998) or executive control (Unsworth et al., 2010). So, how does one validate the use of a specific operational definition? A potential approach of validation is offered by the Multitrait-Multimethod matrix (MTMM (D. T. Campbell & Fiske, 1959)). In this framework, the construct validity of a set of measures is assessed by evaluating convergent and discriminant validity. The former refers to the degree to which variables that are theoretically related, are found interrelated in practice. The latter, on the other hand, is the degree to which variables that should not be related in theory, are as well not related in practice. Another possibility entails assessing the *nomothetic span*, which refers to the relationships between the measures of a test (supposed to tap onto a construct), with other measures (Whitely, 1983). From this perspective, measures of one construct that are theoretically related to measures of another construct, should empirically be related. These relationships can be evaluated with multiple methods, from simple correlations to more complex structural equation models.

Figure 1.3

Definitions through operationalisations. Operational definitions of a psychological constructs entail the set of operations used to define it. These operations include a procedure, task and variables. The process should however be bidirectional and different operations should reconcile in the starting construct of interest.



1.5.1 Evidence of validation

Examining the literature, a clear gap appears: a proper examination of the validity of different operationalisations of sustained attention is yet to be undertaken. Using a MTMM as an interpretational framework, a proper investigation should, in fact, include multiple methods (tasks) and multiple measures (variables). Existing studies only partially tested the validity of the assumption of translation validity.

A recent study attempted to validate multiple tasks measuring attention, and including sustained attention (Treviño et al., 2021). Using a large sample size (n = 636), they collected data from both experimental and neuropsychological tests. Sustained attention was measured by dprime in the gradCPT (Rosenberg et al., 2013). With a two-step analysis, firstly employing Exploratory Factor analysis and then Confirmatory Factor Analysis to evaluate the model, they found that one factor which they called *sustained* loaded on, and only, the gradCPT dprime. Another large factor analysis on an attention and intelligence dataset used two tasks to assess sustained attention (Burns et al., 2009), the Sustained Attention to Response Task (Robertson et al., 1997) and the Test of Variables of Attention (TOVA, (Greenberg, 2011)). Their structural equation model, which fitted the data well, included a common factor explaining variables from both sustained attention tasks. These studies supported the notion that sustained attention might be a task-general cognitive construct, however they were both restricted in employing a single variable per task.

In fact, although tasks are designed to measure a specific construct, it does not seem to be suitable to assume that all variables extracted from task data refer to a unitary latent construct. A recent study attempted to investigate the underlying latent structure of a dataset obtained with the Conner's CPT. Employing a large, mixed clinical/general population dataset, Egeland and Kovalik-Gran (2010) extracted measures of speed, accuracy, errors and changes in variables over time and ran a principal component analysis. They found a solution that included 5 components, showing that CPT data is driven by multiple underlying factors (Egeland & Kovalik-Gran, 2010b, 2010a). Another recent study ran a similar analysis on the gradCPT using a very large (> 10.000) and representative sample size. It was found that driving performance in the gradCPT there was not a unitary factor, but two distinct ones (Fortenbaugh et al., 2015). Although the two above studies both investigated the structure of datasets obtained from a CPT, the resulting solutions were not equivalent probably due to differences in the design of the tasks (Conner's and gradCPT). Another work, on the other hand, found that all variables extracted from a CPT were explained by a single underlying factor (Mirsky et al., 1991). It hence seems that multiple factors might be measured by computerised tasks, and that specific task-differences influence the variable structure. Having acknowledged these differences, is it still possible to find a task-general construct?

A more recent investigation provides a partial answer to the issue in what is perhaps the closest application of an MTMM approach. Unsworth and colleagues (2021) collected data from a large (n = 358) sample of participants who performed a large number of computerised tasks and questionnaires. These included multiple tasks assessing sustained attention (such as the SART and the PVT), cognitive control, working memory. Their factor analysis showed that effectively a latent factor explained all the variables of attentional lapses across tasks (Unsworth et al., 2021). Additionally, they showed some evidence in terms of nomothetic span, where the factor correlated with other cognitive domains as hypothesised (refer to section 3.1.1 for more information on nomothetic span). Nonetheless, the study was limited such that from the design stage, the interest of the researchers was in the specific aspect of sustained attention of attentional lapses which includes only a set of potential variables extracted from the tasks. This approach also precluded the inclusion of the more traditional tasks, such as the Mackworth Clock test, which refers to the capacity of detecting rare targets and is not ideal for measuring lapses.

To summarise, no existing study has examined the validity of different operationalisations of sustained attention appropriately, and it is therefore not yet possible to conclude that a task-general facet exists. Chapter 3 will attempt to address the issue.

1.6 Sustained attention and motivation

Sustained attention supports most daily activities, such as driving (Walker & Trick, 2018), long-distance flights (Naeeri et al., 2019), airport security monitoring (Meuter & Lacherez, 2016), or serving in the army (Wilson et al., 2015). Sustaining attention for an extended period of time, however, is difficult, it requires effort and is intrinsically fallacious (Warm et al., 2008) resulting in distractions, attentional lapses, errors and the vigilance decrement. Losing focus during some of these activities can result in potential security breaches (Hancock & Hart, 2002), failures of military operations (McBride et al., 2007), or even a nuclear meltdown (Reinerman-Jones et al., 2016). It is then unsurprising that a significant portion of literature of sustained attention has attempted to find the factors mediating performance, both in and out of the laboratory (Ballard, 1996; Claypoole et al., 2019; Gartenberg et al., 2018; Parasuraman & Davies, 1977), and to investigate techniques and approaches to improve performance (Al-shargie et al., 2019). Improving one's ability to maintain a focused state of mind for an extended period of time would not only avoid incidents or unwanted events, but increase in safety, productivity and overall quality of life. Among the many possible methods to defeat the vigilance decrement, manipulation of the difficulty (Marty-Dugas et al., 2020) or the monotony (Thomson, Besner, et al., 2015) of the task at hand, the administration of caffeine (Cooper et al., 2020), neurostimulation with transcranial direct current stimulation (McIntire et al., 2014), exercise and yoga (Sheela et al., 2013), mental training (Lutz et al., 2009) and video games (Szalma et al., 2018) have been proven effective in improving performance in sustained attention.

A particularly relevant candidate is motivation. Most of the methods listed above, although undeniably useful, might not be easily employed in empirical settings. Motivation, on the other hand, would prove particularly flexible: for instance, if motivation was considered in relation with reward, it would be useful for an employer to balance compensation and performance of their employees; alternatively, if motivation was considered in terms of individual differences, it would be useful as a screening tool to allocate appropriately to the right role. Additionally, the concept of motivation is admitted in each of the theoretical models of sustained attention, in different forms. The understanding of the relationship between motivation and sustained attention would hence provide not only empirical applicability, but also theoretical implications. Before examining the existing evidence, the next section will provide a general introduction to the concept of motivation.

1.6.1 Motivation: definitions and dimensions

Motivation is another difficult concept to define. Different theories, models and perspectives can be found in the literature. For instance, in the early 1900s, drive and drive-reduction theories intended motivation as a biological aversive state that directed behaviour to reduce an unpleasant state (e.g. thirst or anger) (Hull, 1951). Alternative views saw motivation as the biological drive to anticipated positive states (Toates, 1986). Referring directly to the origin of the word motivation, which in Latin means movement (movere), it was considered the study of the "*contemporary (immediate) influences on the direction, vigour and persistence of action*" (Atkinson, 1964). Expanding on that, motivation can also be defined as the "*set of independent/dependent variable relationships that explain the direction, amplitude, and persistence of an individual's behaviour* [...]" (J. P. Campbell & Pritchard, 1976). The shared aspect of these definitions is that motivation drives behaviour towards an anticipated goal state, and that motivation is not a unitary variable, but includes multiple dimensions.

1.6.1.1 Intrinsic and extrinsic motivation

Although past and current topic of debate (E. A. Locke & Schattke, 2019; Reiss, 2012), a potential dissociation between motivational dimensions is between intrinsic and extrinsic motivation. Using the words of Ryan and Deci, intrinsic motivation can be defined as "*the doing of an activity for its inherent satisfactions rather than for some separable consequence*" (Ryan & Deci, 2000a). In this sense, intrinsically motivated humans find enjoyment in the doing, rather than the specific outcome: it is the "*inherent tendency to seek out novelty and challenges, to extend and exercise one's capacities, to explore, and to learn*" (Ryan & Deci, 2000b). On the other hand, extrinsic motivation can be considered the "*construct that pertains whenever an activity is done in order to attain some separable outcome*" (Ryan & Deci, 2000a). Therefore, intrinsically motivated individuals engage in a behaviour for the enjoyment of doing it; extrinsically motivated individuals engage in a behaviour for the instrumental gain.

1.6.1.2 Trait and state motivation

The construct of motivation can also be seen in terms of trait/state dichotomy (Wasserman & Wasserman, 2020b). A trait is usually considered in psychology as a construct closer to being part of an individual's personality, an internal *disposition* that remains mostly unchanged in the lifespan. Traits might determine individual differences in the tendency to act in specific ways in certain situations. A state, on the other hand, is a temporary *occurrence*, a sporadic act, mood or behaviour that does not last longer than a few hours (Csizér & Albert, 2021; Fridhandler, 1986).

Applied to the context of motivation, the dichotomy trait/state can be found mainly in the intrinsic aspect. Intrinsic motivation as the natural tendency to engage and persist to an activity for its inherent joy, can both be seen as trait and a state: individuals might be characterised by a natural, dispositional tendency to find enjoyment in the activity, rather than in the outcome; at the same time, however, this tendency might show temporary fluctuations. Trait and state intrinsic motivation are correlated constructs (Kawagoe et al., 2020), but separated (Choi et al., 2012): state intrinsic motivation could be considered the result of an interaction between trait intrinsic motivation and immediate environmental and psychological factors (Tremblay et al., 1995). Extrinsic motivation, conversely, is usually considered in relation to an external reward, and it is therefore associated to a short-term state.

1.6.2 Motivation effects on sustained attention

Motivation has a significant role in the theoretical accounts of sustained attentions as it can be found in each of the models. For the sake of clarity, theoretical accounts and evidence of different dimensions of motivation will be presented in separate paragraphs.

1.6.2.1 Intrinsic motivation

Intrinsic, state motivation is particularly relevant for the overload accounts, which states that sustained attention is dependent upon a limited pool of cognitive resources, and that sustained attention for an extended period of time is difficult and stressful (Warm et al., 2008). These resources, although of difficult (and sometimes ambiguous) definition, have been associated to arousal (Matthews et al., 1990) and to the construct of task-engagement (Matthews, 2021). This construct relates to a state of the individual of commitment to effort, as they strive to accomplish the task at hand. It comprises elements of arousal, interest in the task, concentration (avoidance of distraction) and critically state intrinsic motivation. From this perspective, intrinsic motivation can then be considered as a marker for resource availability which can be directed to the sustained attention task. Higher intrinsic motivation, and task engagement, should then be associated to better overall performance (Szalma & Matthews, 2015).

Although not as clearly defined, a role of intrinsic motivation can also be found in other theoretical perspectives of sustained attention. The underload account proposes an opposing view to the overload perspective, explaining sustained attention failures in terms of under stimulation due to the low demanding nature of computerised tasks (Manly et al., 1999; Robertson et al., 1997). As a consequence to the low engagement to the task, attention drifts away towards alternative, more interesting activities, such as mind-wandering (Smallwood & Schooler, 2006). In this context, a combination of trait/state intrinsic motivation might indicate less susceptibility to the boring aspects of sustained attention tasks: more intrinsically motivated individuals might be able to find more value in the task at hand, and therefore would resist the tendency to drift towards a mindless state (Thomson, Besner, et al., 2015).

1.6.2.1.1 Evidence of intrinsic motivation effects

In most domains of cognitive performance, the more intrinsically motivated, the better participants will perform. A recent, large meta-analysis based on a sample size of more than 200,000 participants showed that intrinsic motivation is a consistent positive predictor of performance in a multitude of cognitive tasks (Cerasoli et al., 2014). Intrinsic motivation is also a reliable predictor of persistence and productivity at work (Grant, 2008), of school achievement (Taylor et al., 2014), of employee outcomes (Kuvaas et al., 2017), creativity and innovation (Fischer et al., 2019). In sustained attention, research on intrinsic motivation effects has been neglected focussing mostly on extrinsic motivation, and the existing literature is insufficient to clarify the influence of intrinsic motivation of sustained performance.

Most of the publications come from the overload account school which employed the Dundee Stress State Questionnaire (DSSQ, (Matthews et al., 2002)) to measure intrinsic motivation as part of a larger factor of task engagement. This line of research showed a general, overarching finding that task engagement is a predictor of sustained attention performance. For instance, DSSQ scores of task engagement predicted overall performance accuracy in multiple works (Helton et al., 2009; Matthews et al., 2014; Matthews & Campbell, 2009; Reinerman et al., 2006, 2007). At times, engagement also predicts not only overall measures, but also the vigilance decrement over time (Shaw et al., 2010). Nonetheless, task engagement is a high-level DSSQ-factor and includes, as mentioned above, multiple sub-states.

Studies only utilising the raw indices of motivation obtained from the DSSQ are lacking. A recent study attempted to find intrinsic motivation correlates of sustained attention performance across two different tasks. It was found that intrinsic motivation predicted performance accuracy in both tasks (Neigel, Claypoole, & Szalma, 2019). Another study which used the DSSQ, however, failed to detect any relationship between intrinsic motivation and vigilant performance (Cardeña et al., 2015). Utilising a different measure of intrinsic motivation, a recent study also did not find any relationship with performance (McGough & Mayhorn, 2022). With the existing literature it is hence not yet possible to conclude whether intrinsic motivation really influences sustained attention performance.

1.6.2.2 Extrinsic motivation

Extrinsic motivation has a more prominent role in the resource allocation accounts of sustained attention. These models explain performance in terms of allocation of cognitive resources over the course of the task at hand (Thomson, Besner, et al., 2015). This operation, ran by an executive control system, is, however, effortful and with time individuals tend to allocate resources to alternative, easier and more appealing activities such as mind-wandering. The effort, and the resulting ease of re-allocation of resources to distraction, can be viewed in terms of a dynamic trade-off between perceived costs and benefits (Kurzban et al., 2013). These models explicitly assume that manipulating extrinsic motivation through some sort of reward will increase the perceived benefits while reducing the costs, hence supporting performance on the task. This prediction is also admitted, although not as clearly, by underload models: more extrinsically motivated participants will drift less easily to distraction as they would find more engagement in the task (Robertson et al., 1997).

Interestingly, overload models provide a different prediction on the effects of extrinsic motivation on performance. Although intrinsic motivation is used as an index of processing resources, as mentioned above, extrinsic motivation may actually not improve performance. Stepping into the neuroscience of attention, overload account explains resource allocation (and the vigilance decrement) in terms of cerebral blood flow velocity in a system of areas mainly located in the right hemisphere (Shaw et al., 2013; Warm & Parasuraman, 2009). Part of these areas have been found with an increased neural activation following reward (Engelmann et al., 2009): motivation would lead to increased effort with increased activation, a faster usage of cognitive resources and therefore a worse performance over time (Smit et al., 2004).

Compared to the effects of intrinsic motivation, extrinsic motivation might have an even higher influence on sustained attention performance due to the very nature of the task-requirements. These tasks are in fact repetitive, simple and do not rely on complex cognitive operations in order to be completed. They are a good example of *quantity* tasks. *Quality* tasks, on the other hand, tend to require more cognitive effort, are more complex and engage more intensively. Motivational theories such as the Self-determination theory (Ryan & Deci, 2000b) and extensive evidence point towards an interaction between motivation type and task type: if intrinsic motivation is believed to affect quality tasks more, extrinsic motivation through external incentives is more relevant in quantity performance (Gilliland & Landis, 1992).

1.6.2.2.1 Evidence of extrinsic motivation effects

Extrinsic motivation through manipulation of reward has been associated with improved performance across several domains such as memory (Miendlarzewska et al., 2016), learning (Ortega-Arranz et al., 2019), creativity (Eisenberger et al., 1998), performance of employees (Ibrar & Khan, 2015) and students (Hidi & Harackiewicz, 2000). As predicted (see section 1.6.2.2 above) a recent large meta-analysis indeed confirmed that when the focus of the performance is on quantity, as in sustained attention tasks, extrinsic motivation predicts more variance than intrinsic motivation, especially when the incentives are directly tied to performance (Cerasoli et al., 2014; Jenkins Jr. et al., 1998).

In the literature of sustained attention, the effects of extrinsic motivation are studied by introducing a reward which could be monetary or of a different nature. This manipulation either takes place before the beginning of a computerised task or throughout, and can be based on speed, accuracy or both. The overarching finding is that increasing extrinsic motivation, performance improves. For instance, Sipowicz et al. (1962) found that the possibility of obtaining an additional compensation upon an excellent (in terms of detection of targets) performance increased accuracy and decreased variability of responses. Similar results were found in Corkum et al. (1996), where reward increased performance sensitivity. More recently, Esterman and colleagues (2014) studied the effect of both a monetary and a time reward on sustained attention performance. In multiple experiments where they offered participants either a monetary compensation, or a shortening of the task based on their performance, they found that reward improved accuracy and response variability (Esterman et al., 2014). Additionally, they found that although overall indexes of performance were affected by motivation, the vigilance decrement was still present in each condition.

It is indeed fundamental to examine performance from multiple perspectives, and not limit the analysis to specific indices, to obtain a clearer picture of how reward affects sustained attention. A few other studies considered the temporal dimension of sustained attention performance. Bergum and Lehr (1964) saw that with a monetary reward, performance at the beginning of the task was higher for the motivated participants, but as time on task increased, performance levelled with the control group (Bergum & Lehr, 1964). Another more recent study manipulated reward only towards the end of the experimental session: 60 minutes after starting the task, participants were informed of the potential of obtaining additional compensation. This was followed by an increase of performance which, however, did not reach initial levels and was immediately followed by a decrement (Reteig et al., 2019). This evidence seems to point towards a resource explanation: motivation improves performance but is not effective over time due to the limited cognitive resources, which cause a vigilance decrement.

Nonetheless, the evidence does not exclude a resource allocation account. Others studied the effects of reward administered towards the end of the task, and found that performance was restored to ideal levels directly challenging the resource account (Hopstaken et al., 2015). Comparing performance between a sample of students who obtained a compensation through university credits, and a sample of paid individuals, the monetary compensation prevented a vigilance decrement (Tomporowski & Tinsley, 1996). A recent study tested multiple forms of monetary reward and found that with a large, unexpected reward, participants were able to maintain stable performance over time (Esterman et al., 2016). A resource allocation explanation therefore is more fit for the current evidence: reward interacts with the balance between costs and benefits of the task directing attention appropriately. The picture is however not completely clear. A recent study directly tested this hypothesis by measuring the subjective cost of performance. What was found was an increase in performance following reward, however the vigilance decrement was still present (Massar et al., 2016). It is hence not possible to conclude that the magnitude or type of reward could explain the discordance of findings: some decisive, additional factor is yet to be found.

1.6.3 The bottom line: open questions in motivation research

The literature does not provide a robust, replicable answer to the relationship between motivation and sustained attention both regarding the intrinsic and the extrinsic factors and further investigation is required. Several factors need to be included to the picture.

Firstly, looking at intrinsic motivation, disagreement is found in the literature regarding the predicting value of intrinsic motivation on sustained performance. How can the inconsistent results be explained? An answer could be found in the employed methodology. All of the research that found an effect of intrinsic motivation on sustained attention performance implemented tasks with a very low signal-to-noise ratio (signal probability 0.02 – 0.20) (Helton et al., 2009; Matthews et al., 2010; Shaw et al., 2010). This is usually characteristic of the traditional vigilance tasks (see section 1.4.1.1, where these tasks were introduced). The two studies that failed to see an effect, on the other hand, both employed the SART which required participants to respond much more often (probability around 0.90). It might then be possible that effects of intrinsic motivation on sustained attention are mediated by task requirements, and specifically by the target rate. Furthermore, the SART, an example of CPTs, is usually found in the context of the underload accounts, whereas traditional vigilance tasks are more employed by the overload account. In order to more clearly understand the role of intrinsic motivation in sustained attention performance, it would be required to control for target rate. This would also provide a bridge across the two models, eliminating the clearer methodological difference from the equation.

Secondly, the literature is not clear on the effects of extrinsic motivation on performance. Existing evidence failed to consider all the factors that might mediate this relationship and explain the discordant results across studies. Although most of the more recent work tended to agree on a resource-allocation account of performance (Esterman et al., 2016), an alternative would be a combination of the resource allocation approach and the classic resource limitation account (Lenartowicz et al., 2013): participants direct attentional resources based on the trade-off of subjective costs and benefits, however the pool of resources would be limited, in contrast to what is normally hypothesised in the allocation accounts (Thomson, Besner, et al., 2015). This perspective would provide an essential role to individual differences in intrinsic motivation, if considered as indicative of resource availability (Matthews, 2021). Accounting for intrinsic motivation is also motivated by research that points towards the potential interaction between extrinsic motivation through reward and individual differences in intrinsic motivation: from a neuroscientific perspective, activation of areas associated with reward and attention are mediated by individual differences in intrinsic motivation (H. S. Locke & Braver, 2008); from a more theoretical perspective, rather than an additive relationship, an interaction between intrinsic and extrinsic motivation has been hypothesised by which motivating individuals with an external reward might impact their commitment to the task (Deci, 1972), a perspective that some believe to be essential in vigilance research (Hancock, 2013).

Finally, resource allocation accounts (and underload models in general) posit that when the executive system fails to direct resources to the task at hand, the unideal allocation to alternative activities such as mind-wandering would be accompanied by attentional lapses (Manly et al., 1999). Studies mentioned in section 1.6.2.2.1 (studies with evidence of extrinsic motivation effects), however, did not include measures of attentional lapses in the analyses, potentially missing on relevant information. Although many of these studies utilised measures of attentional variability (such as standard deviation or coefficient of variation), recent research suggests there are more appropriate ways of operationalise attentional lapses such as Ex-Gaussian parameter tau (Yamashita et al., 2021). Additionally, evidence identifies attentional lapses as an important variable with clinical significance (Gallagher et al., 2015; Machida et al., 2022), and shows how lapses might be the more appropriate operationalisation of sustained attention across different computerised tasks (Unsworth et al., 2021). It is hence important to include multiple behavioural variables to the analysis in order to obtain a complete account of the effects of motivation on sustained attention performance.

1.7 Attentional oscillations and motivation

The final aim of the project consisted in looking at sustained attention data from an oscillatory perspective, consistently with the general intention of moving beyond traditional methods of analysis. A new approach will be presented, together with a potential link to motivation.

As extensively discussed in the present chapter, IIV is usually computed as overall indexes of performance by collapsing the trial-level RT data to indices such as standard deviation and coefficient of variation. This method however fails to characterise the more dynamic dimension of variability which unfolds across the length of the task and is based on the statistical assumption that RT variability can be considered random response noise. The shortcoming of this approach is revealed when considering that human cognition, as all biological systems, does not exhibit randomness but is characterised by dynamic periodicities over multiple timescales (Van Orden et al., 2003).

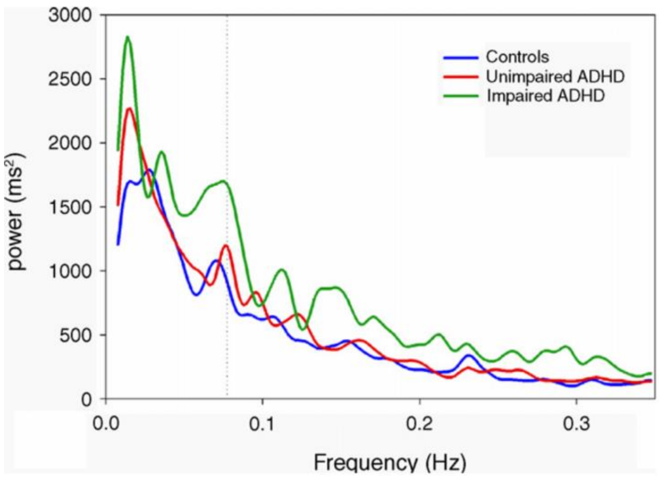
The idea that sustained attention performance might not just deteriorate over time (the vigilance decrement), and that it could periodically fluctuate, was suggested by the extensive evidence that cognition works rhythmically (N. Shalev et al., 2019). More specifically, sustained attention has been linked to the coordinated activity of multiple functionally relevant cortical oscillations (M. S. Clayton et al., 2015). Among the range of observed frequencies, alpha (8-14Hz) and theta (4-8Hz) have been most commonly detected in electrophysiological recordings, and have been associated with the idea of dynamic attention as fluctuating with the underlying brain rhythms (VanRullen, 2018). Remarkably, recent advancements in behavioural paradigms have allowed dense recordings of data with a temporal resolution comparable to neurophysiological recordings (Kienitz et al., 2021). This permitted researchers to find theta-related oscillations in both physiological data and behaviour (Dugué et al., 2016).

1.7.1 Infraslow behavioural oscillations

Although not within the traditional frequency ranges, infraslow frequencies ($>$ 0.10Hz) also seem to be as relevant in sustaining attention and can be detected even in traditional behavioural tasks. The most common method to investigate oscillatory patterns in behavioural data is spectral decomposition. This method, usually implemented using the Fast Fourier Transform (FFT), entails extracting the relevance (power) of the oscillatory curves (characterised by a period, or frequency) which, if combined, result into the original signal. In the obtained curve, if any periodic, recurring changes is present in the RT data, they will be shown as peaks of strength at the specific frequency. Remarkably, increased peaks were found between the interval of 0.02 and 0.07Hz, and centred around 0.05Hz, in clinical samples with sustained attention deficits, compared to the controls (Figure 1.4) (Castellanos et al., 2005; Di Martino et al., 2008; Vaurio et al., 2009).

What is driving these very-slow oscillations? A potential hypothesis comes from the observation of a large network of brain areas including the ventral medial prefrontal cortex, the dorsal medial prefrontal cortex and the posterior cingulate cortex, which are particularly activated during introspective states, and deactivated during goal-directed attention (Raichle et al., 2001). This network, called Default Mode Network (DMN, or task-negative network) has been extensively studied in the last 20 years (Raichle, 2015), and seems to be particularly relevant in explaining the brain correlates of sustained attention. More specifically, its patterns of activation have been associated with a strong anticorrelation (high negative correlation) with another large scale brain

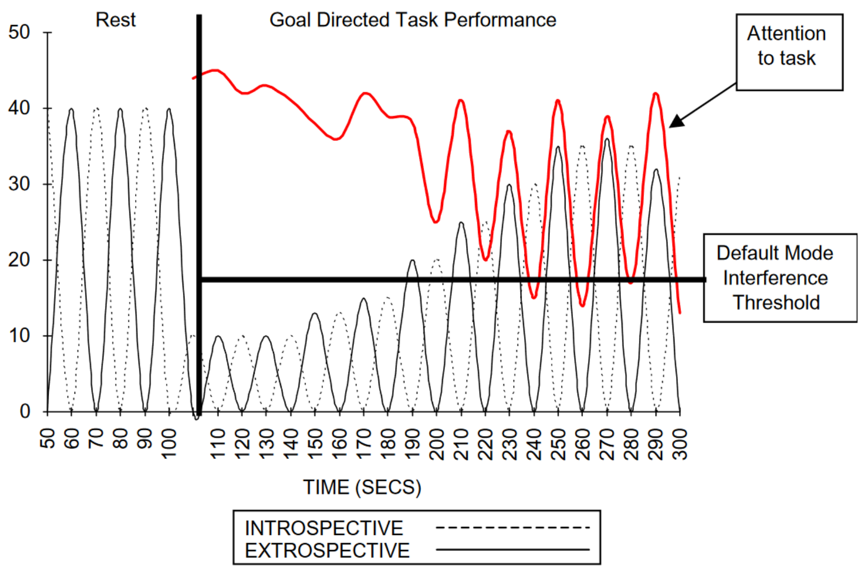
Figure 1.4
Spectral curves of RT data obtained from healthy controls and ADHD participants. The Y axis represent spectral power; the X axis the corresponding frequency. It is clear the impaired ADHD group showed higher overall power and that wider differences are located at frequencies < .01Hz. From (Johnson et al., 2007)



network which comprises areas of the dorsal attention network (DAN) (Fox et al., 2005). This network of areas, referred to as task-positive network, is usually active during attention tasks, compared to default/baseline, and its activation supports attention performance (Lanssens et al., 2020).

Figure 1.5

Representation of the DMN interference hypothesis. As one begins a demanding task, the DMN deactivates and the DAN activates, however, as time-on-task increases the DMN might reactivate interfering with task-positive areas. Its activity follows slow-oscillations which are reflected in oscillatory behaviour. From (Sonuga-Barke & Castellanos, 2007).



Following this observation, sustained attention performance should then be characterised by a reciprocal relationship and antagonism of this large network of areas: if in the resting phase, the DMN is active, as the individual requires attention for a task, the DAN activates and the DMN deactivates. In other words, the brain toggles between an introspective, self-directed state (with DMN activation) and an extrospective, task-dependent state (with activity of the DAN) (Fransson, 2005). If the DMN fails to deactivate during goal-directed attention, an interference will take place and unideal performance will follow (Sonuga-Barke & Castellanos, 2007): attentional lapses (Weissman et al., 2006) and mind-wandering (Poerio et al., 2017) are associated with reduced deactivation of the DMN (Figure 1.5). The final piece of the puzzle is the finding that activation of the DMN follows a familiar multi-second temporal frequency (< 0.1Hz) (Fox et al., 2005).

Although the link between DMN interference and attentional lapses was of speculative nature, some preliminary evidence of a direct association between DMN and behavioural association has recently been provided: using fMRI, a recent study showed that while the task positive network was activated during a sustained attention task, the DMN fluctuated over slow frequencies (< 0.1Hz); additionally the same oscillations were found in RT variability, and correlated with DMN activity (Zhang et al., 2022).

1.7.2 A link to motivation

Extensive evidence has shown that it is possible to counteract the higher variability found in clinical populations with sustained attention deficits by administering stimulants such as methylphenidate (Coghill et al., 2014). In addition to reducing overall variability, stimulants seem to be able to modulate the oscillatory behaviour of RT making it comparable to general levels (Castellanos et al., 2005; K. A. Johnson et al., 2008), by targeting dopamine transporters and increasing overall levels of dopamine (Volkow et al., 2004). In turn, dopamine facilitate DMN deactivation (Liddle et al., 2011; Tomasi et al., 2009), which is essential for ideal sustained attention performance.

DMN activation should not be modulated only by stimulants, but additional factors both state and task related should also influence the degree of attenuation (Sonuga-Barke & Castellanos, 2007). Recent evidence suggests that it might, in fact, be the case. Based on the observation that higher task-engagement is accompanied by an higher degree of deactivation of the DMN (McCormick & Telzer, 2018), recent work attempted to manipulate task engagement through gamification, and showed that with higher engagement, performance improved with more effective deactivation of the DMN (Howard-Jones et al., 2016). Additionally, motivational reward manipulations have been shown to modulate DMN deactivation (Liddle et al., 2011), potentially through dopaminergic mechanisms (Berridge & Robinson, 1998).

It should now be clearer why this perspective is relevant for the present project, which is focused on the effects of motivation on sustained attention performance. Since reward and individual differences in state variables have been shown to modulate DMN deactivation, corresponding reduced behavioural oscillations should also be found. The current project therefore investigated the potential effect of motivation on attentional fluctuations to not only contribute to the limited literature of infraslow behavioural oscillations, but to explore a new way in which motivation might influence sustained attention performance.

1.8 Summary and research questions

The project attempted to answer several research questions which will be summarised below.

Chapter 3 The relationship between motivation and sustained attention is yet to be clearly identified, however, before even attempting further investigation, it is essential to acknowledge the vast variability in the methods, tasks, variables and, in general, the definitions attributed to sustained attention. Without a clear identification of what the best operationalisation of sustained attention is, findings obtained from a specific combination of tasks and variables might result in study-specific findings, without the possibility of comparisons. Therefore, the first phase of the project investigated different operationalisations of sustained attention obtained from multiple methods of assessment and attempted to find a task-general construct.

- Study 1 examined the underlying factors of a sustained attention task.
- Study 2 investigated whether a shared task-general factor could be found across multiple sustained attention tasks.

Chapters 4, 5: The second part of the project was focussed on furthering the understanding of the titled relationship by building on existing research on the topic, whilst improving on the typical methodology. More specifically, it is not clear exactly how intrinsic motivation interacts with sustained attention as existing, contradictory findings might be due to methods-related factors. Additionally, the trait-level dimension of intrinsic motivation has never been considered in the literature. On the extrinsic side of motivation, research has been more extensive but failed to account for unexpected results. With guidance from Chapter 3, this part investigated how reward impacts the task-general metrices of performance, whilst also controlling for state-related individual differences in intrinsic motivation.

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- Study 3 explored how trait-intrinsic motivation influences sustained attention performance across multiple tasks.
- Study 4 looked at state-intrinsic motivation influences on sustained attention, while controlling for task-specific factors.
- Study 5 tested the effects of reward and intrinsic motivation on a non-traditional sustained attention task.
- Study 6 investigated reward and state intrinsic motivation effects on a traditional CPT.

Chapter 6 Finally, the third part of the project explored the oscillatory side of sustained attention performance, by applying a recent neuro-biological hypothesis that links very slow oscillations in behaviour to oscillations in a large-scale brain network. Both the effects of intrinsic and extrinsic motivation were investigated, to test whether the hypothesis could be applied to the general population.

- Study 7 tested the effects of intrinsic motivation on oscillatory behaviour.
- Study 8 tested how reward might affect oscillatory behaviour.

Chapter 7 Although not directly part of the project, this application chapter was an example of how oscillatory behaviour could be investigated in clinical populations (specifically, mood disorders).

- Study 9 tested whether sustained attention oscillations are a condition-specific endophenotype.

Chapter 2 - Methodological notes

This part of the document will report a short, empirical description of the most relevant techniques and approaches implemented in the project. All phases of data wrangling, manipulation, analyses and plotting were performed using the R programming language (R Core Team, 2021) and several additional libraries including the *tidyverse* suite (Wickham et al., 2019), *lme4* (Bates et al., 2015), *ggpubr* (Kassambara, 2022) and *psych* (Revelle, 2022).

2.1 Characterising sustained attention

In order to obtain an appropriate representation of sustained attention, multiple variables can be calculated from the data extracted from computerised tasks. These variables should represent overall performance accuracy, variability, speed and changes over time. An overview of the variables usually found in the literature can be seen in the section 1.4. The present section reports practical notes only.

2.1.1 Performance accuracy

One of the aspects of performance that needs to be quantified is accuracy. It can be quantified in multiple ways, depending on the researchers' preferences, and the task requirements. It can take the form of positive indexes such as the number or proportion of correct responses, or negative indices including errors or missing responses. An approach that would produce useful overall indices of performance is Signal Detection Theory (SDT, (Macmillan & Creelman, 2005)). The baseline reasoning of this approach is that individuals often require to make decisions under conditions of uncertainty and can be used in any situations where one needs to distinguish meaningful, relevant information (signal) from additional, irrelevant information (noise). Compared to raw variables of performance, the advantage of SDT is obtaining parsimonious indices that reflect both accuracy, and consider bias in individuals' responses, that is the general tendency of responding.

The first step to implement this approach is to categorise each outcome of a trial in a task as:

- HIT: response in the presence of signal
- FALSE ALARM: response in the absence of signal

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- MISS: no response in the presence of signal
- CORRECT REJECTION: no response in the absence of signal

Although several potential indices can be extracted from the data in this framework, *perceptual sensitivity* is the most relevant variable in the tasks used to measure sustained attention as it indicates the overall ability of the individual to detect signal.

Sensitivity or dprime (d') is calculated as follows:

$$d' = z(H) - z(F)$$

Where:

- $z(H)$: z transformation of the HIT rate
- $z(F)$: z transformation of the FALSE ALARM rate

Dprime values are always positive and higher values are interpreted as higher sensitivity, accounting for response biases.

For the reported analysis, the library *psycho* (Makowski, 2018) was used to calculate dprime. The library also includes a correction for extreme values following (Hautus, 1995).

2.1.2 Reaction times

Several variables can be extracted from reaction time (RT) data of correct responses, including the traditional mean and standard deviation representing overall speed and variability of responses, respectively. The issue of utilising these measures is the assumption that the underlying distribution of the data follows a Gaussian curve. Empirical RT data, however, rarely is symmetrical around a mean, and it usually displays positive skewness (long, positive tail) (Balota & Yap, 2011).

In order to overcome this limitation, alternative distributions have been proposed to be used to represent RTs, one of which is the Ex-Gaussian, which successfully fits empirical data (Luce, 1986). The Ex-Gaussian is the mathematical combination (convolution) of a Gaussian and an exponential distribution. It can be described by a combination of three parameters:

- μ: *mu*, the mean of the Gaussian component
- σ: *sigma*, the standard deviation of the Gaussian component

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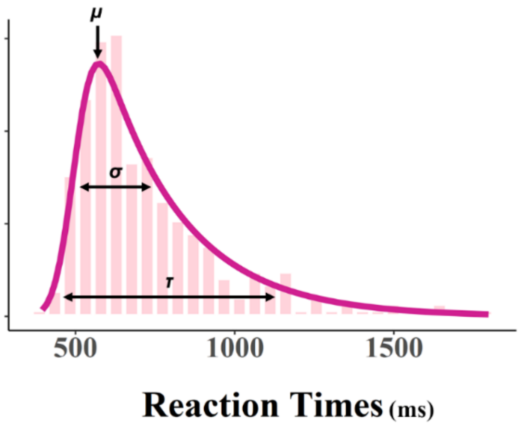
- τ: *tau*, scale of the exponential component

A visual representation of the effects of the parameters on the distribution can be found in Figure 2.1 and Figure 2.2. Mu and sigma represent the familiar Gaussian parameters and are interpreted as overall speed and variability of RT, respectively. Tau, on the other hand, is an additional parameter which is not found in traditional Gaussian modelling and can be interpreted as the tendency of an individual to make very slow responses (which will contribute to the long-tail aspect of the distribution). Tau was utilised as a measure of attentional lapses.

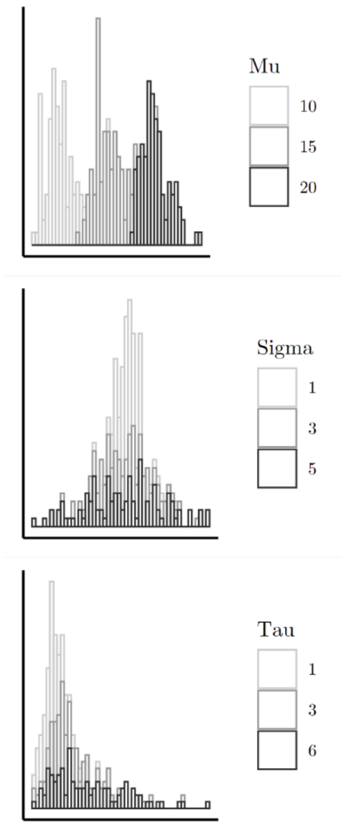
Figure 2.1
Ex-Gaussian distribution fitted to empirical RT data. The plot provides a simplified representation of the parameter contribution to the curve.



Fitting of the Ex-Gaussian distribution and the extraction of the parameters was performed using the R library *retimes* (Massidda, 2013), which is based on a Maximum Likelihood estimation algorithm.

This approach was used whenever the amount of data-points that could be used reached the minimum amount of n = 100 required to obtain adequate estimation of the Ex-Gaussian parameters (Ratcliff, 1979). Whenever it was not possible, an alternative approach inspired by recent literature (Unsworth & Robison, 2016) was implemented. This method entailed extracting RT data from correct responses of each individual, ranking them and separating the datasets at the 80% percentile. Mean and standard deviation were then obtained from the RT below the 80% and used as measures of speed and variability. Lapses, on the other hand, were represented by the mean of the 20% slowest RT (above the 80% percentile). Significant, positive correlations between tau and this alternative measure of lapses were verified to be of high magnitude (> 0.50) in multiple occasions throughout the project.

Figure 2.2
Effects of the ExGaussian parameters Mu, Sigma and Tau. When one of the parameters is changed, the others are held constant.



2.1.3 Vigilance decrement

The vigilance decrement is the most frequent phenomenon associated with sustained attention performance; however, there is not a standardised method to obtain it in the literature. The method utilised in the project consisted in fitting linear growth models with mixed-effects regressions (Mirman, 2017). Growth (curve) modelling is a general category of regression models in which the dependent variable is modelled longitudinally (as in repeated-measures designs). After fitting the model, the slope of the regression line can be used as a measure of change over time for the dependent variable.

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More specifically, this approach entails separating trials in multiple bins of which number depended upon the total number of trials, to obtain an adequate trade-off between number of bins and sufficient trials to get credible variables. This number varied between 4 and 10. Then, the relevant variables described as above were obtained for each bin of trials. For RT data, since the trials were consistently lower than 100, the alternative approach based on 80% percentile split was used (see above).

Mixed-effect models were used to obtain an estimate of the vigilance decrement. This category of models is particularly useful in longitudinal data where sequential measures are non-independent, as in most experimental psychology (Meteyard & Davies, 2020). The mixed models are called in such way because they allow the introduction of both fixed and random effects. The former represent the main effects of interest such as an experimental manipulation and refer to the population level; the latter are sources of random variation such as individual differences. To estimate the vigilance decrement for, for instance, dprime, the model included a fixed effect of block number (bin of trials), and a random intercept and slope for each participant. In this model's random effects, the random intercept represents the individual differences in baseline ability; the random slope represents the individual differences in how block number affects dprime in each individual (Figure 2.3).

More formally, the example model of block (*i*) and individual (*j*) would take the following equation (W. Johnson et al., 2013):

$$Y_{ij} = \beta_{0j} + \beta_{1j}(Block_{ij}) + e_{0ij}$$

$$\beta_{0j} = \beta_0 + \mu_{0j}$$

$$\beta_1 j = \beta_1 + \mu_{1j}$$

In the equation above:

- Y_{ij} : prediction of the model for dprime at block *i* and participant *j*
- β_{0j}: intercept coefficient which includes both average fixed effect β_0 and random individuals' *j* deviations μ_{0j}
- β_{1j} : slope coefficient which includes both average fixed effect β_1 and random individuals' *j* deviations μ_{1j}
- e_{0ij} : residual error

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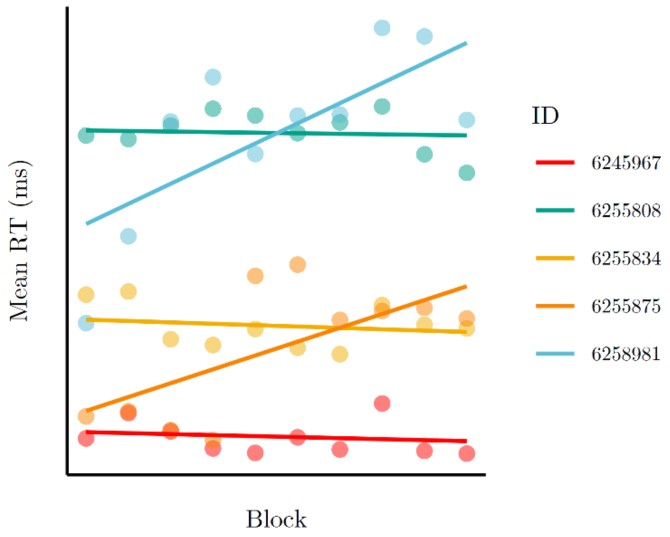
After fitting the model, the term β_{1j} was used as estimation of the individuals' vigilance decrement.

Figure 2.3

Example of mixed model. The model accounted for individual differences in baseline ability (random intercept) and effect of time-on-task (random slope).



Fitting of models was performed using the *lme4* library (Bates et al., 2015).

2.2 General approach of analysis

In addition to the estimation of the vigilance decrement, linear mixed models were used as the main tool of analysis in each study presented here. The general procedure entailed fitting a model that included all fixed predictors, driven by theory, and appropriate random effect structure, driven by design. In the case of a very complex design, an iterative procedure of model selection was employed to find the best fitting model using the AIC index. Both standardised and non-standardised coefficients were reported. Significance of the fixed predictors was firstly assessed using a type-3 F-test, followed by the t-tests on each coefficient. Both steps relied on the Satterthwaite's approximation of degree of freedom implemented in the R package *lmerTest* (Kuznetsova et al., 2017). Corrected multiple comparisons followed if required using the R package *emmeans* (Lenth, 2022).

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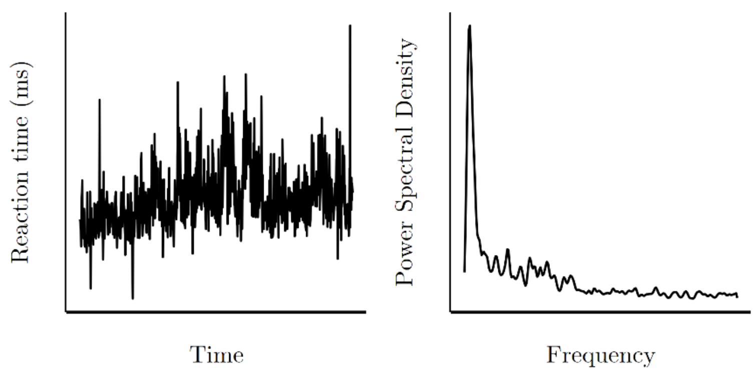
2.3 Frequency analysis

To investigate the oscillatory components of RT data it is possible to use spectral analysis techniques. The underlying assumption of this approach is that individual's RT collected from a cognitive tasks represent correlated observation which can be decomposed into a set of component waves (Van Orden et al., 2003). Loosely speaking, the purpose of this method is to convert the data from the *time* domain to the *frequency* domain (Figure 2.4). The specific method presented here, which entailed obtaining the Power Spectral Density (PSD) of RT data, was designed following (Castellanos et al., 2005; Holden, 2005; K. A. Johnson, Kelly, et al., 2007). Depending on whether the dataset included evenly spaced trials (equal inter-stimulus-interval) or not, the Fast Fourier Transform (FFT) or the Lomb-Scargle method were respectively used.

2.3.1 PSD through the FFT method

When evenly spaced data was present in a dataset, the PSD was evaluated using a modified Welch's method (Welch, 1967), which instructs to split the signal (RT data) in multiple overlapping segments, to extract the FFT for each and average them, and to then compute the PSD.

Figure 2.4
Spectral analysis transforms RT data from the time domain (seconds, or trials) to the frequency domain, potentially revealing oscillatory behaviour.



More specifically, in an example dataset where participants completed a certain amount of trials where multiple outcome measures were possible (see section above on SDT), the method began with extracting only the trials with a HIT for each individual. The relevant data consisted of the trial's RT over the course of the task session. The total number of trials was then split in overlapping segments (of which percentage varied depending on the task). Each segment was iteratively examined for missing (non-HIT) responses and excluded if surpassing a maximum threshold. If it was not, missing responses were interpolated, and detrended. To apply the FFT is in fact necessary to have a continuous and stable signal; if it was not, segmentation would produce incomparable segments of signal. The obtained segments were then windowed using a Hamming function to reduce spectral leakage and zero-padded to increase spectral resolution, and the FFT was computed. To obtain the spectral power, the squared magnitude was calculated from the real FFT output, which was then averaged across segments.

The resulting values represented the spectral power of a two-sided spectrogram, therefore only the positive half was kept, and the obtained values were doubled. The PSD of the signal was then obtained by multiplying the spectral power by a scaling factor which accounted for the windowing function and the sampling frequency. Finally, the respective frequencies were obtained as an evenly spaced vector of values constrained by 0 (the DC term, which is 0Hz), and the Nyquist (which corresponds to half the sampling rate) frequency. This procedure was then repeated for each participant and further calculations were then performed.

2.3.2 PSD through the Lomb-Scargle method

The Lomb-Scargle method is a least-square method of PDS evaluation that can be applied to unevenly-sampled time-series data (Lomb, 1976). In the reported analysis, this method was performed with the support of the package *lomb* (Ruf & Astropy, 2022). As in the FFT method, only RT data from correct responses were used, and detrended before the Lomb-Scargle periodogram was calculated following the procedure described in (Ruf, 1999) and implemented in the package. The resulting output corresponded to the normalised PSD of the RT data, at frequencies obtained iteratively by the least-square fitting method.

2.4 Datasets

The project used an extensive number of datasets, which will be briefly described below. More details regarding the exact criteria for the included sample size, thorough descriptions of the materials and variables extracted, can be found in the empirical chapters.

2.4.1 Dataset A – Studies 1, 8, 9

This dataset was previously used in a recent publication (Gallagher et al., 2015). It included a sample of 111 healthy individuals (46 females and 65 males) and 132 mixed patients (60 females and 72 males). The patients group included 61 euthymic bipolar disorder patients (Thompson et al., 2005), 38 medication-free patients diagnosed with major depressive disorder (Porter et al., 2003) and 33 bipolar disorder patients in a depressive episode (Gallagher et al., 2014). Each participants completed the Vigil CPT (Vigil Continuous Performance Task (Cegalis & Bowlin, 1991)), to measure sustained attention and a series of cognitive tests including the NART (National Adult Reading Test (Nelson & Willison, 1991)) to measure premorbid IQ, the DSST (Digit Symbol Substitution Test (Wechsler, 1955)) to measure processing speed, the Rey-AVLT (Rey Auditory Verbal Learning Test (Rey, 1964)) to measure verbal learning and the COWAT (Controlled Oral Word Association Test (Benton et al., 1983)) to measure verbal fluency. Additionally, participants performed several tests from the CANTAB (Cambridge Neuropsychological Test Automated Battery (Cambridge Cognition, Cambridge, United Kingdom)) battery including a pattern and spatial recognition tasks and spatial working memory task.

2.4.2 Dataset B – Studies 2, 3

The dataset included 179 participants recruited online following the criteria: no ongoing, or history of, mental health condition, an age included between 18 and 45, and residence in the United Kingdom. Data was collected using Gorilla (Anwyl-Irvine et al., 2020), an online platform for psychological experiments. Each participant completed a session of 4 sustained attention tasks: Mackworth Clock test (Mackworth, 1948), the Sustained Attention to Response Task (Robertson et al., 1997), the Psychomotor Vigilance Test (Dinges & Powell, 1985) and the Test of Variables of Attention (Greenberg, 2011). Additionally, participants filled the Starkstein Apathy Scale questionnaire (Starkstein et al., 1992), before the other computerised tasks.

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2.4.3 Dataset C – Study 4

The dataset comprised data from 33 participants collected by an undergraduate Psychology student at Newcastle University for her graduation project. After recruitment, participants were directed to Gorilla to complete a session of the TOVA task. Additionally, before and after the sustained attention task, they completed the Dundee Stress State Questionnaire (Matthews, 2016).

2.4.4 Dataset D – Study 7

The dataset had already been used for a publication (Brosowsky et al., 2020), and was obtained from the Open Science Framework (OSF, osf.io) with permission from the first author. It included data from 166 participants who completed the Metronome Response Task (Seli, Cheyne, et al., 2013). Throughout the task, participants were also presented with questions probing their motivational level.

2.4.5 Dataset E – Study 5

This was an existing dataset used for a recent publication (Robinson et al., 2012). It included data from 40 individuals who completed two sessions of the Attentional Network Test (ANT) (Fan et al., 2002). Before testing, participants were split into two groups, one of which was informed of potential additional reward before the start of the second session. Furthermore, participants completed a short version of the Intrinsic Motivation Inventory (Ryan, 1982).

2.4.6 Dataset F – Study 6

The dataset comprised data from 212 participants recruited through Prolific and collected using Gorilla. The same recruitment criteria of Dataset B were used. Each individual performed a session of the Sustained Attention to Response Task, and the pre/post- task versions of the DSSQ. Before the start of the experimental session, participants were split in two groups. The reward group was informed of obtaining additional compensation if ranked the best of the sample in terms of performance; the control group received the same instructions at the end of the task.

Chapter 3 - Validating operationalisations of sustained attention

3.1 Introduction

The present chapter was designed to test the assumption that different operationalisations of sustained attention refer to the same underlying construct, through two complementary factor analyses. Validation of different definitions would allow generalisability and comparability across a wider range of literature.

Each individual has an experience of what it means to sustain attention for an extended period of time, however, a standardised definition is yet to be formulated. Defining an abstract, intangible construct can, in fact, prove difficult and the only available approach is through a reduction to a set of empirical measurement methods. The resulting representation is an operationalisation (Stevens, 1935).

The literature of sustained attention is rich with operational definitions. Each is a combination of a set of operations, which in Psychology comprise procedure, computerised task and variables of interest. The choice of operations is dictated by the adopted school of thought (e.g., underload or overload perspectives), researcher's interests and preferences, settings and various other subjective factors. The subjectivity (and convenience) of the various definitions introduces an issue of translation validity, a component of content validity, which relates to the extent to which the operational definitions properly represent the psychological construct of interest, and to how different definitions might not necessarily refer to the same underlying latent variable (Slife et al., 2016).

Validity of the different operationalisations of sustained attention is usually assumed, rather than properly tested. This simple assumption is, in fact, necessary for definitions that differ in terms of employed methodology to be comparable and generalisable. The issue, however, arises when the methods traditionally associated with sustained attention (e.g., a CPT) are used to measure other cognitive domains such as impulsivity (Behforooz et al., 2017) or executive control (Unsworth et al., 2010).

To assess validity of a set of operationalisations an effective approach is the Multitrait-Multimethod matrix (MTMM) (D. T. Campbell & Fiske, 1959). This method allows one to test the relationships between multiple measures and multiple tasks through a set of correlations. From these relationships, it is then possible to verify convergent and divergent evidence, which refer to the strength of relationships between variables that are expected to relate, and to not relate, respectively. In other words, convergent validity regards the intensity of relationships between variables that should measure the same construct, whereas divergent validity refers to whether relationships between variables that should not represent the same construct are null or disagreeing. Although originally the MTMM entailed a simple correlation matrix, more modern applications use factor analytical approaches (Miller et al., 2018).

Existing research has attempted to investigate the construct of sustained attention using factor analyses. For instance, Treviño and colleagues (2021) showed that one factor explained only dprime of the gradCPT, among a dataset with a number of tasks and tests. Another study showed that a factor would explain only two variables extracted from two CPTs (Burns et al., 2009). Mirsky and colleagues (1991), on the other hand, found that multiple variables extracted from a CPT would be explained by one factor. Although these studies might suggest that underlying performance in sustained attention tasks there might be an only psychological construct, they were limited by the employment of one variable per task, or multiple variables from one task, therefore not providing an exact application of the MTMM.

A rigorous application of the MTMM would in fact require multiple methods and multiple variables believed to measure the same latent construct. By utilising this method, it would be possible to ascertain which variables from which method (task) systematically correlate to indicate a shared, underlying psychological construct which, in this specific case, is believed to be sustained attention.

3.1.1 Study 1

The first study aimed at investigating the variable structure of a sustained attention task, and how the underlying factor(s) relate to other cognitive domains.

Traditional research used single outcome variables from computerised tasks to represent a construct (e.g., rate of missing targets in Mackworth, 1948). These approaches relied on the assumption that driving task performance, only one psychological factor should be found. However, recent research does not seem to support this assumption. Egeland and Kovalik-Gran (2010) extracted a large variety of measures from the Conner's CPT and showed that underlying the dataset, multiple latent constructs could be found. Similary, Fortenbaugh and colleagues (2015), showed that even in a narrower set of measures obtained from the gradCPT, multiple factors could be extracted. The question that needs to be addressed regards which of the underlying factors may be representing sustained attention.

Partially adopting a MTMM perspective, the present study used an existing dataset (Gallagher et al., 2015) that included data of a sustained attention task (CPT) and a battery of tests assessing other domains of cognition obtained from a large sample of individuals. An exploratory factor analysis was used to explore the vast net of relationships in the variables within the CPT and between CPT and cognitive domains, in terms of convergent/divergent validity. It was considered only a partial MTMM approach as it included only one method assessing sustained attention.

Even with an exploratory aim, convergent and divergent evidence is based on expected relationships. In terms of convergence, it was expected that measures within the CPT should be heavily interrelated. In terms of divergence, CPT measures were expected not to be correlated with the other cognitive domains. These simplified results would correspond to a latent factor explaining only CPT variables, with little to no correlations with other cognitive domains, and would potentially represent sustained attention. In the case of multiple factors explaining CPT variables, the one most likely associated with the construct of sustained attention would be assessed based on convergent/divergent evidence.

3.1.2 Study 2

The second study aimed at investigating whether a shared, underlying psychological construct could be found across multiple sustained attention tasks. More specifically, building on the outcome of Study 1 which indicated which variables most likely represented sustained attention within a task, Study 2 tested whether the same construct would be shared across different tasks.

- Validating operationalisations of sustained attention

Existing research only has one application that resembles the present study, which is found in (Unsworth et al., 2021). This work attempted to uncover the factors underlying a vast dataset that included multiple sustained attention (and non-) tasks, and questionnaires. Their analysis indeed hinted at a shared factor explaining most sustained attention tasks, yet it was limited by their specific interest in attentional lapses which reduced the choice of variables extracted. Additionally, they did not include a task representing traditional vigilance tasks.

The present study was designed in order to find an underlying construct across tasks that would represent most sides of the literature. For instance, to represent traditional vigilance tasks and the overload account, the Mackworth Clock test was included; the Sustained Attention to Response Task, on the other hand, represented the more recent CPTs and the overload theory. Two additional tasks, the Test of Variables of Attention and the Psychomotor Vigilance Test completed the battery.

To appropriately apply the MTMM approach, multiple variables were extracted from each task to represent all possible aspects of performance, that is, accuracy, variability, speed, attentional lapses, and the vigilance decrement. Extracting the underlying factor structure, and consequently glance at the variable separation would provide an indication of task-specific and task-general factors. The former refers to factors influencing performance that would not generalise across tasks; the latter, on the other hand, refers to generalisable aspects of performance that could be detected across tasks.

As the aim of the study was to find a shared underlying factor driving performance across multiple tasks representing the main theories of sustained attention, the main interest was on the task-general factors. Finding which variables from each tasks proved task-general would provide an indication of the more ideal performance index to draw generalisable conclusions.

The study was exploratory by design; however, it was hypothesised that a shared factor would be found across tasks with variables potentially relating to attentional lapses. As no existing studies looked into the specifics of the variable separations across multiple tasks, no predictions were made.

- Validating operationalisations of sustained attention

3.2 Study 1

3.2.1 Method

3.2.1.1 Participants

The study used data obtained from a total of 243 participants (38.9 mean age (SD = 11.74)), pooled from multiple pre-existing studies and used previously in an existing publication (Gallagher et al., 2015). This included 111 healthy controls (46 females and 65 males) and 132 patients (60 females and 72 males). The patients group included 61 euthymic bipolar disorder patients (Thompson et al., 2005), 38 medication-free patients diagnosed with major depressive disorder (Porter et al., 2003) and 33 bipolar disorder patients in a depressive episode (Gallagher et al., 2014). The inclusion of samples of participants from different populations was motivated by the main purpose of the study being the investigation of the content validity of the Vigil task. Content validity refers to the extent an instrument measures the targeted construct, and therefore should not be dependent on the population tested. Examples of similar designs which included mixed samples can be found in the literature (Egeland & Kovalik-Gran, 2010b, 2010a).

3.2.1.2 Materials

Each participant completed a battery of cognitive tasks designed to assess not only sustained attention, but cognitive functioning on a wide range of domains. Administration of the tasks followed tests protocol.

3.2.1.2.1 Vigil CPT

The Vigil CPT (Vigil Continuous Performance Task (Cegalis & Bowlin, 1991)) is a computerised task used to assess sustained attention in human participants. In each of the 480 trials, a random letter is presented for 85ms, followed by 900ms of inter-stimulus interval (showed as a centred white letter on a dark screen). Participants detect, and respond to, the letter sequence of an A followed by a K. The total number of targets is 100, semi-randomly distributed across the length of the task (25, in each of the 4 blocks of 120 trials).

- Validating operationalisations of sustained attention

3.2.1.2.2 Neurocognitive battery

The NART (National Adult Reading Test (Nelson & Willison, 1991)) is a reading test used to measure premorbid intellectual functioning. It requires participants to read a list of 50 irregular words, and scoring is based upon correct pronunciation. The DSST (Digit Symbol Substitution Test (Wechsler, 1955)) is a pen-and-paper task in which participants are asked to match symbols to numbers within 90 seconds of maximum allowed time. The total number of correct answers is used to index processing speed. Several tasks from the CANTAB (Cambridge Neuropsychological Test Automated Battery (Cambridge Cognition, Cambridge, United Kingdom)) were also included to measure: pattern recognition, using a visual-recognition memory task where participants are shown two sets of 12 patterns, and then are asked to recognise them in a two-forced-choice paradigm (correct responses are used as dependent variable); spatial recognition, showing participants 4 sets of 5 squares at different positions on the screen, and then asking to recognise previously shown positions in a two-forced-choice task (correct responses are recorded); spatial working memory, with a self-ordered test where participants are asked to search for tokens (targets) across an increasing number of coloured boxes presented on the screen (number of errors are recorded). The Rey-AVLT (Rey Auditory Verbal Learning Test (Rey, 1964)) is a verbal learning task that consists of a list-learning paradigm and attempted recall with and without interference. Total number of recalls after 5 presentations of the list, and delayed recall were recorded. The COWAT (Controlled Oral Word Association Test (Benton et al., 1983) is a verbal fluency test in which participants are asked to produce words beginning with letter F, A and S in 1-minute time limit. Number of correct responses is recorded.

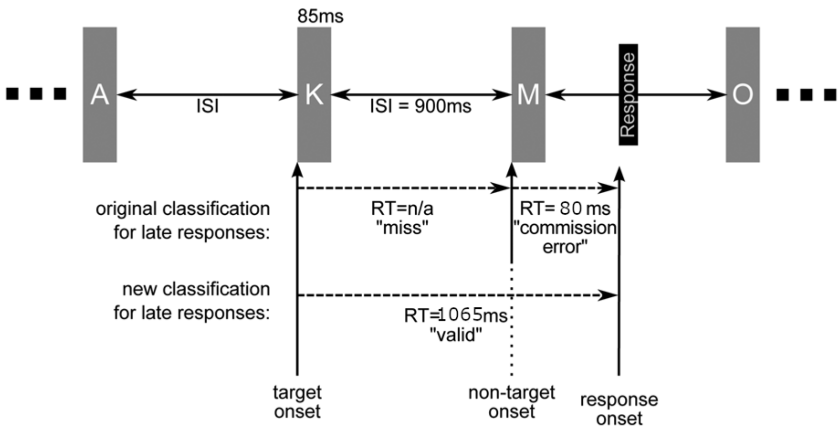
3.2.2 Data analysis

All data extraction, pre-processing and analysis were performed using the R programming language (R Core Team, 2021), in addition to multiple packages including *tidyverse* (Wickham et al., 2019), *retimes* (Massidda, 2013), *lme4* (Bates et al., 2015) and *psych* (Revelle, 2022).

3.2.2.1 Pre-processing of Vigil CPT data

The raw data from the 243 participants was re-extracted from the original files. The processing of data followed a different algorithm compared to other publications based on the same dataset (Gallagher et al., 2015), as follows. Traditionally, reaction times (RT) in the Vigil CPT can have a range of 0ms to 985ms (the interval between the onsets of two consecutive stimuli). In this updated procedure (Figure 3.1), the window of response was increased to 1135ms (985ms + 150ms within the following stimulus' response window). The increased response window was implemented in order to obtain a wider range of reaction times. Categorisation of responses followed a similar procedure to a traditional Signal Detection Theory (SDT) approach (Stanislaw & Todorov, 1999). If the participant responded to a target sequence, it was considered a "hit", a correct response. If the response was recorded to a non-target sequence, it was considered a "commission error" or false positive. If no response was recorded to a target sequence, it was considered a "miss". Finally, if no response was registered for a non-target sequence, it was categorised as "correct rejection".

Figure 3.1
Task structure of the Vigil CPT and updated classification of the responses. A wider response window was implemented to provide a wider range of reaction times. Adapted from (Gallagher et al., 2015)



3.2.2.1.1 Reaction times

Several variables were extracted from the RT of correct responses above 100ms (Basner & Dinges, 2011) for each individual. An Ex-Gaussian distribution was fitted to the RT data using the *timefit* function of the package *retimes* (Massidda, 2013). The Ex-Gaussian curve is the convolution of a Gaussian and an exponential distribution which fits empirical RT data, usually characterised by positive skewness (Osmon et al., 2018). The distribution is described by three parameters: μ (*mu*) is the mean of the Gaussian component (equivalent to the traditional mean) and is used to measure overall speed; σ (*sigma*) is the standard deviation of the Gaussian, and corresponds to RT variability; τ (*tau*) is the mean and standard deviation of the exponential component and represents an alternative measure of RT variability due to very long responses (tendency of the Ex-Gaussian distribution to show skewness), and relates to attentional lapses (Yamashita et al., 2021).

3.2.2.1.2 Accuracy

Although several aspects of performance accuracy such as the quantity of commission errors, or misses, might reveal relevant (and potentially different) facets of sustained attention (Carriere et al., 2010; Egeland & Kovalik-Gran, 2010a), for the sake of parsimony SDT's *dprime* was calculated as the z-transformed difference between the hit rate and the false-alarm rate, using the *psycho* package (Makowski, 2018) for R. Given the very low proportion of targets over the total number of trials, and the probability (ratio) of false alarms approaching zero, the calculation of dprime included a correction for extreme values following (Hautus, 1995).

3.2.2.1.3 Time-on-task changes

In order to obtain an indication of how performance changed over the course of the task, it was assumed that such change would be linear (Lara et al., 2014; Luna et al., 2021), allowing a linear-growth-modelling framework to be adopted. Firstly, relevant variables were calculated over 8 blocks of 60 trials. Then, each variable was modelled separately using block (1-8) as predictor in a linear-mixed-effect model fitted using the package *lme4* (Bates et al., 2015). Each model included a random intercept (individual's mean) and a random slope (individual's change over time) as random effects for each participant. After fitting the models, the individuals' slopes were extracted and used as a measure of linear change over time for the specific variable. Considering however the reduced number of trials available (an average of 12.5 target trials) in each block, the Ex-Gaussian could not be fitted appropriately (given the indication of having around 100 units to obtain an adequate estimation of the parameters (Ratcliff, 1979)), and a different approach was used to extract the required variables to represent RT speed and variability (and lapses). To obtain a measure of attentional lapses, reaction times were ranked and the average RT exceeding the individual's 80^{th} percentile was calculated (Unsworth et al., 2020). This would provide an equivalent indication of what the Ex-Gaussian *tau* represents, that is the slower RT variability. Using the RT below the 80^{th} percentile, Mean RT and coefficient of variation (CoV, the standard deviation corrected for individual's mean) were calculated representing respectively *mu* and *sigma*. Finally, dprime was also calculated as described above.

3.2.2.2 Exploratory Factor Analysis

The structure of the dataset was examined using Exploratory Factor Analysis (EFA) implemented following guidance from (Hair, 2009; Watkins, 2020). Most of the steps required by this analysis were driven by a compromise of theory-driven reasoning and standardised criteria. The first phase entailed constructing the variable matrix, which included all of the variables extracted from the Vigil CPT and the neurocognitive battery, as described above. Then, the appropriateness of the dataset for the analysis was tested by a set of operations: the correlation matrix was visually examined to detect excessive multicollinearity and avoid singularity; the Kaiser-Meyer-Olkin (KMO) index was calculated as a test for sampling adequacy; finally, the Bartlett test of sphericity was run to test whether the variables were sufficiently correlated (by testing whether the correlation matrix did (not) equal the identity matrix). The number of factors to retain was selected using parallel analysis (Horn, 1965), and by comparing multiple factor solutions iteratively, as further described below. Different methods for factor extraction can be used. The main distinction is between methods that use routines with maximum likelihood or least squares. Due to the relatively small sample size and that some of the variables in the dataset did not follow a perfect univariate or multivariate normal distribution, a weighted least square method was used which has no distributional assumption (Mac Callum et al., 2012). After the extraction of the factors, a rotation was implemented to the analysis to improve the interpretation of the structure. More specifically, a *promax* oblique rotation was selected, as it allows correlations between factors (likely to be found given that most variables are extracted from an attention task). Pattern loadings were therefore extracted from the rotated solution and interpreted as the regression weights of the model equations with all the factors, resulting in each variable. With the goal of obtaining a simple structure (Thurstone, 1931), following guidelines from (Hair, 2009), significance of pattern loadings was set a priori to ± 0.38 and salience for interpretation at ± 0.30. Appropriateness and robustness of the results was ascertained by iteratively testing different extraction methods, different rotations and different numbers of factors. Evaluation criteria included the root mean squared residual (RMSR), a measure of model fit which can be used for model comparisons. Lower values are preferred, and lower values than 0.08 are ideal (Brown, 2015). The root mean square error of approximation (RMSEA), traditionally used for confirmatory factor analysis, can also be used to aid model comparisons. Larger values indicate poorer fit, and differences of 0.015 or higher indicate different fit (Finch, 2020). Finally, symptoms of over- or under-factoring were evaluated.

3.2.3 Results

Visual inspection of the Pearson correlation matrix showed no evident signs of multicollinearity (Figure 3.2), and therefore no variable was excluded (Table 3.1). The KMO index resulted being 0.64, hence mediocre to middling (Kaiser, 1974), but adequate for factor analysis. Bartlett test of sphericity also supported the implementation of the analysis, being significant ($\chi2(120) = 1326.00$, $p < 0.001$), indicating that correlations had enough magnitude. 500 iterations of parallel analysis suggested a solution with 5 or 6 factors, therefore the two models were extracted and compared. Although the 6-factor solution showed good RMST = 0.02, the difference in RMSEA values was lower than 0.015 (ΔRMSEA = 0.007) indicating no differences in model fit compared to the 5-factor solutions. Additionally, it produced a problematic ultra-Haywood case (when communality is higher than 1) potentially indicating over-factoring (Cooperman & Waller, 2022). The 5-factor solution, on the other hand, did not output any errors in the estimation of the parameters, and had adequate RMSR = 0.04. The 5-factor solution was therefore preferred and used for interpretation. Since the fundamental aim of the analysis was to identify the sustained attention factor, and not to find all of the underlying latent variables driving the variance in the dataset, it was decided not to name the extracted factors. In general, the factor solution showed excellent separation and a remarkably simple structure with no significant cross-loadings (see Figure 3.3, Table 3.2 for the same data presented visually or on a table and Table 3.3). Factor 1 loaded on a few of the neurocognitive measures, in addition to tau and dprime from the Vigil CPT. Factor 2 and 3, on the other hand, explained variance only in variables from the Vigil (sigma/mu and all of the RT variables slopes, respectively). Factor 4 related only to the Rey's measures, and it was not surprising given the strong correlation found between the two measures. Finally, Factor 5 explained variance in the slopes of dprime extracted from the Vigil.

Table 3.1
Descriptive statistics of the variables included in the factor analysis of Study 1. FAS: controlled oral word association test; RVLT.recall: Rey auditory verbal learning test, recall with delay; RVLT.total: Rey auditory verbal learning test, total recall; SWM: CANTAB spatial working memory; Spatial.recog: CANTAB spatial recognition; Pattern.recog: CANTAB pattern recognition; DSSQ: digit symbol substitution test; NART: national adult reading test.

Variable	Mean	SD	Min	Max	Skew	Kurtosis
FAS	41.72	11.14	18.00	82.00	0.36	0.04
RVLT.recall	9.56	3.13	1.00	15.00	-0.35	-0.56
RVLT.total	49.11	9.13	24.00	69.00	-0.05	-0.38
SWM	30.90	21.31	0.00	82.00	0.40	-0.98
Spatial.recog	15.69	2.54	6.00	20.00	-0.82	0.76
Pattern.recog	21.06	2.89	10.00	24.00	-1.18	1.11
DSST	57.42	12.73	23.00	84.00	-0.53	-0.23
NART	109.77	9.74	77.00	131.00	-0.47	0.003
Dprime.slopes	0.004	0.02	-0.07	0.06	-0.46	0.74
Lapses.slopes	-0.91	7.89	-24.92	30.04	0.34	0.81
CoV.slopes	<0.001	0.003	-0.009	0.02	0.95	2.70
RT.slopes	-0.10	6.38	-20.83	25.39	0.14	1.62
Tau	78.42	37.48	2.32	222.31	0.98	1.49
Sigma	34.27	26.04	<0.001	173.02	2.24	6.54
Mu	308.58	75.15	167.25	601.72	1.18	1.44
Dprime	4.48	0.86	1.54	5.59	-0.74	0.14

Figure 3.2
Correlation plot of the variable matrix extracted from the Vigil CPT and the neurocognitive battery of tasks in Study 1.

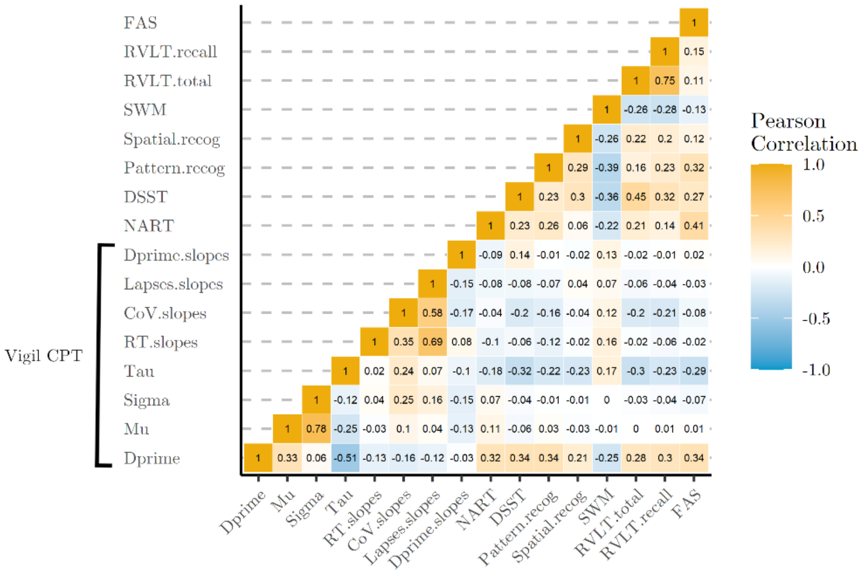


Figure 3.3
Factor plot of the pattern loadings of the 5-factor solution of Study 1. Colour of the bar depends on the sign of the loading. Bars crossing the dashed line reach significance (0.38).

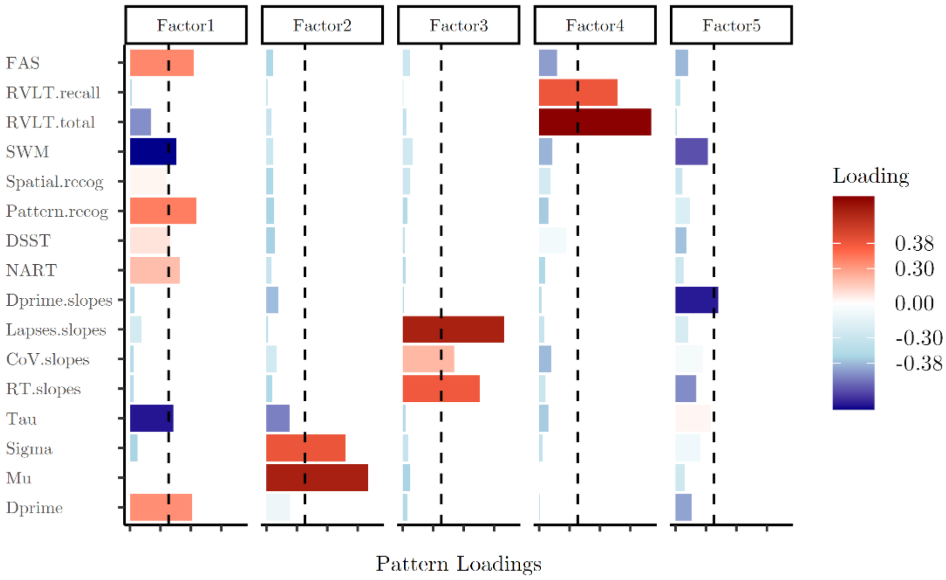


Table 3.2
Pattern loadings of the 5-factor solution in Study 1. Values in bold are above the ± 0.38 threshold of significance and values in light grey are below ± 0.30 for interpretation.

Variable	Factor1	Factor2	Factor3	Factor4	Factor5
FAS	**0.630**	-0.066	0.071	-0.175	-0.125
RVLT.recall	-0.018	0.012	-0.005	**0.773**	0.048
RVLT.total	-0.202	0.051	0.035	**1.104**	0.015
SWM	**-0.459**	0.068	0.094	-0.132	-0.317
Spatial.recog	0.351	-0.069	0.076	0.114	0.067
Pattern.recog	**0.655**	-0.075	-0.048	-0.091	0.145
DSST	**0.394**	-0.082	0.018	0.264	-0.110
NART	**0.492**	0.051	-0.028	-0.059	0.078
Dprime.slopes	-0.045	-0.118	-0.012	-0.021	**-0.421**
Lapses.slopes	0.111	-0.018	**1.000**	0.050	0.122
CoV.slopes	-0.035	0.099	**0.507**	-0.121	0.268
RT.slopes	-0.033	-0.057	**0.757**	0.062	-0.206
Tau	**-0.427**	-0.228	-0.027	-0.089	0.346
Sigma	-0.074	**0.778**	0.055	0.036	0.247
Mu	0.000	**1.005**	-0.074	0.003	0.091
Dprime	**0.613**	0.234	-0.045	0.004	-0.161
Variance proportion	0.13	0.11	0.12	0.12	0.04
Cumulative proportion	0.13	0.24	0.36	0.48	0.52

Table 3.3
Correlations of the factors extracted from the 5-factors solution in Study 1.

	Factor1	Factor2	Factor3	Factor4	Factor5
Factor1	1.00	0.12	-0.22	0.57	-0.11
Factor2		1.00	0.09	-0.02	-0.05
Factor3			1.00	-0.19	0.14
Factor4				1.00	-0.13
Factor5					1.00

3.3 Study 2

3.3.1 Method

3.3.1.1 Participants

A total of 179 participants took part in the study. Recruitment was performed using the Newcastle University local database, VOICE (voice-global.org, Newcastle upon Tyne), and online advertisement. Criteria for inclusion entailed no self-reported ongoing, or history of, mental health condition, an age included between 18 and 45, and residence in the United Kingdom. After a first briefing, participants were directed to Gorilla (Anwyl-Irvine et al., 2020) to complete the study. At completion, they received a debrief with the option of asking further questions and a £15 compensation. Due to the online nature of the study, a series of checks were run in order to include meaningful data. Four participants were excluded due to an abnormal number of trials in some of the tasks: two of them interrupted one of the tasks (Clock test) before completion; one individual showed too many trials in one of the tasks (TOVA); the remaining one had too many trials in another task (SART). Furthermore, a series of criteria were implemented to identify participants who did not adhere to the study instructions. These included extreme values of recorded responses or number of errors. After the filtering, the resulting sample size included 113 participants (29.00 mean age (SD = 7.19)). The sample comprised 32 cisgender men, 69 cisgender women, 5 non-binary individuals and 7 who preferred not to say. Although factor analytical approaches call for very high sample sizes and that the planned final sample size was of 150 individuals, the available data was still deemed suitable for analysis: given the ratio of the expected number of variables and factors (6.5), and the high to wide levels of communality due to the variables being extracted from sustained attention tasks, the size of 113 participants could be considered adequate for factor analysis (Mundfrom et al., 2005). The study received approval from the Newcastle University Ethics Committee (Ref: 8948/2020).

3.3.1.2 Materials

The study included multiple computerised tasks (Figure 3.4). Each one was recreated on Gorilla (Anwyl-Irvine et al., 2020), an online platform for psychological experiments following the original designs found in the literature. At times, parameters were changed in order to increase the taxing of sustained attention. The study also included a questionnaire measuring intrinsic motivation, which was not included in this analysis.

3.3.1.2.1 Mackworth Clock test (CLOCK)

This computerised task was an adaptation of the original task designed by Mackworth (1948). A black clock-like image was presented on a white background. In each trial, a little red dot moved across the seconds (in 1-second intervals). At times, the dot jumped one of the seconds, and participants were instructed to press a button ("space" bar on the keyboard) when they detected it, the target stimulus. This version of the task included a total of 2100 trials, among which 180 were targets, lasting approximately 32 minutes. Before the start of the task, participants were presented with 30 practice trials which provided feedback to their responses. The distribution of targets was uniform across the length of the task; however, the randomised order was fixed across participants.

3.3.1.2.2 Psychomotor Vigilance Test (PVT)

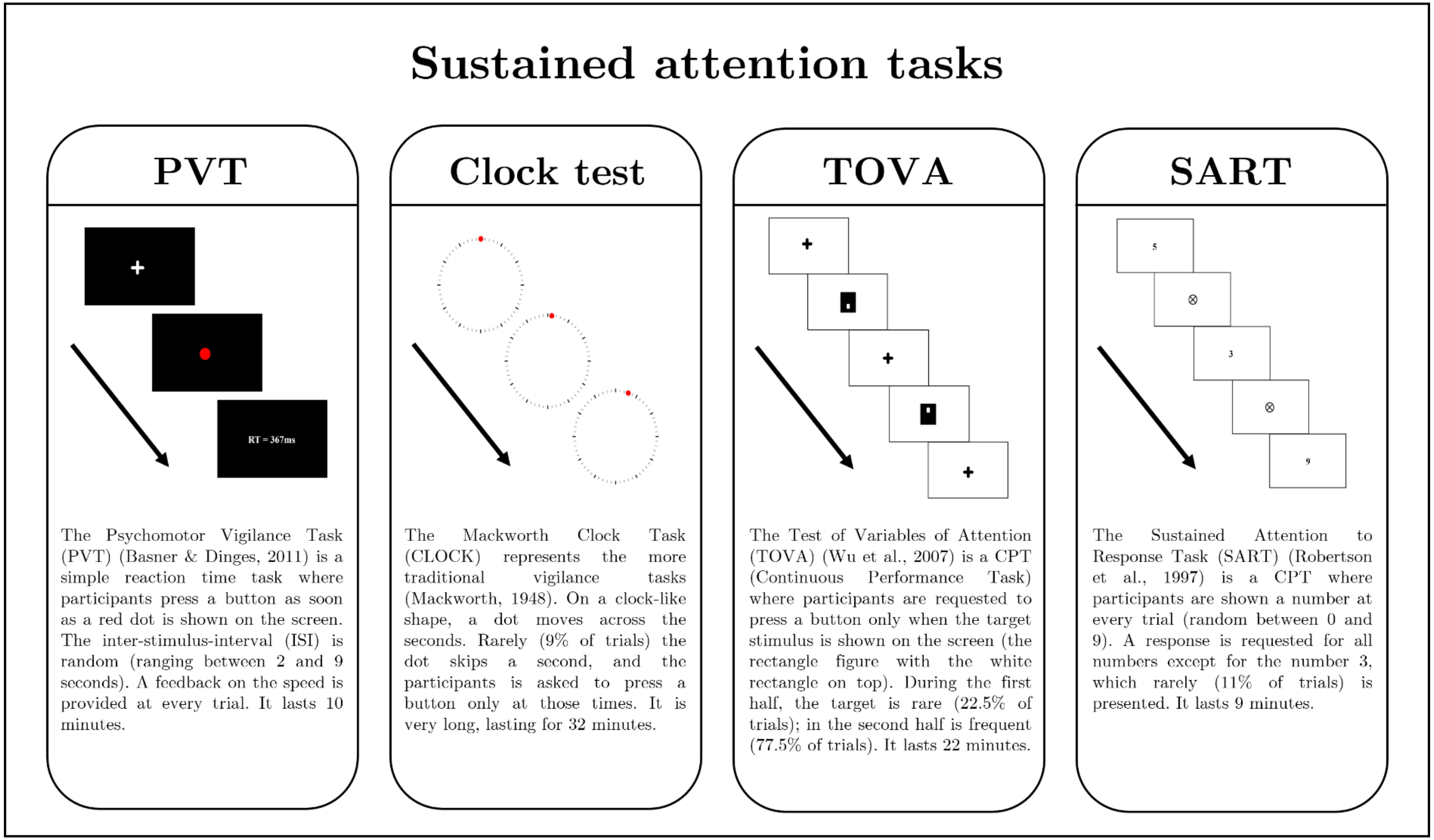
This version of the PVT was recreated following the original design by Dinges and Powell (1985). In this task, participants had to press a button ("space" bar on the keyboard) whenever a red dot appeared on the screen. They were instructed to be as fast as possible. The interval between the stimuli (ISI, inter-stimulus-interval) was randomised at every trial and had a range of 2 seconds to 10 seconds. During the ISI, participants were instructed to fixate a black cross presented on a white background. At the end of each trial, feedback on the recorded reaction time (RT) was presented for 1 second. The task had a total of 100 trials, lasting 10 minutes. Before the start of the experimental trials, participants completed 4 practice trials.

3.3.1.2.3 Sustained Attention to Response Task (SART)

The original SART (Robertson et al., 1997) was used as reference for this version created on Gorilla. In this continuous performance task (CPT), a random number (0-9) was presented on a white background in each trial. Participants were instructed to produce a response for each number, except for the number 3. In each of the 450 trials (lasting approximately 8.5 minutes), the number was presented for 250ms, with a fixed ISI of 900ms. The stimuli could be randomly presented in 5 different font sizes (48,72,80,100,110), in a black colour on a white background. During ISI, a black fixation cross was presented. Among the 450 total trials, 50 were targets. Before the start of the task, participants completed 15 practice trials which provided an accuracy feedback on their performance.

Figure 3.4

Computerised tasks used in Study 2.



- Validating operationalisations of sustained attention

As opposed to the Clock test, participants had to produce responses to the majority of trials (89%) whilst withholding the response for the target trials.

3.3.1.2.4 Test of Variables of Attention (TOVA)

This task was modelled after the original TOVA (Greenberg, 2011). In this CPT, participants were instructed to identify and respond to a target stimulus, a black rectangle within which a smaller white rectangle was placed on its lower part, and to ignore the non-target stimulus, the same rectangular shapes but placed upside-down. For a total of 648 stimuli, the stimulus was shown for 100ms, with an ISI of 1900ms. The total number of target trials was 324, however, the target rate was not constant throughout the total length of the task. In the first half (324 trials), the targets (n = 72) were shown very rarely; whilst in the second half, the targets (n = 252) were shown much more frequently. The order of stimuli presentation was randomised across participants. Before the beginning of the task, participants performed 5 practice trials with an accuracy feedback to familiarise with the stimuli.

3.3.1.3 Procedure

Following recruitment, participants were sent a briefing form explaining how the study was structured, instructions and recommendations. After giving consent, they were sent an invitation link to direct them to Gorilla where the study was hosted. The study included the 4 sustained attention tasks which were split across two sessions lasting between 40 to 60 minutes. The order of the tasks was pseudo-randomised as the Clock test lasted almost 40 minutes, and hence required one full session of the two to be completed. The other session included the other three tasks, in a randomised order. The order in which the two sessions were performed was randomised. Participants were requested to begin the study when they felt rested, to close any other browser tab and window, to stop music, and in general to eliminate potential distractions. 23 hours after the end of the first session, participants were then sent an invitation link to finish the study with the second session.

3.3.2 Data analysis

Every aspect of the analysis followed the approach used in Study 1, where it is described in a more detailed manner. Firstly, variables representing overall speed, variability, accuracy and changes over time were extracted from each task, then an exploratory factor analysis was performed. The R programming language was employed for all operations described below.

3.3.2.1 Variable extraction

At completion of the recruitment process, the raw data was downloaded from Gorilla and inspected. This led to the exclusion of 66 participants as described above. Categorisation of responses in each task, excluding the PVT (as it only measures reaction times) used the same outcomes described for Study 1: “hits”, “commission errors”, “misses” and “correct rejections”. Due to the differences between the tasks implemented, the outcome variables were not always the same ones.

3.3.2.1.1 Reaction times

RT variables from the SART, the Clock test (CLOCK) and the TOVA were computed from correct responses and excluding RT lower than 100ms, considered physiologically impossible (Luce, 1986). In the PVT, an upper boundary of 2500ms was also implemented to exclude outliers from the analysis. This value was more conservative than alternative, standardised methods such as the median absolute deviation (Leys et al., 2013), and it was selected to avoid the exclusion of data due to attentional lapses. As in Study 1, Ex-Gaussian parameters mu, sigma and tau were calculated from the RT data in each task.

3.3.2.1.2 Accuracy

The PVT did not provide a measure of accuracy, hence only the data from the CLOCK, the TOVA and the SART was used to obtain a measure of performance accuracy. To maintain consistency with Study 1, and for parsimony, SDT’s dprime was used.

3.3.2.1.3 Time-on-task changes

The same approach described for Study 1 was implemented here to obtain a measure of changes over time in task performance. Data from the TOVA was not used as the task requirements changed (target rate) at mid-point, and therefore the assumption of linearity could not be supported. Variables were therefore calculated across 8 blocks of trials, and linearly modelled over the blocks. Individuals' slopes represented the change over time and they were obtained for mean reaction times, coefficient of variation, attentional lapses and dprime. From the PVT, only RT variables were obtained.

3.3.2.2 Exploratory Factor Analysis

As in Study 1, the first step of the analysis required a visual inspection of the variable matrix. Then, the Kaiser-Meyer-Olkin (KMO) index for sampling adequacy and the Bartlett test of sphericity were performed. The number of factors to extract was initially selected by parallel analysis, and then by iterative comparisons across models with different number of factors to find the best simple structure. Considering sample size and distributional assumptions, a weighted least square routine was used to extract the factors. A promax oblique rotation was then performed to aid interpretation. Following (Hair, 2009), significance of loadings was set to ± 0.58, and salience threshold for interpretation to ± 0.30. Model selection was done comparing RMSR and RMSEA values, in addition to checking for evident signs of under- or over-factoring.

3.3.3 Results

The correlation matrix of the variables included in the analysis (Table 3.4) showed adequate magnitudes across the tasks (Figure 3.5). A few of the variables from the PVT showed a potential linear dependency (values close to 1), but they were included anyway as theoretically relevant. The matter was however acknowledged (multicollinearity could lead to issues in the extraction of the factors). The KMO resulted being 0.67, therefore mediocre to meddling (Kaiser, 1974), and the Bartlett test of sphericity was significant ($\chi 2(325) = 2402.00$, $p < 0.001$), determining the data was suitable for exploratory factor analysis. Parallel analysis and visual inspection of the scree plot suggested solutions with 5, 6 or 7 factors, which were thus extracted and compared. At extraction, the 7-factor model produced an ultra-Haywood case and was excluded. Residuals indices of fit for the 5-factor and the 6-factor models (table 3.5) showed adequate values ($RMSR < 0.08$) but did not differ extensively ($\Delta RMSEA = 0.007$) (Table 3.5). Examining the pattern loadings, the 6-factor model showed a more complicated structure (farther from the sought-after simple structure), and therefore the 5-factor model was selected as an adequate compromise of complexity and interpretability (Figure 3.6, Table 3.6, Table 3.7). The purpose of the study was examining the underlying structure of the dataset and whether a critical factor shared across tasks would emerge, therefore it was decided not to name the extracted factors.

Table 3.4
Descriptive statistics of the sustained attention variables extracted from Study 2.

Task	Variable	Mean	SD	Min	Max	Skew	Kurtosis
TOVA	Tau	92.59	43.32	18.73	306.89	1.56	4.10
	Sigma	47.91	28.53	13.61	308.63	6.74	58.88
	Mu	342.25	68.09	204.83	703.05	1.91	6.72
	Dprime	3.77	1.02	0.11	5.92	-0.73	0.70
SART	Lapses.slopes	4.13	5.60	-8.64	19.66	0.18	-0.10
	CoV.slopes	0.006	0.005	-0.008	0.02	0.26	0.13
	RT.slopes	-0.59	5.25	-14.69	12.98	0.25	0.02
	Dprime.slopes	-0.05	0.09	-0.33	0.20	0.12	0.63
	Tau	89.89	53.84	2.24	245.61	0.57	-0.45
	Sigma	59.53	33.38	16.80	214.10	1.73	3.58
	Mu	304.47	78.30	158.37	652.15	1.62	3.82
	Dprime	2.29	0.93	0.09	4.38	-0.15	-0.70
CLOCK	Lapses.slopes	6.70	1.94	1.42	12.10	0.18	0.27
	CoV.slopes	$<$-0.001	0.001	-0.004	0.004	0.45	2.68
	RT.slopes	4.74	2.95	-0.90	14.61	0.67	0.61
	Dprime.slopes	-0.08	0.11	-0.53	0.07	-1.86	4.39
	Tau	58.20	33.47	1.04	164.03	0.23	0.53
	Sigma	52.86	27.83	21.90	164.15	1.90	4.14
	Mu	574.36	127.10	388.15	951.18	1.15	0.89
	Dprime	4.02	1.19	1.41	6.22	-0.22	-0.62
PVT	Lapses.slopes	19.45	18.37	0.81	102.60	2.30	5.68
	CoV.slopes	0.005	0.006	-0.003	0.03	2.26	5.94
	RT.slopes	6.75	9.26	-3.95	68.12	3.49	17.53
	Tau	111.18	100.09	19.08	600.42	2.48	6.72
	Sigma	21.59	13.73	0.00002	74.26	1.15	2.02
	Mu	286.97	40.43	203.27	441.06	0.70	0.90

In general, the extracted solution presented an adequate structure with no significant crossloadings and good interpretability. It is however noted that factor 5 loaded on just two variables which might not be ideal. Factor 1 explained a large amount of variance (39%) and loaded on many variables from each of the 4 sustained attention tasks. Factor 2, on the other hand, only loaded on Mu and Sigma from both SART and TOVA. Factor 3 and 5 explained only variables from the Clock. Finally, Factor 4 loaded onto variables of change over time of the SART.

Figure 3.5

Correlogram of all variables extracted from the 4 sustained attention tasks in Study 2.

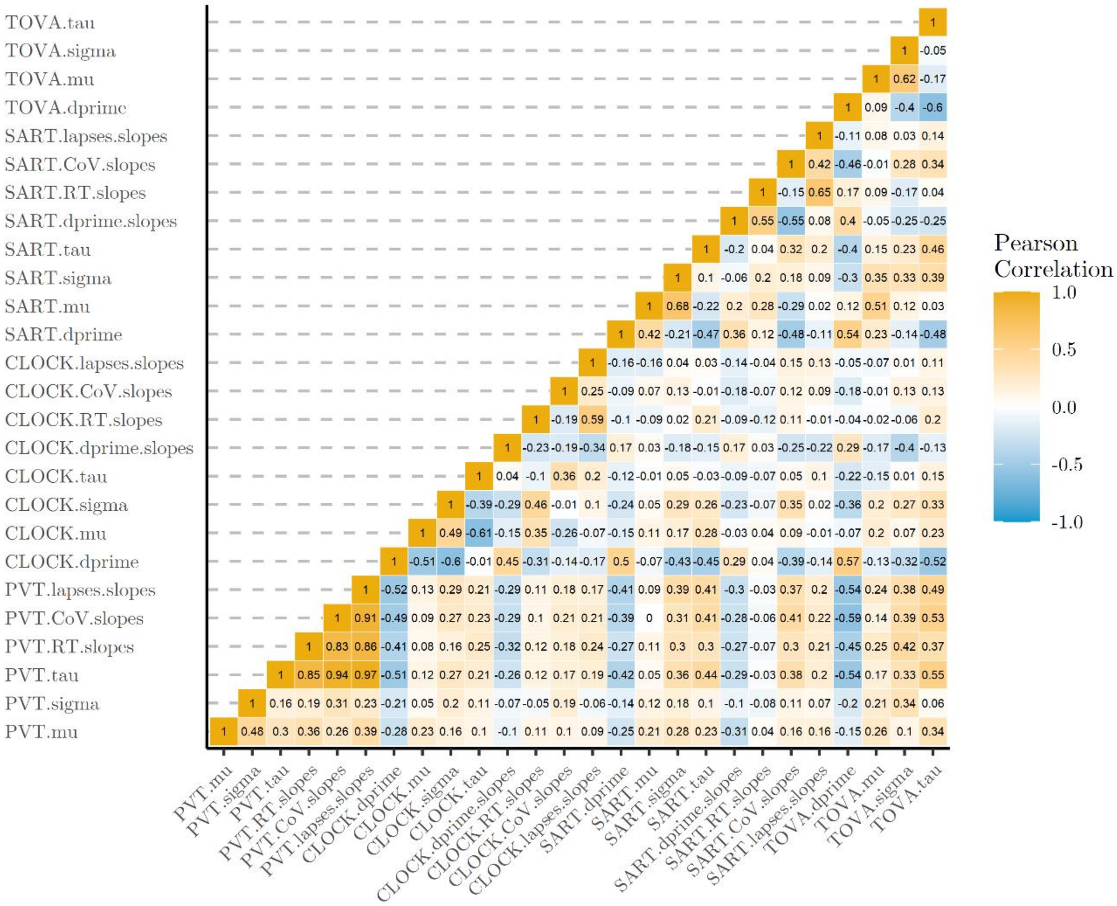


Table 3.5

Model fit indices of the solutions with 5 and 6 factors.

	RMSR	RMSEA
5-Factor	0.07	0.19
6-Factor	0.06	0.183

Table 3.6
Pattern loadings extracted from the 5-factor structure in Study 2. Values in bold reach significance (±0.58). Values in grey are below the +0.30 threshold of salience for interpretation.

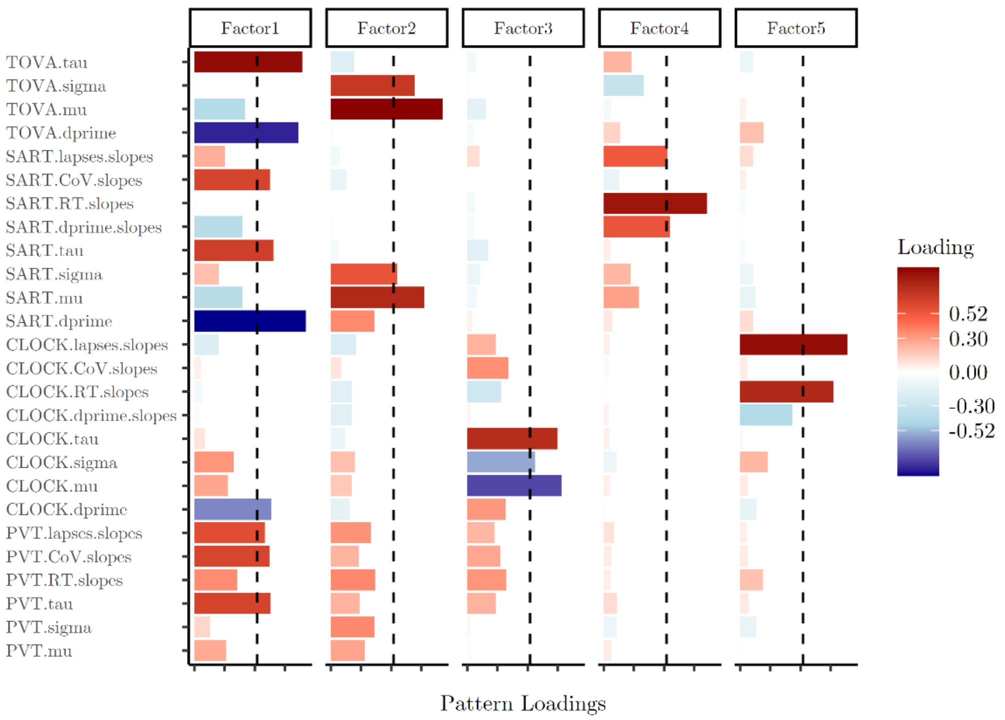
Task	Variable	Factor1	Factor2	Factor3	Factor4	Factor5
TOVA	Tau	**0.895**	-0.192	-0.074	0.233	-0.106
	Sigma	-0.013	**0.695**	0.010	-0.330	-0.005
	Mu	-0.423	**0.927**	-0.154	-0.063	0.045
	Dprime	**-0.862**	0.021	-0.053	0.137	0.193
SART	Lapses.slopes	0.252	-0.075	0.103	0.526	0.109
	CoV.slopes	**0.627**	-0.126	-0.010	-0.131	0.049
	RT.slopes	0.012	-0.004	-0.063	**0.856**	-0.048
	Dprime.slopes	-0.398	-0.024	-0.053	0.547	-0.019
	Tau	**0.656**	-0.063	-0.172	0.058	-0.044
	Sigma	0.200	0.549	-0.108	0.223	-0.110
	Mu	-0.399	**0.773**	-0.079	0.293	-0.126
	Dprime	**-0.924**	0.360	0.044	0.073	0.109
CLOCK	Lapses.slopes	-0.199	-0.210	0.236	0.051	**0.889**
	CoV.slopes	0.054	0.083	0.340	-0.041	0.060
	RT.slopes	-0.065	-0.176	-0.278	0.014	**0.775**
	Dprime.slopes	-0.041	-0.176	0.029	0.045	-0.435
	Tau	0.086	-0.118	**0.748**	0.050	0.025
	Sigma	0.326	0.200	-0.562	-0.108	0.228
	Mu	0.277	0.172	**-0.782**	0.054	0.065
	Dprime	**-0.638**	-0.156	0.320	-0.020	-0.138
PVT	Lapses.slopes	**0.584**	0.332	0.226	0.088	0.058
	CoV.slopes	**0.624**	0.233	0.272	0.062	0.067
	RT.slopes	0.354	0.366	0.323	0.055	0.191
	Tau	**0.633**	0.235	0.236	0.110	0.068
	Sigma	0.130	0.360	0.025	-0.105	-0.132
	Mu	0.262	0.280	-0.032	0.062	-0.015
Variance proportion		0.21	0.12	0.08	0.07	0.06
Cumulative proportion		0.21	0.33	0.41	0.48	0.54

Table 3.7
Correlation across the factors in Study 2.

	Factor1	Factor2	Factor3	Factor4	Factor5
Factor1	1.00	0.49	0.16	-0.09	0.53
Factor2		1.00	0.14	0.07	0.32
Factor3			1.00	-0.02	0.02
Factor4				1.00	-0.07
Factor5					1.00

Figure 3.6

Visual representation of the pattern loadings in the 5-factor solution of Study 2. The vertical dotted lines represent the significance (±0.58) threshold.



3.4 Discussion

The purpose of the studies was to evaluate the validity of different operationalisations of sustained attention using a factor analytical approach applied to two datasets. Taken individually, Study 1 investigated the structure of a dataset including variables extracted from a sustained attention task (CPT) and other cognitive domains and proved that the many dimensions of the task are not explained by a uniform underlying construct: sustained attention might have driven part of individuals' performance (attentional lapses and accuracy), however, many of the variables were explained by other factors and might have been representing task-specific contributions. Study 2 expanded on this and investigated whether a shared task-general construct would emerge among variables extracted from multiple sustained attention tasks. The analysis showed that, although many variables seemed to relate to task-specific factors, an underlying construct consistently explained attentional lapses and accuracy across tasks, suggesting that these parameters might constitute the more appropriate task-independent, core facet of sustained attention.

- Validating operationalisations of sustained attention

3.4.1 Study 1

Examining the extracted solution of the 5-factor model, it was clear that the many variables extracted from a CPT were not explained by a single factor: Factor 2 explained mu and sigma; Factor 3 loaded onto linear slopes of mean RT, CoV RT and RT lapses; Factor 5 explained slopes of dprime. The remaining CPT variables of dprime and tau were explained by Factor 1.

Regarding the CPT-specific factors (2,3 and 5), the variable structure did not seem to follow similar investigations. Mirsky et al. (1991) utilised only three variables from the CPT (number of correct responses, commission errors and mean RT) which loaded together. In the study by Egeland and Kovalik-Gran (2010) where a more extensive number of variables from a CPT was extracted, one of the factors again explained mean RT and commissions. Conversely, in the present study, dprime, as an aggregated measure of correct responses and false alarms (commission errors), was not explained by the same factor of mean RT (mu).

This discordance could be explained by the different task requirements in the CPT of the present study. In the Vigil task, participants were asked to produce a response whenever they detected the target sequence of stimuli, similarly to what participants were asked in the other previously mentioned study. The difference, however, lies in the target ratio of the stimuli: the Conner's CPT (and the CPT used in (Mirsky et al., 1991)) is considered to be a test with high signal-to-noise ratio (90%), where participants respond to most stimuli; the Vigil, on the other hand, has a low signal-to-noise ratio (21%).

Difference in the target ratios in CPTs are known to have an effect on performance and participant's strategy (Moss et al., 2016). The fact that participants have to physically produce a response often whilst inhibiting responses for rare stimuli, compared to detecting rare targets, might induce an under-aroused state that results in more automated responses and ultimately a different response strategy affected by the speed-accuracy trade-off (Manly et al., 1999; Seli, Jonker, Cheyne, et al., 2013). These differences in the factor structures might, in fact, be due to the fact that in the Vigil mean RT (mu) and performance accuracy (dprime) were not correlated due to different task requirements.

- Validating operationalisations of sustained attention

Nonetheless, not every aspect of the present analysis was different from Egeland and Kovalik-Gran (2010) as a similar pattern of results were found regarding the performance changes over time. More specifically, Factor 3 from both analyses explained measures of RT changes over time in terms of mean and variability. It is possible that these comparable results across different forms of CPT might indicate a task-general construct of vigilance (decrement), or fatigue (Robison & Brewer, 2019). Interestingly, Factor 5 in both analyses explained changes in an accuracy measure over time, potentially indicating that although overall speed and accuracy might be correlated (in the Conner's CPT), they may not be in how they change over time (Reteig et al., 2019).

Focus will now be on Factor 1 of the present analysis, as it may be the most interesting aspect of the factor solution, and a potential representation of sustained attention. Firstly, this factor explained two particularly relevant variables in sustained attention: dprime, the indication of overall detection accuracy and traditional index of vigilant performance (Mackworth, 1948), and tau, the tendency of participants to have very slow reaction times and indication of attentional lapses (Gallagher et al., 2015). Secondly, the factor also explained multiple other measures from the other cognitive test, including intelligence (NART), processing speed (DSST), fluency (FAS) and working memory (SWM, Pattern recognition).

Although these correlations within Factor 1 might be indicative of undesirable convergent validity under a MTMM approach, an alternative but complementary perspective is the *nomothetic span*. This concept refers to the network of relationships between measures of the same and of different constructs (Strauss & Smith, 2009). In this framework, convergent validity should not only be about correlations between measures of the same construct, but also between constructs *expected* to be correlated. Individual differences investigations of multiple cognitive domains have shown that sustained attention is in fact associated with a task-general executive control factor (in this study, FAS, SWM, Pattern recognition), and factors of speed (DSSQ) and fluid abilities (NART) (Buehner et al., 2006; Unsworth et al., 2009, 2010).

This evidence seems to point towards Factor 1, and more specifically tau and dprime calculated in the Vigil CPT, as the more robust measure of sustained attention.

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A recent factor analytical study adds to that by investigating whether tau as an indicator of attentional lapses is task-general: Unsworth and colleagues collected a large sample size of participants who completed multiple tasks measuring several cognitive abilities, as well as multiple sustained attention tests; their analyses proved that measures of lapses from all the sustained attention tasks was explained by a shared underlying factor (Unsworth et al., 2021). It might then be tempting to consider the Vigil tau as part of this task-general construct of attentional lapses and the correct operationalisation of sustained attention, as well as dprime, as it is computed by not only correct response but also by commission errors (which are frequently used as indicators of lapses). Study 2 investigated whether this factor could be considered task-general.

3.4.2 Study 2

Study 1 showed that dprime and tau might be the most appropriate operationalisation of sustained attention using a CPT, but what if a different task was used? In Study 2, variables were extracted from the most widely used types of sustained attention task, with the aim of investigating the presence of a task-general construct. Interestingly, as with Study 1, a 1-factor solution did not seem appropriate to capture all the variance of the dataset, showing that underneath the variable matrix there were multiple latent constructs. In order to understand exactly what the nature of these factors was, it is important to examine the details of the factor loadings.

Firstly, considering Factor 2 which explained mu and sigma (overall speed and variability) of the SART and the TOVA. This factor might represent CPT-specific requirements, similarly to Factor 2 found in Study 1. The SART, the TOVA and the Vigil (Study 1) all have characteristics of a traditional CPT, with a fast, continuous presentation of stimuli and a constant inter-stimulus-interval. Interestingly, they had different target rates: the SART has a high signal-to-noise ratio; the Vigil a low signal-to-noise ratio; the TOVA, on the other hand, has both rates, split in the two halves of the task. Although with differences in the task features, this robust correlation between response speed and variability might indicate the overall finding that in CPTs participant tend to become slower and variable in their responses when sustained attention is sufficiently taxed to induce a vigilance decrement (Esterman et al., 2013; Thomson, Smilek, et al., 2015).

Factor 3 and Factor 5 explained variables extracted only from the Clock test. The fact that these factors did not contribute to any other task's variables could be explained by the unique nature of the Clock test: among the tasks implemented in the present study, it had the lowest target rate and the longest length. Compared to the CPTs and the PVT, participants had in fact to wait and produce a motor response only for very rare targets, for a very long time (the entire experimental session). These unique requirements might have driven the separation in the factor structure.

Factor 4, on the other hand, loaded only on variables of change over time obtained from the SART, in a similar way as Factor 5 did for the Clock. In this example of multiple underlying latent components driving performance in a task, Factor 4 (SART) and Factor 5 (Clock test) might represent a construct associated with the vigilance decrement, or the individual's sensitivity to fatigue due to the tasks' demanding requirements, sometimes found dissociated from overall levels of performance (Esterman et al., 2014).

Finally, Factor 1 was found associated with many variables extracted from each sustained attention task. Remarkably, this factor explained most dprime variables of accuracy (except in the PVT, which does not provide an accuracy measure), and all variables tau of attentional lapses, similarly to Factor 1 in the Vigil CPT in Study 1. The Clock test was the only task were tau was not associated with Factor 1, and it can be explained by the particular emphasis in the instructions on detecting the rare targets, rather than fast responses (Kaida et al., 2007).

Interestingly, factor 1 also explained some measures of change over time in the PVT and in the SART which could be related to the vigilance decrement. The fact that these time-on-task effects were not explained by a single underlying factor (Factor 1, 4, 5), could mean that the rate of change in individual's performance might be more dependent on task-specific features, rather than an individual differences trait, although alternative views exist in the literature. Robison and Brewer (2019) in fact showed that across multiple studies a vigilance decrement could be consistently found as an individual differences. It is hence not possible to conclude with certainty whether vigilance decrement is a task-general or task-specific construct and further research is recommended.

Nonetheless, considering the findings from both studies, it was possible to infer that across these multiple tasks there actually was a task-general latent variable explaining overall accuracy (dprime) and the tendency of experiencing attentional lapses (tau), and that this construct could represent the individual's sustained attention ability. Consequently, the appropriate operationalisation of the function did not seem to depend on the task utilised, but rather on the variables extracted.

What does this mean in the context of 50 years of past research? Thankfully, from the literature, a relieving picture emerges. Studies utilising the PVT usually focus on lapses as primary variable of interest, even though different definition of lapses exist (e.g., RT $>$ 500ms (Basner & Dinges, 2011; Lee et al., 2010)). Traditional studies which employed the Clock test consistently focused on perceptual sensitivity (dprime) as the ability of detecting rare targets (Mackworth, 1948). Finally, research implementing CPT tasks relied on performance accuracy measures of dprime or commission errors (which participate in computing dprime as an aggregated measure), or measures of response variability which are believed to represent attentional lapses (Carter et al., 2013; Manly et al., 1999). The present studies therefore suggest that a significant portion of the literature, although characterised by a large variability in methods and definitions, may be referring to the same underlying facet of sustained attention.

To conclude, the more robust operational definition of sustained attention should be focused on either the capacity of detecting rare targets, or the tendency of experiencing attentional lapses. This definition is robust across tasks, however task-specific factors should be considered in the research design.

Chapter 4 - Sustained attention and intrinsic motivation

4.1 Introduction

The path to understanding the interaction between motivation and sustained attention will focus first on intrinsic motivation. An extensive introduction to the general topic of motivation can be found in section 1.6.

Sustaining attention for an extended period of time in a difficult task is demanding, however, feeling motivated may, intuitively, improve the individuals' task performance. Indeed, the literature has shown that motivating participants can lead to better sustained attention performance (Esterman et al., 2016). Yet, motivation is a complex construct comprising multiple dimensions, and its role in affecting sustained attention has not been wholly comprehended: research has, in fact, focussed mostly on extrinsic manipulations of motivation through some forms of reward (Sipowicz et al., 1962), and it has largely neglected the most intrinsic characteristic of motivation, which can be considered an individual difference.

Before examining what existing research has demonstrated, it is worth considering the construct definition of intrinsic motivation. Intrinsic motivation can be defined as the tendency of pursuing a goal and persist for its inherent satisfaction and joy, rather than for some external incentive (Ryan & Deci, 2000a). From this perspective, intrinsic motivation is seen as a *trait*, a construct closer to being part of an individual's personality, a stable, predictable and enduring disposition (Wasserman & Wasserman, 2020a). Motivation can however also be considered a *state*, a temporary mental condition that one experiences for a limited amount of time. In this case, intrinsic motivation is associated to achievement motivation, which is activity- and situation-specific and usually related to goal-setting (E. A. Locke & Schattke, 2019): when individuals find an activity in which they can identify their interests, or when they find it particularly enjoyable, they will feel more motivated and more likely to participate actively.

In the context of sustained attention research, intrinsic motivation is usually considered as being part of a larger model of stress and close to the concept of task engagement which relates to the willingness of participants to do well in a task, how concentrated they feel and how interested they are (Matthews, 2016). Intuitively, the more intrinsically motivated, the better participants will perform in an activity. A recent, large meta-analysis based on a sample size of more than 200,000 participants showed that intrinsic motivation is a consistent positive predictor of performance in many cognitive tasks (Cerasoli et al., 2014).

A similar picture can be found in the sustained attention literature: for instance, intrinsic motivation as representation of task engagement was found predicting signal detection capability in a vigilance task (Matthews & Campbell, 2009). These results can be explained in the resource depletion hypothesis framework (Warm et al., 2008): sustaining attention for an extended period of time draws from a limited amount of cognitive resources that are depleted as time on the activity progresses; from this perspective, task engagement represents resource availability to the individual (Szalma & Matthews, 2015): more intrinsically motivated participants may have a larger pool of resource to use for the task and therefore may obtain better performance.

Other theoretical models of sustained attention also offer predictions on the effects of intrinsic motivation. The resource-control theory, the most comprehensive alternative view to the resource depletion, posits that as time-on-task unfolds, participants progressively lose motivation and fail to allocate cognitive resources to the task at hand, resulting in additional mind-wandering (Thomson, Besner, et al., 2015). From this point of view, higher intrinsic motivation might result in better allocation of the cognitive resources and less mind-wandering (or alternative activities).

Although the effect of motivation on sustained attention might seem particularly straightforward, and the initial examination of the literature seems to support this, there are instances of inconsistent effects on performance. For example, in a study investigating sustained attention performance in zen meditators - which also included measures of task engagement - intrinsic motivation did not predict commission errors and reaction time measures obtained from a CPT (SART) (Cardeña et al., 2015). The different conclusions might be due to different task characteristics and overall task demands. Research that found intrinsic motivation as a significant predictor of performance utilised tasks with a low signal-to-noise ratio (signal probability 0.02 – 0.20) (Helton et al., 2009; Matthews et al., 2010; Shaw et al., 2010), whilst the SART has a different design where participants produce a response much more often (probability around 0.90) and inhibit their response for rare target stimuli.

The relationship between intrinsic motivation and sustained attention performance might then depend on the task-requirements, and a conclusive answer to how they interact irrespective of the task is yet to be found. Additionally, it is worth considering that, to the author's knowledge, all existing research has investigated state intrinsic motivation, whilst neglecting its trait-level. The two present studies were therefore designed to contribute to these issues.

4.1.1 Study 3

Study 3 aimed to explore the interaction between trait level motivation and sustained attention performance measured across multiple tasks. This study was a continuation of Study 2: after the extraction of the 5-factor structure, the individual's factor scores were estimated to have a parsimonious index of cross-tasks performance. Then, a measure of trait intrinsic motivation was used to predict factor scores.

Although the study had an exploratory approach as no previous research has looked into the effects of trait-intrinsic motivation on sustained attention performance, it was hypothesised that a relationship would be found. As traits are characteristics of a persona that are stable over time, different levels of trait-motivation might change the overall strategy in approaching a task (e.g., focusing more on accuracy, instead of speed, or vice versa), rather than inducing a higher/lower performance overall.

4.1.2 Study 4

Study 4, on the other hand, aimed at clarifying the effects of intrinsic motivation on sustained attention performance by controlling for the potential confounding factors of task target-rate.

The study employed a task that was characterised by two different target rates, with either low or high signal-to-noise ratio. This unique task characteristic permitted to control for differences between the two halves of the task, and to obtain a more accurate estimation of the predicting capabilities of intrinsic motivation on sustained attention variables. As previously shown in existing research it was hypothesised that

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state intrinsic motivation would explain performance in the task, and it was predicted that higher intrinsic motivation would predict better sustained attention performance.

4.2 Study 3

4.2.1 Method

This study is a further analysis of Study 2 in which a factor analysis was run on variables extracted from multiple sustained attention tasks. The description here will focus on elements of the design which were not mentioned previously. For details on the participants, on the sustained attention tasks and on the analyses, it is recommended to refer directly to Study 2.

4.2.1.1 Materials

The 5-factor solution obtained in Study 2 was used to obtain factor scores for each individual as comprehensive indices of sustained attention performance across the multiple tasks: Mackworth Clock test (Clock), Sustained Attention to Performance Task (SART), Psychomotor Vigilance Test (PVT) and the Test of Variables of Attention (TOVA). Details of the associations between task variables and factors can be found in Table 4.1. As part of the original design, participants also completed the Starkstein Apathy Scale (AS) questionnaire (Starkstein et al., 1992) before performing any sustained attention task. This questionnaire was originally developed to provide a measure of apathy, however, the inversed scores can also be used as a trait-level measurement of intrinsic motivation (Kawagoe et al., 2020).

4.2.1.2 Data analysis

The factor extraction utilised in Study 2 implemented an oblique rotation to allow correlations among factors. In order to compute factor scores whilst also preserving the inter-factor correlations, the ten Berge method was employed (Ten Berge et al., 1999). Data from the AS was extracted from the raw datasets downloaded from Gorilla and scored following author's instructions. The relationship between the trait motivation and the factor scores was then investigated using Pearson correlation tests.

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4.2.2 Results

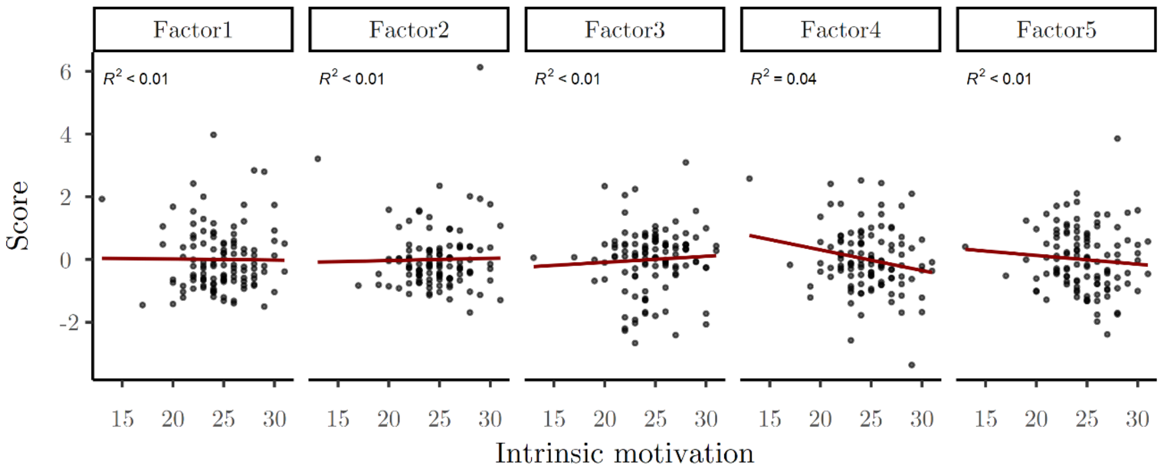
The intrinsic motivation index (Figure 4.1) did not correlate with Factor1 (r(111) = -0.01, p = 0.92), or Factor2 (r(111) = 0.02, p = 0.82), Factor3 (r(111) = 0.06, p = 0.54), nor Factor5 (r(111) = 0.08, p = 0.38). Motivation however showed a significant negative correlation with Factor4 (r(111) = -0.20, p = 0.04).

Table 4.1
Distribution of variables obtained in the 5-Factor structure extracted from Study 2. Variables reported here reached the minimum significance threshold in their pattern loadings. The minus sign indicates negative pattern loadings whilst the positive sign is omitted for positive loadings. Refer to Study 2 for details on the pattern loadings.

Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
-TOVA dprime	TOVA sigma	Clock tau	SART lapses slopes	Clock lapses slopes
-SART dprime	SART sigma	-Clock sigma	SART RT slopes	Clock RT slopes
-Clock dprime	TOVA mu	-Clock mu	SART dprime slopes	
TOVA tau	SART mu			
SART tau				
PVT tau				
SART CoV slopes				
PVT lapses slopes				
PVT CoV slopes				

Factor4 loaded onto measures of performance change in the SART (Table 4.1): positive pattern loadings of the lapses' slopes, RT slopes and dprime slopes indicated a potential speed/accuracy trade-off – participants with higher Factor4 scores tended to have slower responses with time-on-task but showed higher performance accuracy.

Figure 4.1
Visual representation of the correlations between trait-motivation and the factor scores of Study 3. Only Factor4 showed a significant negative correlation, although of low extent – as can be seen from the low amount of variance explained by motivation.



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The negative correlation with intrinsic motivation (Figure 4.1) meant that with higher motivation participants showed a shift in their response strategy as the task unfolded: at the cost of fewer accurate responses, they tended to produce faster responses and less attentional lapses.

4.3 Study 4

4.3.1 Method

4.3.1.1 Participants

A sample of 33 Newcastle University Psychology students was recruited using the online SONA Systems (https://www.sona-systems.com), who were then compensated with course credits. The advertisement of the study included a link to Gorilla (Anwyl-Irvine et al., 2020), an online platform where the study was hosted. After completion of the data collection, 2 participants showed irregular datasets (higher than normal number of task trials) potentially due to technical issues and were hence excluded from the analysis. The resulting 31 participants had an age range of 18 – 21 (19.40 mean age (SD = 0.84)), and included 25 females, 5 males and 1 who preferred not to respond. The study received approval from the Newcastle University Ethics Committee (Ref: 16968/2021).

4.3.1.2 Materials and procedure

Each participant performed in a session of the Test of Variables of Attention (TOVA, (Greenberg, 2011)) a Continuous Performance Task (CPT) recreated on Gorilla. Parameters, stimuli and a detailed general description of the task can be found in Study 2. In this particular version of the task, the order of the two halves (corresponding to high/low target rate) was counterbalanced to avoid any order effect. Additionally, participants completed the Dundee Stress State Questionnaire (DSSQ, (Matthews, 2016)) twice, before and after the TOVA. The DSSQ is a questionnaire developed to measure several aspects of stress and state variables and is pervasively used in vigilance research. It comprises 90 items measuring the broad factors of task engagement, distress and worry. Of particular interest for the present study, within task engagement, two measures of state motivation can be computed: *intrinsic* *motivation,* measuring one's interest in the task at hand, and *success motivation,* which assesses the intention of performing well in the task. Scoring of the items followed the original author's instructions, obtained with permission. The online session took place at a convenient time selected by each participant, who were instructed to close any other additional browser tab, application or distraction to focus on the study. Once started, participants were recommended not to leave until completion or else the data would be invalidated.

4.3.1.3 Data analysis

Upon completion of the data collection, the raw data from Gorilla was downloaded, extracted and inspected. Two participants were excluded due to irregularity in the datasets as mentioned above.

4.3.1.3.1 Variable extraction

In order to obtain a good characterisation of sustained attention performance, several variables were computed from the TOVA, in a similar manner as the previous studies. From reaction times (RT) of correct responses over 100ms (Luce, 1986), an Ex-Gaussian curve was fit to individuals' datasets, and parameters mu, sigma and tau were used to represent overall speed, variability and tendency of attentional lapses, respectively. Due to the multi-faceted requirements of the TOVA (detection and inhibition of rare targets), d-prime was used as a comprehensive measure of performance accuracy. Using a specific type of error instead (e.g., commission error) would've been more representative of one half of the dataset only (commission errors are in fact more relevant for the inhibition-half). These variables were extracted for the two halves of the task separately for each individual. Data from the DSSQ was scored according to standardised instructions and indices of intrinsic and success motivation were calculated for each individual.

4.3.1.3.2 Statistical Analysis

Firstly, as a preliminary step, it was assessed whether the order of presentation of the two TOVA halves (high/low target rate) had an effect on performance. To do this, two groups were computed based on the two possible orders, and performance differences were tested using simple between-subject t-tests. Secondly, a regression

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analysis was performed to test whether the state motivation measures from the DSSQ would explain variance in the TOVA variables. These regressions also included a variable of task-half, which represented the effect of target-rate, and allowed the investigation of the effects of intrinsic motivation regardless of target-rate. After fitting the equations, model residuals were examined and in case of abnormal distributions, a transformation of the dependent variable was implemented. Additionally, the correlation matrix of the motivation variables was computed. This was necessary to examine the potential multicollinearity of multiple indices obtained from the same questionnaire which may impact the parameter estimation.

4.3.2 Results

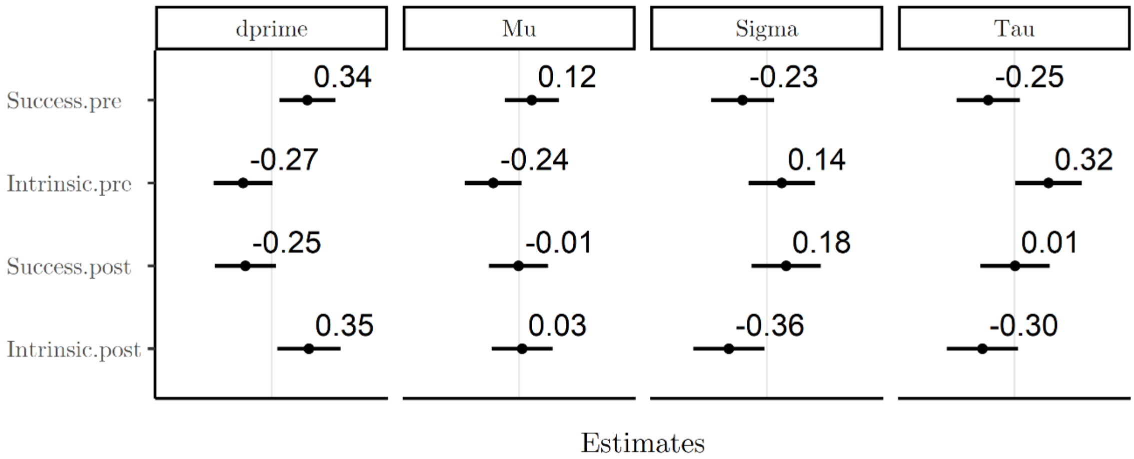
4.3.2.1 Order effects

RT variables did not differ between the two orders of task requirements: mu ($t(29) = -0.60$, $p = 0.60$), sigma ($t(29) = 0.10$, $p = 0.90$) and tau ($t(29) = 0.20$, $p = 0.80$) did not depend on the order of the TOVA. Performance accuracy measured by dprime also did not differ between the two groups ($t(29) = 0.05$, $p = 1.00$).

4.3.2.2 Regression analysis

The regression models (Figure and Table 4.2) included a term indicating the target rate (low and high) corresponding to the two halves of the task. As it was not relevant to the purposes of the study, results relative to this term will be omitted here

Figure 4.2
Forest plot of the regression models, including only the motivation estimates of Study 4. The estimates are standardised for ease of interpretation. Bars represent confidence intervals, and the vertical lines represent the 0.



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(see however Table 4.2 for complete parameter estimates). The regression model investigating the effects of state motivation and task-half on the Ex-Gaussian mu did not show any significant effects of intrinsic motivation ($p > 0.05$). Sigma, on the other hand, was predicted by intrinsic motivation measured after the task ($b = -1.50$ ($\beta = -0.36$), $p = 0.037$); as motivation increased, RT variability decreased. Tau was predicted by intrinsic motivation measured before the task ($b = 4.01$ ($\beta = 0.32$), $p = 0.044$); with increased motivation, tendency of attentional lapses increased. Dprime was predicted by success motivation measured before the task ($b = 0.065$ ($\beta = 0.34$), $p = 0.013$) and intrinsic motivation measured after the task ($b = 0.07$ ($\beta = 0.35$), $p < 0.001$): as both motivation variables increased, perceptual accuracy also increased. The correlation matrix of the motivation predictors did not display critical evidence of multicollinearity (Table 4.3).

Table 4.2
Regression coefficients of the models predicting sustained attention variables in Study 4. Significant predictors are in bold.

Dprime		Estimate	Std. Error	T-value	P-value
	(Intercept)	2.807	0.554	5.068	< 0.001
	Success.pre	**0.065**	**0.025**	**2.556**	**0.013**
	Intrinsic.pre	-0.067	0.034	-1.941	0.057
	Success.post	-0.045	0.027	-1.712	0.092
	Intrinsic.post	**0.074**	**0.031**	**2.366**	**0.021**
	Target.rate	**-0.454**	**0.111**	**-4.101**	**0.000**

Mu		Estimate	Std. Error	T-value	P-value
	(Intercept)	378.213	40.583	9.319	< 0.001
	Success.pre	1.731	1.850	0.935	0.354
	Intrinsic.pre	-4.607	2.524	-1.825	0.073
	Success.post	-0.090	1.942	-0.046	0.963
	Intrinsic.post	0.447	2.291	0.195	0.846
	Target.rate	**-43.150**	**8.118**	**-5.315**	**< 0.001**

Sigma		Estimate	Std. Error	T-value	P-value
	(Intercept)	70.576	12.478	5.656	< 0.001
	Success.pre	-0.874	0.569	-1.537	0.130
	Intrinsic.pre	0.701	0.776	0.903	0.370
	Success.post	0.671	0.597	1.123	0.266
	Intrinsic.post	**-1.503**	**0.704**	**-2.133**	**0.037**
	Target.rate	-4.891	2.496	-1.959	0.055

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Tau		Estimate	Std. Error	T-value	P-value
	(Intercept)	136.662	31.332	4.362	< 0.001
	Success.pre	-2.362	1.429	-1.654	0.104
	Intrinsic.pre	**4.006**	**1.948**	**2.056**	**0.044**
	Success.post	0.061	1.500	0.040	0.968
	Intrinsic.post	-3.172	1.769	-1.793	0.078
	Target.rate	7.399	6.268	1.181	0.243

Table 4.3
Correlation matrix of the motivation variables obtained from the DSSQ.

	Success.pre	Intrinsic.pre	Success.post	Intrinsic.post
Success.pre	1.00	0.11	0.52	0.03
Intrinsic.pre	0.11	1.00	0.31	0.61
Success.post	0.52	0.31	1.00	0.41
Intrinsic.post	0.03	0.61	0.41	1.00

4.4 Discussion

The aim of the present studies was to provide a better understanding on how intrinsic motivation interacts with sustained attention. Study 3 tested for the first time whether intrinsic motivation measured at the trait-level predicted performance across multiple sustained attention tasks and showed that this does not seem to be the case. Study 4, conversely, tested whether state intrinsic motivation predicted performance in a sustained attention task while controlling for target rate, and found that different facets of intrinsic motivation predict different variables of sustained attention.

4.4.1 Study 3

Study 3 was a direct continuation of Study 2, where factor analysis was employed to investigate the structure of a variable matrix obtained from multiple sustained attention tasks. Using the factor scores estimated from the factor structure provided parsimonious measures across tasks. The results showed that trait intrinsic motivation only predicted Factor4 scores. This factor was related to measures of change over time in the SART task of mean RT, attentional lapses and dprime. The relationship found here meant that with increased motivation, participants tended to show negative linear change over time in response speed, attentional lapses (tendency to have very slow RT) and perceptual sensitivity. In other words, more motivated participants tended to have a shift in their response strategy, leading to a faster response behaviour at the cost of performance accuracy.

This finding entailing a speed-accuracy trade-off in the SART is unsurprising as it frequently shows the phenomenon (Dang et al., 2018; Seli, Jonker, Cheyne, et al., 2013). What is interesting is that motivation seemed to influence response strategy, rather than overall indices of performance, with participants prioritising response speed over accuracy. This result is somewhat unintuitive and disagrees with what theories of sustained attention predict. In fact, the implicit difficulty of the SART is to avoid the natural tendency of developing an automatic manner of responses due to the high number of non-target trials while inhibiting responses for rare target trials (Robertson et al., 1997).

It is then possible that more motivated participants would be less vulnerable to this as the task unfolded and would attempt to maintain high performance accuracy at the cost of slower responses. This pattern of performance would be in accordance with the resource control theory of sustained attention (Thomson, Besner, et al., 2015): more motivated participants would exert more control over their natural tendency of drifting towards easier, automated responding, maintaining high performance accuracy. This however was not what the data showed, as motivated participants tended to prioritise speed over accuracy, potentially due to more automated, less deliberate responses as the SART progressed over time.

In the perspective of the opportunity cost model (Kurzban et al., 2013) that posits that individuals choose the activity depending on the trade-off between perceived costs and benefits, more motivated participants seemed to lean towards an automated response strategy which required less effort, potentially due to higher perceived costs in the alternative strategy (slower and deliberate) or higher benefits in the easier option. In the context of sustained attention tasks, the alternative activity is usually considered mind-wandering, however, evidence has shown that participants with higher trait intrinsic motivation have a lower tendency for mind wandering (Kawagoe et al., 2020).

It might then be that the phenomenon observed cannot be explained by these models. Although disagreeing with the evidence that motivation can alone improve both speed and accuracy (Manohar et al., 2015), a potential explanation of this phenomenon is that the SART is a difficult task that induces fatigue, and fatigue is usually accompanied by a slower motor response (Rozand et al., 2015) that traduces to slower reaction time. Possibly, more motivated participant tried to counteract the effects of fatigue by attempting faster responses with the consequence of more commission errors that were then reflected by a decrease in dprime. These motivated participants might have been aware of their mental fatigue which caused worry over their performance level, a state that was shown to drift the speed-accuracy trade-off towards faster and less accurate responses (Hallion et al., 2020). This interpretation is nonetheless speculative as the subjective state of worry was not assessed and should be considered with caution.

This explanation aligns with a recent study that found that higher (reward) motivation corresponded to faster performance with more commission errors, potentially due to higher proactive control strategy (H. S. Locke & Braver, 2008) employed by the participants facing the increasing costs of performing the task. Proactive control usually refers to the retention of contextual information to prime responses, and in this case it might have been constituted by the continuous presentation of trials that required a response.

Nevertheless, to the author's knowledge, very few studies looked at correlations between motivation measures and changes in performance over time. Although focusing on state motivation (see below Study 4), recent research found that intrinsic motivation predicted not only overall levels of performance accuracy (positive correlation), but also changes of performance over time showing that higher motivation corresponded to lower change over time (Matthews et al., 2010).

The present results should then be interpreted with caution. Two reasons might explain them: firstly, the correlation significance might be resulting from a type-1 error; in fact, a more strict, confirmatory approach implementing a p-value correction would've caused the correlation to be non-significant; secondly, the instrument used to measure trait-level motivation might not have been the most ideal as it was originally designed to measure apathy which is not necessarily a construct at the axial opposite of motivation. Finally, Study 2 showed that the more robust operationalisation of sustained attention did not include the measures of change over time in the SART task. It is then not possible to conclude whether these results, credible or not, could be generalised to other sustained attention tasks or sustained attention itself, or whether they are the produce of the specific combination of SART and apathy scale.

4.4.2 Study 4

After the initial exploration of how trait-level intrinsic motivation might influence sustained attention performance, Study 4 focused on state intrinsic motivation. This study employed the Test of Variables of Attention (TOVA), a test that allowed to control for the effect of target rate and obtain a better estimation of how state motivation interacts with sustained attention variables. Although the general consensus among different theories of attention is that intrinsic motivation aids performance in sustained attention tasks, not every study has found this effect (Cardeña et al., 2015), likely because of different tasks employed that differed in target-stimuli rate. Excluding the effect of target rate would allow a clearer estimation of the relationship between intrinsic motivation and sustained attention performance.

Results showed that higher DSSQ index of intrinsic motivation measured post-task predicted lower RT variability and better accuracy; that higher intrinsic motivation measured pre-task predicted a higher tendency for attentional lapses; finally, higher success motivation pre-task predicted higher performance accuracy.

For a clearer interpretation of these results, it is essential to summarise how DSSQ intends intrinsic motivation. The questionnaire was originally developed to measure situational stress in operators, and included three main factors of task engagement, distress and worry (Matthews, 2016), tapping into the domains of motivation, cognition and affect. The motivational domain was considered part of the broader task engagement factor and included the dimensions of *intrinsic* and *success* motivation. Intrinsic motivation describes the enjoyment of doing an activity regardless of the outcome; success motivation closely relates to achievement motivation, and refers to the willingness to perform well, even whilst disliking the activity (Matthews et al., 2001). As these measures are obtained before and after the task, using a slightly different wording, their interpretation needs consideration.

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The first part of the questionnaire attempts to measure the individual's expectations towards the task ("at the moment"), and their interest in performing well. In the second part, although the content of the items is the same, they specifically request participants to refer to how they felt "during the task". Some of the items reflect pre-task expectations (e.g., "I expect to find the task boring") versus post-task judgements ("I found the task boring"). Pre-task measurements can be considered as indices closer to trait motivation, as they are measured independently of an activity, and they have been found correlated with trait/personality measures (Matthews, 2021; Matthews, Gerald et al., 2013). Although they can be used as predictors of performance, their most common use is as baseline estimation of individuals' state to be compared to the post-task indices which represent states *during* the task.

The present results are now considered with reference to these descriptions. The two different sub-indices of intrinsic motivation obtained before and after the task predicted different task-variables. Intrinsic state motivation post-task predicted more favourable sustained attention performance in terms of accuracy and RT variability. Success motivation pre-task also contributed to predicting overall performance accuracy. Interestingly, higher intrinsic motivation pre-task predicted an increase in RT tau which represents the tendency to have very long responses (attentional lapses). These results partially replicate a similar study in which the effects of state motivation (measured using the DSSQ) were correlated to sustained attention performance across two different tasks (sensory and cognitive). More specifically, both post-task intrinsic motivation and pre-task success motivation contributed in predicting performance accuracy (Neigel, Claypoole, & Szalma, 2019).

Although measured at different times, intrinsic and success motivation are considered part of a larger task-engagement factor, that is frequently found predicting vigilant performance either measured before or after the task (Helton et al., 2008; Matthews et al., 2010; Reinerman et al., 2007). This task-engagement component, which relates to commitment to effort, is usually associated with the pool of limited cognitive resources participants draw from during a sustained attention task: higher task engagement corresponds to availability of resources and therefore better performance (Matthews, 2021). An alternative view of task engagement is in terms of resource allocation (Szalma & Matthews, 2015), and this could explain the relationship between post-task intrinsic motivation and RT variability of the present results. Motivated participants might have felt more inclined to allocate the available resources to the task, resulting in a more consistent, less variable performance (Herlambang et al., 2021).

The unexpected finding from the present study is that more intrinsically motivated participants before the task produced more attentional lapses, which goes against the most recent investigations on the topic (Unsworth et al., 2021). One potential reason explaining this pattern of results is that task engagement is believed to be a predictor of performance only when the task at hand is sufficiently difficult to tax sustained attention (Matthews et al., 1990). It may be possible that participants who had higher intrinsic motivation felt the task to be too easy, failed to allocate the required cognitive resources to the task at hand, and experienced mind-wandering/task-unrelated-thoughts, which can sometimes be seen in more skilled individuals (Levinson et al., 2012).

Alternatively, a potential - although speculative - explanation might be found in the literature of perfectionisms. Intrinsic motivation is, in fact, closely related to self-oriented perfectionism, which regards the self-imposed beliefs of striving for perfection and to excel. This is in turn associated with test-pressure, and worry, which might have impacted task performance (Stoeber et al., 2009).

Finally, a more straightforward explanation might be that individuals who approached the task with high levels of intrinsic motivation, felt overconfident and underestimated its difficulty, and produced worse performance in terms of lapses. Nonetheless, this proves that intrinsic motivation measured after the task might be the more appropriate index of intrinsic motivation in the DSSQ.

To summarise, Study 3 showed that the effects of trait-level intrinsic motivation on sustained attention performance might not be as relevant as state-level motivation (Szalma & Matthews, 2015). The results here were of difficult interpretation, and additional investigation is certainly required to reach meaningful conclusions. Study 4 showed, on the other hand, that regardless of the target-rate of a sustained attention task, state-level intrinsic motivation predicted overall accuracy and variability in accordance to the resource-control theory of sustained attention and the role of task-engagement (Warm et al., 2008). This study also showed that post-task DSSQ indices are the more appropriate indices of intrinsic motivation.

Chapter 5 - Sustained attention and extrinsic motivation

5.1 Introduction

The project so far has shown that sustained attention is a psychological construct that can be detected across different methods of measurements, in the dimensions of performance accuracy and long-variability (attentional lapses). Furthermore, the investigation of the interaction between sustained attention and motivation showed that trait-level intrinsic motivation might not be enough to elicit any direct effects on performance. State-level motivation, on the other hand, can influence accuracy and variability when the correct assessment tool is used. This chapter focused on extrinsic motivation and attempted to clarify the effects of reward on sustained attention performance, while controlling for individual differences in intrinsic motivation and implementing a careful behavioural examination.

If intrinsic motivation pertains to the doing of an activity for its inherent enjoyment, extrinsic motivation relates to performing an activity for the possibility of obtaining an external incentive (Ryan & Deci, 2000a). One of the reasons for focussing on external incentives can be found in the type of performance sustained attention tasks usually require participants to produce. These tasks are repetitive, simple and do not rely on complex cognitive operations in order to be completed. They are a good example of *quantity* tasks. *Quality* tasks, on the other hand, tend to require more cognitive effort, are more complex and engage individuals more intensively. Motivational theories such as the Self-determination theory (Ryan & Deci, 2000b) and extensive evidence point towards an interaction between motivation type and task type: if intrinsic motivation is believed to affect quality tasks more, extrinsic motivation through external incentives is more relevant in quantity performance (Gilliland & Landis, 1992). A recent large meta-analysis indeed confirmed that when the focus of the performance is on quantity, as in sustained attention tasks, extrinsic motivation predicts more variance than intrinsic motivation, especially when the incentives are directly tied to performance (Cerasoli et al., 2014; Jenkins Jr. et al., 1998).

Theories of sustained attention, as previously discussed in this document, also include an explanation of how extrinsic motivation would impact performance. For instance, the resource control theory posits that in order to sustain attention for an extended period of time, the executive control system needs to allocate the information-processing cognitive resources to the task at hand. This operation is however effortful, especially when alternative, easier activities are available to an individual. With time, the executive control is unable to direct the ideal amount of resources to the primary task, and an increase of mind-wandering or distracting thoughts worsens attention performance (Thomson, Besner, et al., 2015). This model can potentially by seen from the perspective of the opportunity cost model (Kurzban et al., 2013). Decisions regarding what activity the executive control would prioritise are made based on the trade-off between perceived costs and benefits. If, at first, the sustained attention task might be considered mostly in terms of benefits, the related costs would increase over time, resulting in the executive control redirecting resources to a more beneficial and less costly activity such as mind wandering. This framework provides a direct explanatory role to motivation which interacts with the balance of benefits and costs of the task, and consequently improves task performance through a more sustained and effective engagement of the cognitive control system (H. S. Locke & Braver, 2008). Indeed, since very early research in the field, reward was demonstrated to improve performance in terms of perceptual sensitivity, variability and reaction times (Engelmann et al., 2009; Esterman, Poole, et al., 2017; Gergelyfi et al., 2015; Sipowicz et al., 1962).

The more dynamic aspect of the relationship between motivation and sustained attention through the deployment of cognitive control should however be examined in light of performance changes through time. Esterman and colleagues (2014), for instance, showed that although different types of reward (monetary and the potential of ending the experimental session sooner) enhanced overall indices of response accuracy and reduced variability, the vigilance decrement (time-on-task) in the corresponding variables did not seem to be affected by motivation. Utilising a different experimental design, Reteig and colleagues (2019) administered a very long (80 minutes) sustained attention task and presented an unexpected motivational monetary boost 20 minutes before the end of the task. Though the traditional vigilance decrement was present from the beginning of the task, performance immediately improved after the motivation manipulation, however the decrement soon resumed. Additionally, performance never returned to the individuals' best levels (Reteig et al., 2019). Motivation might indeed interact with the trade-off of costs and benefits, however, as predicted by the resource-control theories, the weight of the costs might increase, and the motivation would not be enough to restore performance or to avoid the vigilance decrement.

Nonetheless, other have found that under certain circumstances even the vigilance decrement can be eliminated if enough reward is provided. For instance, comparing the possibilities of losing either continuously a small amount, or abruptly a large amount, the latter condition produced an attenuation of the vigilance decrement (Esterman et al., 2016). To test the hypothesis that the amount of reward could affect all facets of performance, a recent study directly measured the subjective cost of performance. Although reward produced the robust improvements of overall performance, the vigilance decrement was still found (Massar et al., 2016).

A potential solution for these discordant results might be provided by assuming a combination of the allocation account and the resource depletion accounts (Lenartowicz et al., 2013). From this perspective, the allocation of attentional resources would be directed by the balance of subjective costs and benefits; yet the amount of resources would be limited. Effects of reward would then shift the trade-off of costs and benefits; however, the effect would be dependent on the availability of resources. As discussed previously, an indication of resource availability could be provided by state intrinsic motivation. Remarkably, none of the studies discussed above included a measure of state intrinsic motivation. The relevance of individual differences in intrinsic motivation to understand the effects of extrinsic motivation is also driven by the fact that the relationship between the two facets of motivation is not simply additive, but interactive (Cerasoli et al., 2014): reward might negatively affect the intrinsic motivation of an individual (Deci, 1972), potentially explaining the partial effects on performance.

The two studies presented here were designed to provide a clearer understanding of the effects of extrinsic motivation on sustained attention performance. To pursue this aim, in addition to implementing a reward manipulation, state levels of intrinsic motivation were also collected to control for individual differences. Additionally,

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following up on Studies 1 and 2, to obtain generalisable results, the focus of the analysis was on the task-general facets of sustained attention represented by attentional lapses and accuracy.

5.1.1 Study 5

Study 5 utilised a dataset previously published (Robinson et al., 2012), where the effects of individual differences in intrinsic motivation, and of a reward manipulation were examined on task performance. In the original paper, motivation effects were tested on the attention and memory domains. Results of the memory task showed that reward led to improved performance whereas intrinsic motivation predicted fewer errors; attention, on the other hand, showed susceptibility to reward on selective aspects of performance: faster cued responses and less distractions to incongruent cues. The present re-analysis utilised the attention task data.

Although this study did not implement a traditional sustained attention task, as it used the Attention Network Task (ANT, (Fan et al., 2002)) the standard methods of analysis used so far were implemented on the data obtained from the ANT based on the assumption that although the requirements were higher than usual, it still included components of attention, detection and inhibition. Nonetheless, it is important to consider that compared to traditional sustained attention tasks, the ANT might qualify as a *quality* task, given the shorter length and the more various raster of stimuli. If that was the case, reward might not be as effective as in *quantity* tasks.

Whilst acknowledging this potential issue, following the assumption stated above, it was hypothesised that reward would improve performance. It was also hypothesised that intrinsic motivation would predict performance.

5.1.2 Study 6

Study 6, on the other hand, used a newly acquired large sample of participants to further the understanding of how extrinsic motivation through reward impacts performance.

The study required participants to complete a session of the Sustained Attention to Response Task (SART, (Robertson et al., 1997)), a traditional CPT. The choice of the SART was motivated by its inclusion to the factor analysis in Study 2 which

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informed on the task-general variables that should be more carefully examined (attentional lapses and accuracy); additionally, it provided a fast data recording with a short and constant inter-stimulus-interval which was particularly useful in the implementation of frequency analyses of reaction time data, presented in Study 8.

The research protocol also comprised the Dundee Stress State Questionnaire (DSSQ, (Matthews, 2016)), a questionnaires frequently used to assess multiple state variables including intrinsic motivation. This allowed to control for individual differences in the analyses to obtain a clearer picture on the effects of reward.

It was hypothesised that reward would lead to improved performance, and that intrinsic motivation would predict performance.

5.2 Study 5

5.2.1 Method

The present data was originally collected for a past publication (Robinson et al., 2012), and obtained from the corresponding author. The reader is recommended to review the original work for additional details on the methods, and for an alternative approach to the analysis.

5.2.1.1 Participants

A sample of 40 male individuals was recruited from Newcastle University and local advertising. Criteria for participation included an age range between 18 and 35 and the absence of a serious psychiatric or psychotic condition, or personal history of mental illness. Due to missing parts of the datasets, 2 individuals were excluded, leaving a final sample size of 38 participants (mean age 21.50 (SD = 2.53)). The study was approved by the Psychology Ethics Committee at Newcastle University.

5.2.1.2 Materials

In the original data collection participants completed multiple computerised tasks and questionnaires. Here, only the material relevant to the analysis will be described, and it is recommended to the reader to refer to the original publication for all the additional details. The Attentional Network Test (Fan et al., 2002) is a cueing task which measures the three attentional subcomponents of alerting, orienting and executive control. In this task, after a fixation cross shown at the centre of the screen, one or two asterisks (cues) are sometimes presented either below or/and above the cross. This potential cue is then followed by another fixation cross, and lastly by the target stimulus in the form of an arrow pointing left or right, presented below or above the fixation. The arrow is sometimes flanked by other congruent/incongruent arrows. The participants were instructed to indicate the direction the arrows were pointing. After 24 trials of practice, participants completed 144 trials in total. A short version of the Intrinsic Motivation Inventory (IMI (Ryan, 1982)) was also used to measure subjective experience. It comprises multiple scales relating to constructs such as interest, competence, effort, however only the interest/enjoyment subscale was of interest as it can be used as a measure of state intrinsic motivation.

5.2.1.3 Procedure

Each participant completed two sessions of ANT. Upon the beginning of the experiment and following the screening and questionnaires, participants were randomly allocated in two groups corresponding to the extrinsic-motivation manipulation (control and rewarded). Each participant then proceeded to complete the first session of the ANT. The rewarded group was then informed of the possibility of obtaining a variable compensation depending on their performance in the second session of ANT. More specifically, a fixed amount was added to the baseline £20 for each correct response with a RT below the median RT calculated from the first ANT session. The final earned compensation was revealed only at the end of the task. The non-rewarded group, on the other hand, obtained a fixed compensation of £25.

5.2.1.4 Data analysis

5.2.1.4.1 Variable extraction

The ANT is traditionally used to measure multiple aspects of attention by mathematically calculating several indices on the reaction times (RT) data. In this study, the interest was on evaluating the effects of motivation over time on the variables normally extracted from the sustained attention task. Therefore, as in the previous studies, the RT data above 100ms for correct responses from each participant was used to calculate an index of attentional lapses (as the average RT for the 20%

slowest trials), mean and coefficient of variation in RT (excluding the 20% slowest trials). Additionally, a hitrate was calculated as the percentage of correct responses in the total number of trials. This was repeated for 4 blocks of 36 trials, in each of the two experimental sessions. From the Intrinsic Motivation Inventory, the interest/enjoyment subscale was used to index intrinsic motivation.

5.2.1.4.2 Evaluation of the motivation effects

Linear mixed effects models were used to evaluate the effects of time-on-task (Task *Block*), sessions of ANT (*Session*), extrinsic motivation (*Group*) on the sustained attention variables extracted from the ANT. All interactions between these 3 variables were added. Finally, the models included the intrinsic motivation variable (*Intrinsic*). Before examining the results, an iterative procedure was used to find the most appropriate structure for the random effects to account for individual differences and the repeated-measure analysis. The models were tested for convergence issues and then compared in their AIC value (lower is preferred).

5.2.2 Results

In finding the ideal random effect structure, several combinations of random intercepts and slopes were iteratively compared. No issues in model fitting and lowest AIC were obtained with a random intercept for each participant, and a random intercept for each participant within each session. This structure was therefore used for each regression analysis.

5.2.2.1 Mean RT

Looking at mean RT (Figure 5.1, A), a significant effect of Session ($F(1, 157) = 6.75$, $p = 0.010$) showed that RT were on average lower in the second session ($b = 9.89$ ($\beta = 0.06$), $p = 0.010$). A significant interaction effect of Session and Block ($F(1, 224) = 6{,}49$, $p = 0.012$) showed that RT tended to decrease in the first session but increase in the second session ($b = -2.96$ ($\beta = -0.07$), $p = 0.012$). Finally, there was a significant interaction between Group and Block ($F(1, 224) = 4.77$, $p = 0.030$), by which RT decreased over time in the rewarded group and increased in the control group ($b = -2.536$ ($\beta = -0.06$), $p = 0.030$).

5.2.2.2 Coefficient of Variation in RT

Modelling the CoV of RT (Figure 5.1, B), the only significant effect was Group ($F(1, 80) = 7.94$): the rewarded group showed lower variability in both sessions than the control group ($b = -0.025$ ($\beta = -0.25$), $p < 0.001$).

5.2.2.3 Attentional lapses

Session had a significant effect in modelling lapses in reaction times ($F(1, 221.4) = 4.67$, $p = 0.031$) (Figure 5.1, C). Participants had shorter lapses in the second session compared to the first one ($b = 20.57$ ($\beta = 0.02$), $p = 0.031$). Block also had an effect ($F(1, 224) = 13.89$, $p < 0.001$), by which participants tended to increase their attentional lapses with time-on-task ($b = 12.02$ ($\beta = 0.07$), $p < 0.001$). The significant interaction between Session and Block ($F(1, 224) = 5.26$, $p = 0.023$) showed that in the second session participants tended to have a stronger effect of time-on-task, compared to the first session ($b = -7.40$ ($\beta = -0.07$), $p = 0.023$). The significant interaction effect of Group and Block ($F(1, 224) = 6.06$, $p = 0.015$) showed that the control group was more heavily affected by time-on-task than the rewarded group ($b = -7.94$ ($\beta = -0.08$), $p = 0.015$).

5.2.2.4 Hitrate

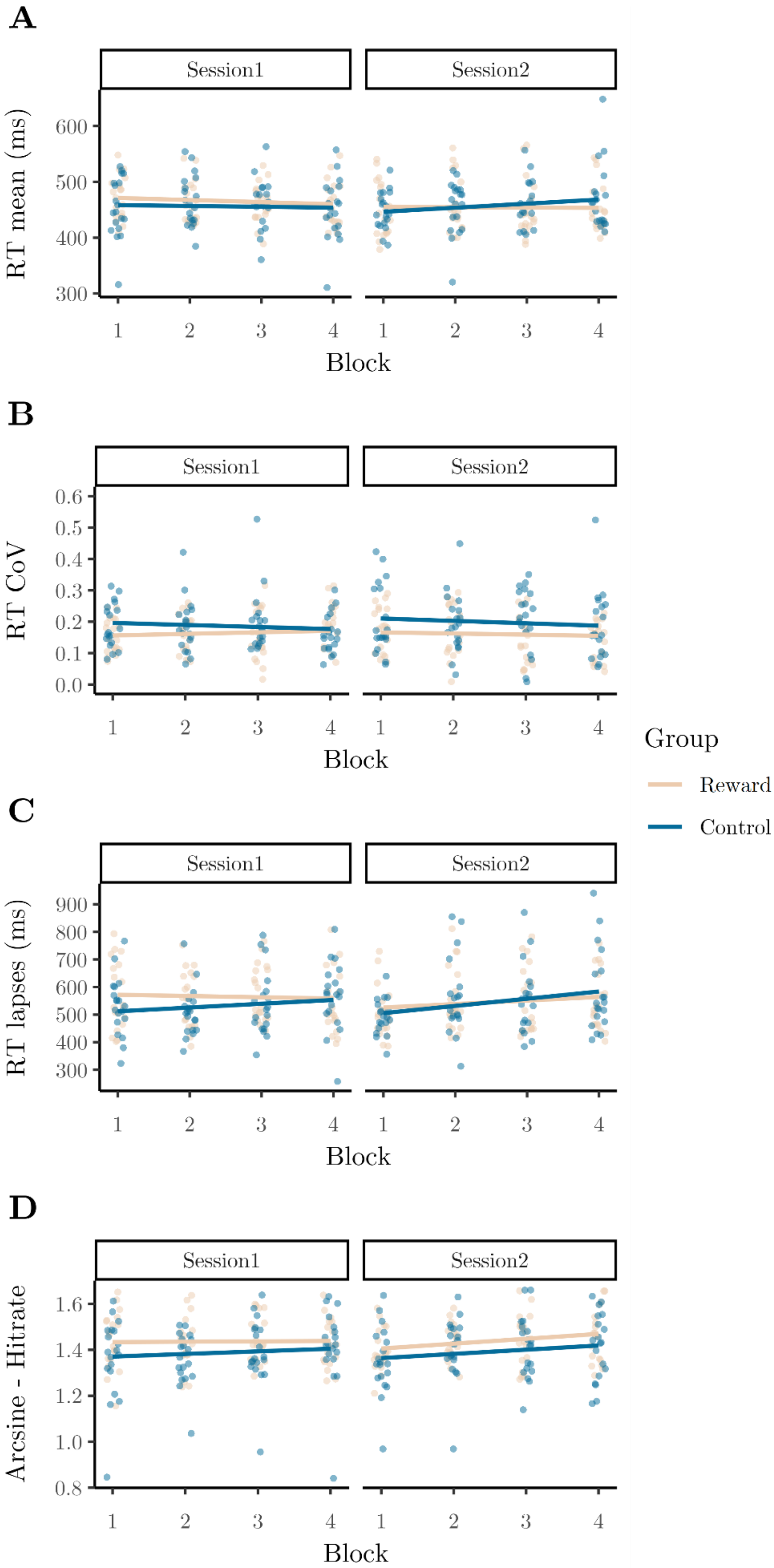
Due to the proportional nature of hitrate, an arcsine transformation was performed on the raw variable. The regression model (Figure 5.1, D) showed a significant effect of Block ($F(1, 224) = 13.62$, $p < 0.001$): participants tended to increase the rate of correct responses with time-on-task in both sessions ($b = 0.01$ ($\beta = 0.12$), $p < 0.001$).

Table 5.1
Summary statistics of the two groups (Control and Reward) through the task blocks (1 to 4), separated by experimental sessions (1 and 2) in Study 5. The reward manipulation took place before session 2, for the rewarded group. Mean (SD)

	Block							
	1		2		3		4	
Session 1	Control	Reward	Control	Reward	Control	Reward	Control	Reward
RT mean (ms)	454.03 (53.73)	470.75 (38.84)	465.43 (45.25)	464.20 (37.77)	460.52 (45.22)	461.31 (34.38)	450.74 (54.79)	459.24 (40.49)
RT CoV	0.182 (0.062)	0.159 (0.033)	0.199 (0.086)	0.162 (0.035)	0.201 (0.103)	0.162 (0.036)	0.160 (0.068)	0.175 (0.042)
RT lapses (ms)	530.35 (105.82)	568.36 (124.78)	508.35 (88.55)	556.34 (101.26)	538.96 (116.95)	575.60 (100.53)	566.15 (122.49)	546.79 (114.59)
Hitrate	93.57 (10.50)	97.37 (2.61)	95.26 (5.98)	97.07 (2.06)	94.66 (7.47)	97.88 (2.04)	95.02 (11.62)	97.36 (2.12)
Session 2								
RT mean (ms)	448.59 (34.09)	450.76 (49.03)	455.06 (48.19)	458.18 (48.91)	461.52 (40.66)	450.45 (49.53)	470.59 (59.39)	451.23 (44.49)
RT CoV	0.211 (0.071)	0.167 (0.034)	0.197 (0.068)	0.167 (0.043)	0.200 (0.069)	0.154 (0.032)	0.184 (0.073)	0.159 (0.048)
RT lapses (ms)	492.01 (64.20)	508.43 (92.52)	563.21 (139.20)	552.43 (113.81)	554.98 (123.82)	554.81 (119.73)	581.88 (147.42)	550.00 (103.62)
Hitrate	93.71 (7.28)	95.91 (3.29)	95.47 (7.95)	97.51 (2.20)	96.08 (4.09)	97.95 (2.14)	96.32 (3.75)	97.88 (2.51)

Figure 5.1

Mixed model plots for the sustained variables in Study 5. Dots represent the individual participants, while the lines are model predictions. Hitrate was transformed using an arcsine transformation.



- Sustained attention and extrinsic motivation

5.3 Study 6

5.3.1 Method

5.3.1.1 Participants

5.3.1.1.1 Power calculation

Sample size for the experiment was calculated beforehand in order to assure appropriate power for the statistical analysis. The main analysis planned to base our power analysis on investigated the effect of reward on variability of reaction times, and its interaction with time-on-task. Firstly, the literature was inspected, and it was found that in previous research on reward and sustained attention it was possible to find large effect sizes of Cohen's d in the range of 0.73 and 1.43 (Esterman et al., 2014, 2016) for the general effect of reward on RT variability. It was decided however to assume a more conservative effect size of 0.70 and run a power calculation using Gpower. Assuming a power of 0.99 and an alpha of 0.05, 60 participants per group for a total of 120 would be required.

This approach however would not necessarily translate to appropriate power for the interaction between reward and time-on-task which is of main interest. The core analysis tool that was planned to be implemented was mixed-effects modelling, which is not supported in Gpower and similar tools. Power calculation in these cases can be produced using Monte Carlo simulations. The package *mixedpower* (Kumle et al., 2021), which offers a good interface for lme4 in R was therefore used. Firstly, pilot data from 30 participants was obtained. Data was then processed and the coefficient of variation of reaction times modelled with Group (reward – control) and Block (1-10) in a mixed effect model. Coefficients were then extracted and used to obtain the smallest effect sizes of interest (SESOI), a method to reduce the risk of running power analyses on over-inflated effect sizes which can often be found in the literature. This entails reducing the empirical coefficients found in the pilot data by 15%. Monte-Carlo simulations were then run for different sample sizes. It was found that in order to obtain a power of 0.99 with an alpha of 0.05, a minimum sample size of 200 participants

(100 for each group) was required. It was therefore decided to recruit this number of participants to assure enough power to detect the effect of interaction.

5.3.1.1.2 Sample characteristics

Recruitment of participants took place on Prolific, an online pool for research participants, who were then directed to Gorilla (Anwyl-Irvine et al., 2020), an online experiment platform. Recruitment criteria were residence in the United Kingdom, no ongoing mental health condition and an age range between 18 and 45 years old. A total of 212 participants completed the experiment, however after an inspection of the datasets, 32 participants were excluded due to technical issues (e.g., internet browser crashing, and restarting) or inappropriate datasets caused by insufficient number of recorded responses in the task, or too many errors. Details on the criteria can be found in the data analysis section. The resulting n = 180 final sample size was considered adequate for enough statistical power and had an average age of 33.20 (SD = 7.05).

5.3.1.2 Materials

To assess sustained attention performance, the Sustained Attention to Performance Task (SART) (Robertson et al., 1997) was implemented to the design. Among the multiple options of sustained attention tasks available in the literature, the choice of SART was driven by certain criteria. Firstly, the design of the task allows for the extraction of multiple variables representing accuracy, variability and linear changes over time. As shown by Study 2, many of these SART variables map onto the main factor of sustained attention, whilst also showing task-specific variability. This would allow to target specific variables in the analysis, and to obtain a more accurate interpretation of the results in relation to other assessment methods of sustained attention.

This SART was based on the Gorilla version described in Study 2, with an increased number of trials (n = 1350) to tax sustained attention even more (and cause a vigilance decrement). The same rate of targets was maintained (11%, n = 150), as well as other parameters, such as the inter-stimulus-interval (900ms) and time the stimuli were shown on the screen (250ms). As in Study 2, participants completed 15 practice trials before the start of the task session.

Before and after the SART, participants also completed an online version of the Dundee Stress State Questionnaire (DSSQ) (Matthews, 2016) to measure several subjective state variables, and most importantly obtain a measure of state intrinsic motivation. The reader is recommended to refer to Study 4 for a description of the DSSQ.

5.3.1.3 Procedure

Participants were recruited from Prolific and directed to Gorilla for the experimental session. Each individual signed a consent form, provided some demographics information and completed the pre-task DSSQ. Then, participants were randomly allocated to one of two groups, corresponding to the extrinsic motivation manipulation. At the beginning of the SART, the rewarded group was informed of the possibility of obtaining an additional compensation (£50) on top of what was originally agreed (8-10£). The compensation would be provided to the best performer. Clear instructions were given to focus on both accuracy and speed to avoid the introduction of any speed/accuracy trade-offs, which are often found in the SART (Seli, Cheyne, & Smilek, 2012). The precise wording of the reward instructions was "*Do you want to win £50? Your performance will be recorded throughout the task. The participant who scores best in terms of accuracy and speed will be awarded an additional £50 on top of the basic compensation*". The control group, on the other hand, was informed about the same possibility only at the end of the task. After the SART session, participants completed the post-task DSSQ and then were debriefed.

5.3.1.4 Data analysis

The data was firstly inspected to exclude participants who did not comply with task instructions. Criteria of a maximum number of missing responses (n = 405), commission errors (n = 105) and a minimum number of hit (n = 867) were employed. Compared to previous studies, these criteria were a little stricter as part of the analysis required non-missing data (as explained with detail in Chapter 6).

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5.3.1.4.1 Variable extraction

As in the previous studies, several sustained attention variables were extracted from the SART. From reaction time (RT) data of correct responses above 100ms (Luce, 1986), an index of attentional lapses was obtained from the mean RT of the 20% slowest trials (lapses RT). Excluding these slow trials, the rest of the data was used to obtain mean RT and the coefficient of variation of RT (CoV RT, standard deviation of RT divided by mean RT). Dprime was used as an indication of overall accuracy. Finally, commission errors were also included in the analysis since it is often the main variable of interest in SART studies (Seli, Jonker, Solman, et al., 2013) given the task requirements of inhibiting a proactive response, and because it provides an insight into individuals strategy (rather than an overall measure of perceptual sensitivity). The variables were extracted from 10 blocks of 135 trials, in order to assess the effects of time-on-task. Finally, from the DSSQ data, indices of success motivation and intrinsic motivation were calculated following the main author's instruction, for both pre- and post-task data.

5.3.1.4.2 Motivation effects

In order to assess the influence of extrinsic and intrinsic motivation on the SART variables of mean RT, CoV RT, lapses RT, dprime and commission errors, mixed effects models including an interaction of time-on-task (block) and grouping (group), and the pre- and post-task success and intrinsic motivation indices were fitted for each of the outcome variables. As previously explained, combinations of random effects were tested to find the ideal structure before running the full models. Convergence issues and lowest AIC values were the criteria implemented. Additionally, as in Study 4, multicollinearity was investigated by computing the correlation matrix of the DSSQ motivation items.

5.3.2 Results

5.3.2.1 Motivation effects

Correlations between the motivation indices were consistent with Study 4 and showed no warning signs of multicollinearity (Table 5.2). In finding the best structure for the random effects, the best AIC value with no convergence issues was obtained with a random intercept for each individual withing each group, and a random slope for the effect of time-on-task (Block). All models were therefore fitted with this random structure on the datasets (Table 5.3).

5.3.2.1.1 Mean RT

In fitting the regression model for average reaction times, no significant effects were found (Figure 5.2, A).

5.3.2.1.2 Coefficient of Variation of RT

Time-on-task (Block) had a significant effect on the reaction time variability ($F(1, 177) = 71.43$, $p < 0.001$) (Figure 5.2, B): CoV RT increased over time ($b = 0.0045$ ($\beta = 0.18$), $p < 0.001$).

5.3.2.1.3 Attentional lapses

In testing lapses in reaction times (Figure 5.2, C), significant effects of block ($F(1, 178) = 43.56$, $p < 0.001$) and of success motivation measured post-task ($F(1, 174) = 6.64$, $p = 0.011$) were found. Participants tended to show longer attentional lapses with time-on-task ($b = 6.84$ ($\beta = 0.14$), $p < 0.001$) and higher post task success motivation predicted longer attentional lapses ($b = 4.72$ ($\beta = 0.22$), $p = 0.011$).

5.3.2.1.4 Perceptual sensitivity

Time-on-task showed a significant effect on dprime ($F(1, 178) = 39.26$, $p < 0.001$) (Figure 5.2, D): participants had lower accuracy as they performed the task ($b = -0.05$ ($\beta = -0.15$), $p < 0.001$).

5.3.2.1.5 Error of commission

Block showed a significant effect on the number of commission errors ($F(1, 178) = 6.87$, $p = 0.009$) (Figure 5.2, E). Participants tended to have an increased number of errors with time-on-task ($b = 0.07$ ($\beta = 0.06$), $p = 0.009$). Group also had a significant effect ($F(1, 180) = 4.51$, $p = 0.035$): the rewarded group showed a higher number of errors ($b = -0.45$ ($\beta = -0.11$), $p = 0.034$). Finally, success motivation measured before the SART had a significant effect on commission errors ($F(1, 174) =$

6.17, p = 0.013). Higher success motivation resulted in higher number of errors (b = 0.12 (β = 0.17), p = 0.013).

Table 5.2
Correlation matrix of the DSSQ motivation variables.

	Intrinsic.pre	Success.pre	Intrinsic.post	Success.post
Intrinsic.pre	1.00	0.36	0.69	0.33
Success.pre	0.36	1.00	0.28	0.69
Intrinsic.post	0.69	0.28	1.00	0.34
Success.post	0.33	0.69	0.34	1.00

Figure 5.2
Mixed effects models testing the effects of time-on-task and group in Study 6. Dots represent the individual participants by block, while the lines are model predictions.

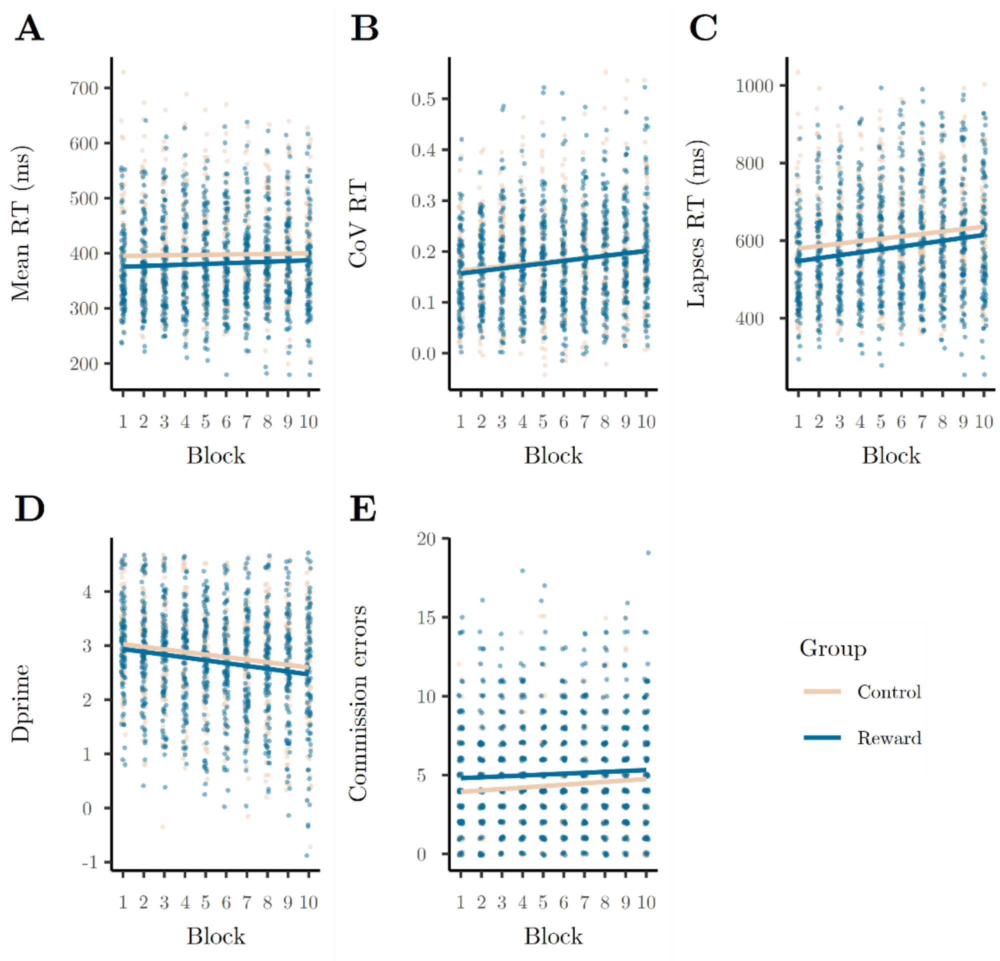

Table 5.2

Descriptive statistics of the SART variables across blocks of trials, split by group in Study 6. Half the blocks were omitted for ease of presentation. Mean (SD)

	Block									
	2		**4**		**6**		**8**		**10**	
	Reward	Control	Reward	Control	Reward	Control	Reward	Control	Reward	Control
Mean RT	384.75 (96.45)	366.30 (80.38)	385.92 (94.75)	369.05 (89.77)	380.26 (96.34)	369.55 (90.75)	382.80 (92.18)	373.02 (85.15)	387.09 (89.78)	364.95 (90.02)
CoV RT	0.17 (0.07)	0.17 (0.07)	0.20 (0.10)	0.18 (0.07)	0.20 (0.08)	0.20 (0.08)	0.20 (0.09)	0.21 (0.10)	0.22 (0.12)	0.21 (0.12)
Lalpses RT	581.69 (146.88)	552.36 (131.40)	608.30 (147.90)	564.12 (140.00)	607.71 (149.55)	581.44 (150.41)	615.88 (149.87)	598.96 (164.44)	640.55 (145.54)	598.01 (171.07)
Dprime	2.80 (1.02)	2.68 (0.98)	2.59 (1.23)	2.54 (1.02)	2.44 (1.14)	2.38 (1.10)	2.43 (1.27)	2.32 (1.12)	2.37 (1.32)	2.21 (1.27)
Comm. errors	4.67 (3.57)	5.78 (4.11)	5.04 (3.86)	6.22 (4.29)	5.15 (3.70)	6.29 (3.99)	5.11 (3.86)	6.02 (4.02)	5.42 (4.40)	6.71 (4.47)

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5.3.3 Discussion

The present chapter aimed at ascertaining the effects of extrinsic motivation on sustained attention performance. Study 5 and Study 6, in general, showed that extrinsic motivation did not improve performance. If anything, higher motivation resulted in worse performance.

5.3.3.1 Study 5

More specifically, Study 5 did not show an effect of rewarding participants. If the reward manipulation had been affecting overall performance levels of task variables, there would have been a significant interaction between session and group (as the reward would've taken effect only in the second session of the rewarded group), which was not the case. The 3-way interaction with block, to check whether reward impacted the changes over time in variables, also was not significant in any model. In some of the models for the task variables, the effects of group (RT variability, CoV RT) and the interaction between group and block (mean RT and attentional lapses), were significant, however, considering the design of the study, it is not possible to confirm the role of the reward manipulation. The missing interaction with session could not confirm whether the effects were due to reward, as the manipulation took place only before the second session. Finally, intrinsic motivation did not predict any of the outcome variables.

Before drawing any conclusions, it is important to consider a few potential complications with the design. The task implemented, the Attention Network Test, was originally designed to measure the three distinct components of the attention system following Posner's model (Posner & Petersen, 1990): alerting, orienting and executive control. In order to obtain a measurement for these components, the task sometimes includes congruent/incongruent/neutral cues presented just before the trial; additionally, the main stimulus at the centre of the screen is sometimes surrounded by congruent/incongruent flanker arrows. From the combination of cues/flankers the three indices can be obtained by subtraction (Fan et al., 2002).

This study used a different approach, by which the outcome variables examined were the traditional sustained attention variables of accuracy, speed, variability and attentional lapses, therefore discarding the three attention networks. This was done following the assumption that sustained attention is a core cognitive functions that contributes to many broader aspects of cognition (Buehner et al., 2006) and that attentional lapses and performance accuracy represent the more robust operationalisation of sustained attention regardless of the task implemented (Studies 1,2). Although the most traditional tasks used to measure sustained attention are the go/no-go type, examples of alternative tools can be found in the literature (e.g. Kostandyan et al., 2019). Furthermore, a modified version of the ANT was recently developed to assess multiple aspects of sustained attention while maintaining the traditional structure (the ANTI-vea, Luna et al., 2018), with the note that the authors used a different approach in extracting the variables indexing sustained attention. Study 5, however, might indicate that the ANT is not an ideal task for this cognitive domain for a few reasons.

Firstly, the original publication (Robinson et al., 2012) found an effect of both intrinsic and extrinsic motivation, however, this was in the traditional indices of the ANT. Importantly, performance in the alerting index, which could be considered the closest index to sustained attention in the Posner conceptualisation of attention (Oken et al., 2006), was improved by the reward manipulation. The fact that motivation did not predict changes in performance in the present analysis shows that the approach of discarding the traditional index might have masked some existing effects. Secondly, the hallmark phenomenon of sustained attention research is the vigilance decrement, the worsening of performance over time, indicating how demanding and difficult it is (Warm et al., 2008). In the present study, the vigilance decrement was minor: participants showed an increase in attentional lapses; however, they also showed an increase in accuracy with time-on-task indicating a potential practice effect throughout the task. This suggested that the additional difficulty compared to simple perceptual tasks such as a CPT might have led participants to feel more engaged with the task and improve their accuracy over time, counteracting a decrement in performance (Thomson, Smilek, et al., 2015).

The engagement due to task difficulty, and variety, might indeed categorise the ANT as a *quality* task, rather than a *quantity* task as most sustained attention tasks.

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This could explain the missing effects of extrinsic motivation; however, it would not explain the null predictive power of intrinsic motivation. Additionally, Study 4 showed that intrinsic motivation measured by the DSSQ predicted performance variability and accuracy. The IMI index employed here, should have provided similar predictive power as it has been found correlated with the relevant DSSQ index of motivation (Neigel et al., 2017). This was not the case, as IMI did not predict any of the variables extracted.

Taken together, it is likely that the ANT task did not measure facets of sustained attention comparable to what is traditionally associated to the construct.

5.3.3.2 Study 6

The outcome of Study 5 told that the ANT might not have been an ideal task to measure sustained attention because it did not induce a vigilance decrement. Study 6, on the other hand, proved to be demanding enough to the participants to elicit a robust vigilance decrement in each variable, except for overall speed: participants tended to be less accurate, commit more errors, and showed more variability and attentional lapses. Remarkably, the vigilance decrement was found regardless of the group. Motivation, both in terms of reward manipulation and state-intrinsic, did not induce better performance. Rather, the rewarded group committed more errors. Furthermore, state variables of the DSSQ success motivation predicted higher number of errors and a tendency of attentional lapses.

These results were partially unexpected. Theories of sustained attention predict that higher motivation through reward would interact with the perceived benefits and costs associated with the task, and improve performance (Kurzban et al., 2013; Thomson, Besner, et al., 2015). Although results might not follow what expected, as the only difference found due to reward was an increase in errors, theories of cognitive control provide a potential explanation. The increase in errors might be indicative of a change in individual performance strategy, potentially suggesting a shift to a more pro-active cognitive control approach, with higher task engagement and more availability of cognitive resources (Botvinick & Braver, 2015; Braver, 2012; H. S. Locke & Braver, 2008). In a CPT such as the SART, motivated participants might be more focused on avoiding omission errors (which therefore require a response), and on providing faster responses. This could result in a higher probability of commission errors, a higher number of correct responses and therefore comparable overall dprime indices. Although the number of correct responses was not explicitly examined, the result seemed to at least partially support this interpretation as rewarded participants committed more errors but were no different in terms of dprime. Reaction times, on the other hand, did not differ between groups, but remained stable across the task. It was not possible to attribute the absence of a vigilance decrement to motivation as RT were stable for both groups.

Nonetheless, the present data did not provide enough evidence to establish whether reward improved performance or not, since the main outcome consisted in more errors following reward. A potential alternative explanation to this otherwise paradoxical effect of reward could be found in the so-called "*chocking under pressure*" phenomenon (Mesagno & Beckmann, 2017). This phenomenon refers to the observation that at times, participants presented with higher rewards and stakes show significantly reduced performance (Gray, 2020). With the presence of potential reward, especially dependant on competition, as the one in the present study (only the best participant in each group obtained the additional compensation), participants might feel performance pressure that leads to an unideal allocation of attentional resources to either distractions or to the self, resulting in a lowered performance (Baumeister, 1984; Baumeister & Showers, 1986). In the case of the SART, participants might have felt pressure due to the competition with others for the compensation, and this might have led them to a more automatic, less demanding response style with increased commission errors indicating failures of inhibition. The performance pressure due to competition for the additional compensation might have been enhanced by a pre-existing pressure felt by participants recruited on Prolific, who are requested to maintain a positive approval rating by providing good quality data to obtain even the baseline compensation. This observation is however speculative and not supported by SART descriptives comparable to existing literature (e.g., Marty-Dugas et al., 2020).

Another relevant outcome of the present analysis is the fact that intrinsic motivation measured with the Dundee Stress State Questionnaire (DSSQ, (Matthews, 2021)) predicted worse performance. More specifically, the index success motivation

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predicted higher number of errors when measured before the SART, and higher number of lapses when measured after the SART. Success motivation (already encountered in Study 4) relates to the construct of achievement motivation, which measures the state of the participant regarding striving to success in the task at hand. Interestingly, the results obtained here did not follow what was found in Study 4: pre-task success motivation predicted higher accuracy, whereas here it predicted higher number of errors. This seemingly incompatibility might be due to two factors: the sample used and the task.

Although with differences in the task design, both studies used a Continuous Performance Task (SART and TOVA), with a similar length and demands. Study 2 showed that accuracy measures from both tasks were explained by the same underlying factor. From this perspective, a motivation state should, in theory, predict both accuracy measures to the same direction. The fact that this was not what was found, might mean that the sample recruited contributed to this unexpected result. The samples were in fact meaningfully different: if here a large online sample of paid participants (with the potential performance pressure factor discussed above) was included, Study 4 used a sample of students who participated for course credits with no compensation at all. The different circumstances might have resulted in different levels of performance pressure and therefore different response strategies with different motivation levels. These results might also be explained considering a potential interaction between intrinsic and extrinsic motivation. The reward manipulation applied to the sample in Study 6 might have impacted their intrinsic motivation (Deci, 1972), whereas the sample in Study 4, who did not receive any monetary compensation, were able to actively engage to the task thanks to their natural intrinsic motivation.

Nevertheless, the state associated with success motivation is conceptually similar to what extrinsically motivated participants might have possessed, hence the results could be discussed in a similar manner to above. Success motivation also predicted a higher number of attentional lapses when measured after the task. Although these results are not immediately intuitive, it could be explained considering that when the DSSQ is completed after the task, participants are asked to make a judgement of their state during the task. Success motivation has been associated with negative moods, task-unrelated thoughts and low self-esteem (Matthews et al., 2001): this result could indirectly indicate that although participants felt more motivated, they also experienced additional states that are known to impair performance.

Chapter 6 - Attentional oscillations and motivation

6.1 Introduction

The two studies presented here aimed at exploring whether behavioural oscillations detected in reaction time data are susceptible to extrinsic and intrinsic motivation.

Performance variability is undeniably one of the most relevant and interesting aspects of sustained attention. It can be obtained from virtually any tasks assessing vigilant performance, it is unaffected by practice and reliable (Flehmig et al., 2007), it relates to attentional lapses and task-unrelated thoughts (Unsworth et al., 2021), and it can be used as behavioural marker for some psychological conditions (Gallagher et al., 2015; O'Gráda et al., 2009; Pagliaccio et al., 2017). Study 1 and Study 2 of the present document also showed that a component of variability, the Ex-Gaussian tau indicating the tendency of long responses, might constitute the more robust operationalisation of sustained attention across tasks. Variability is usually quantified using overall indices of performance (e.g., sigma, tau, coefficient of variation), or can be looked at longitudinally across the length of the task to detect linear changes (to quantify decrements/increments).

In order to obtain an even more detailed picture of intra-individual variability, it may be possible to look at reaction times (RT) fluctuations. This method entails applying a frequency decomposition technique (usually the Fourier Transform) to individual RT time-series data (RT over trials/time) to obtain the relative strength of each frequency detectable in the original time-series data (Castellanos et al., 2005). In the obtained curve, if any periodic, recurring changes is present in the RT data, it will be shown as peaks of strength at the specific frequency. Conveniently, the total area under the curve amounts to the total variance of the signal, and this equivalence allows quantification of the variance distribution across frequencies. Applying this method to the ADHD population, known to have deficiencies in sustained attention variability, Castellanos and colleagues (2005) demonstrated that the patient group had a significantly higher power (strength) in the frequency bin centred around 0.05Hz (20s) compared to the controls, using data from a Eriksen flanker task. Employing what can be considered sustained attention tasks, more recent research highlighted differences in frequency power in the range of 0.07 and 0.33Hz (corresponding to 3-14 seconds) (Helps et al., 2011; K. A. Johnson, Robertson, et al., 2007).

It was hypothesised that these behavioural oscillations might be due to slow oscillations in the default-mode network (DMN), a network of areas usually deactivated during a task (task-negative areas) and believed to be responsible for task-independent generalised cognition (Sonuga-Barke & Castellanos, 2007). These fluctuations are anti-correlated with task-positive areas (the dorsal attention network, DAN), and indeed mediate behavioural RT fluctuations (Zhang et al., 2022). The increased RT oscillatory power could then be explained as altered brain activity by which interference of active, task-positive brain activity occurs because of periodic influence of dysfunctional regulation of the DMN (Helps et al., 2010).

This hypothesis also suggests that state-related factors such as motivation might contribute to the oscillatory activity of attention (Sonuga-Barke & Castellanos, 2007). It was in fact shown that manipulations of task-engagement (as previously discussed, a construct associated with intrinsic motivation) through gamification resulted in a more effective modulation of the DMN (Howard-Jones et al., 2016). Furthermore, DMN deactivation was effectively moderated by manipulations of motivation (Liddle et al., 2011). From this perspective, this hypothesis could also be considered complementary to resource allocation accounts. The supervisory system which regulates the activation of both task-positive and task-negative areas (including the modulation of the DMN) (Botvinick & Braver, 2015) might correspond to the executive control system mentioned by the resource-control theory, which computes costs and benefits of the task at hand and allocates resources (Thomson, Besner, et al., 2015). Higher perceived costs would lead to unideal allocation of resources, and activation of task-negative areas (DMN), resulting in attentional lapses.

It follows that, if state variables can modulate DMN activity, different patterns of reaction time oscillations should be found.

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6.1.1 Study 7

The study used a dataset previously published to test the interaction between motivation, mind-wandering and sustained attention performance (Brosowsky et al., 2020). Critically, it implemented a sustained attention task where participants were required to rhythmically produce responses and should therefore be ideal to investigate intrinsic behavioural oscillations. Additionally, it included motivation ratings throughout the task, which provide a good indication of intrinsic motivation levels to differentiate high and low- motivation participants.

To reiterate, although maintaining an exploratory approach due to the absence of previous attempts in the literature, it was expected that higher intrinsic motivation would reduce both variance overall, as in the published results and following Study 4, and RT oscillations in the 0.07-0.33Hz frequency range.

6.1.2 Study 8

Study 8 was a continuation of Study 6 and used the same dataset. The study utilised a version of the Sustained Attention to Response Task (SART, (Robertson et al., 1997)), which is characterised by a constant inter-stimulus-interval, making it ideal for frequency analysis of RT data. By implementing a reward manipulation, the dataset allowed to explore whether the RT oscillations were susceptible to extrinsic motivation.

Although results of Study 6 showed that reward manipulation did not affect overall performance variability, spectral analysis provides a finer-grain perspective on variability and could have unfolded previously masked results.

It was hypothesised that reward would reduce RT oscillations in the 0.07-0.33Hz frequency range.

6.2 Study 7

6.2.1 Method

This dataset was previously used for an existing publication (Brosowsky et al., 2020), and downloaded from the Open Science Framework (OSF, osf.io) with consent obtained from the main correspondent.

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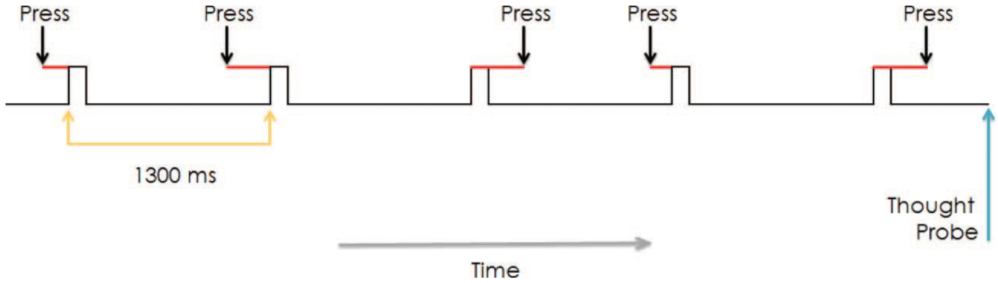
6.2.1.1 Participants

A sample of 166 participants completed the study as part of a "human intelligence task", hosted on the Amazon Mechanical Turk (www.mturk.com). As explained in detail below, 16 participants were excluded after an inspection of the dataset due to their number of omissions and missing responses, leaving a total of 149 individuals used in the analysis. Demographics data was available for only 105 participants (70%) and reported an age range between 19 and 80 (mean age 37.00 (SD = 12.10)) with a gender distribution of 68 males and 38 females. Each individual obtained a compensation of $3 for their participation. The study design was originally approved by the Duke University ethics committee.

6.2.1.2 Materials

The Metronome Response Task (MRT) is a rhythmic sustained task developed to specifically measure response time variability (Seli, Cheyne, et al., 2013). Participants were instructed to produce a physical response following sound stimuli played every 1300ms by the task. The instructions clearly stated to attempt to predict when the next tone would be played, and to make a response at that exact time. Each of the 800 experimental trials was constituted by 650ms of silence, the sound stimulus which lasted 75ms, followed then by 575ms of silence, for a total of 1300ms of trial length. Before beginning the experimental trials, participants completed 18 practice trials. The task included 8 thought probes to measure participants' state motivation, which were presented at trial numbers 90, 182, 290, 382, 490, 582, 690, 782. In these instances, participants were asked to rate their motivation levels across the previous few moments in the task, with response options ranging from 1 (not motivated) to 5

Figure 6.1
Structure of the Metronome Response Task (MRT). The vertical lines correspond to the metronome tones; the red segments represent rhythmic response times (individuals' approximation of the metronome). From (Seli, Cheyne et al., 2013).



(highly motivated). Finally, the task also presented 16 additional probes to rate the depth of mind-wandering which were not used in the present analysis. It is however recommended to review the original publication for details.

6.2.1.3 Data analysis

6.2.1.3.1 Rhythmic-response times and motivation

The first phase of the analysis entailed a (partial) replication of the results reported in (Brosowsky et al., 2020). The main variable of interest extracted from the MRT is the rhythmic-response times (RRT), which indicates the ability of the participants to approximate when the sound tone would play in the task. This was obtained following the author's instructions (Seli, Cheyne, et al., 2013) and the code published on the OSF, as the difference between the onset of the sound tone and the response made by the participant. Rather than the MRT per se however, the variability in responses was the more relevant outcome variable and it was calculated as follows: firstly, the 5 initial responses and the 5 responses following each probe were excluded; then, using a 5-trial moving window, the variability of RRT was calculated and log-transformed; finally, the RRT variance was averaged across 4 blocks of 200 trials. In order to obtain the corresponding measures of motivation in each of the 4 blocks for subsequent analysis, the 8 original recording were collapsed into 4, averaging the two measures within each block. The resulting dataset was then inputted in a linear mixed-effect model explaining the RRT variance using motivation and block as fixed effects and including a random slope and intercept for each individual accounting for multiple measures per-subject and individual differences, respectively.

6.2.1.3.2 Frequency analysis

The following step of the analysis investigated whether oscillatory behaviour was affected by levels of motivation. Firstly, the motivation measures were used to split participants into two groups of *low* and *high* motivation. In order to use most information obtained from the probes, and not simple averages, a k-means clustering was implemented on the 4-blocks data. This resulted in a high-motivation group (n = 83, motivation mean = 4.16, SD = 0.78) and a low-motivation group (n = 66, motivation mean = 2.40, SD = 0.90).

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6.2.1.3.3 Power Spectral Density estimation

The reader is invited to review the details of this method in the introductory chapter, as only a summary of the processes will be provided here. Individuals' RRT datasets were used to extract the Power Spectral Density using the Welch modified periodogram method (Welch, 1967). The whole signal (RRT over time) was split into multiple segments of 300 trials, with a 70% overlap. Each segment was firstly inspected for the number of omissions and excluded if that exceeded a threshold (n = 25). Then, the RRTs for omissions were linearly interpolated and detrended. Additionally, the effects of the breaks due to the probes (motivation and mind-wandering) were calculated via linear modelling and subtracted from the 5 RRTs following a probe. The resulted segment therefore had an evenly sampled signal, no missing data and no statistical effect of breaks. The segment was then windowed using a Hamming function, and zero-padded to a total length of 512 data-points. Finally, the squared amplitude of the Fast Fourier Transform was extracted. This process was repeated for each segment, and the resulting spectra were averaged and scaled to obtain the power spectral density (PSD) of the signal, over the frequency range 0 to the Nyquist limit (0.38). The PSD is a method used to describe how the power (or variance, in a statistical process) is distributed across a range of frequencies and allows for a deeper investigation of the variance of the data, showing whether the variance is found at specific timescales (peaks in the spectra).

6.2.1.3.4 Functional data analysis

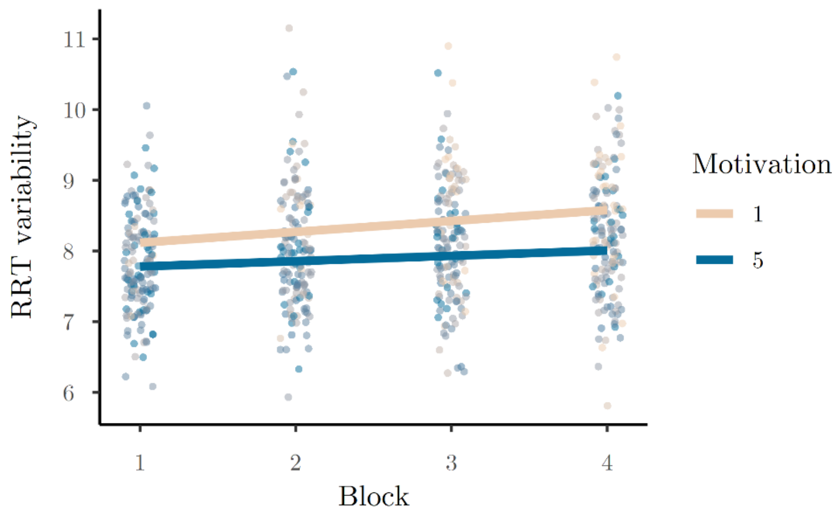
Once the PSD data was extracted for each individual in the two groups, differences between the spectra were investigated. Traditionally, the area under the curve at specific frequencies intervals of interest is calculated through integration, and simple comparisons are performed (K. A. Johnson, Kelly, et al., 2007). A more data-driven, exploratory approach, is provided by functional data analysis, which provides information along the entire length of the curves (Ramsay & Silverman, 2005). This was implemented using the *fda* package for R (Ramsay et al., 2022). Firstly, the individuals' spectra had to be transformed in functional data, that is data (y, PSD) expressed as function of another variable (x, Frequencies). To do this, a b-spline function of order 4 (cubic polynomials) and 35 bases was used to smooth the data. The number of bases was selected as a good compromise of underfitting (overly smoothed data) and overfitting (introduction of noise and computational costs). Once each individuals' dataset was smoothed, a functional pointwise t-test was then performed between the curves of the two groups.

6.2.2 Results

6.2.2.1 RRT

In analysing the effects of motivation (Figure 6.2), time-on-task or their interaction over the RRT variance, it was found that motivation levels did not show a significant effect ($F(1, 298) = 2.22$, $p = 0.14$), nor was there an interaction between motivation and time-on-task ($F(1, 226) = 2.15$, $p = 0.14$). Time-on-task produced, however, a significant effect ($F(1, 230) = 12.52$, $p < 0.01$). Participants showed increasing variability in RRT as time on the task increased ($b = 0.17$ ($\beta = 0.14$), $p < 0.01$).

Figure 6.2
RRT variability modelled across blocks and motivation levels in Study 7. The points represent the individual data, whilst the lines are the model predictions. Motivation was a continuous variable, but for the sake of simplicity, only the highest (5) and lowest (1) values of motivation were included in the plot. Motivation seemed to have a beneficial effect in variability and in maintaining a stable performance throughout the task, however, the model reported no significant effects of motivation or any interactions. The only variable affecting performance was time-on-task.

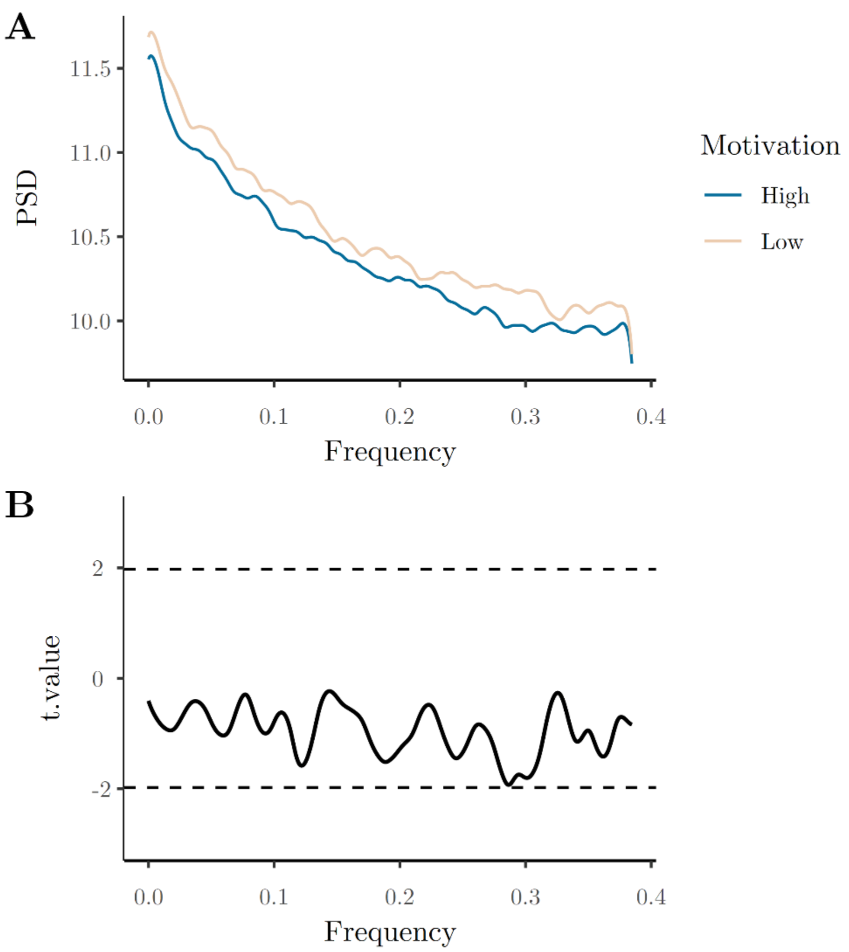


- Attentional oscillations and motivation

6.2.2.2 PSD

The second part of the analysis entailed evaluating differences in the RRT spectra produced by the two groups of participants, split by their motivation levels throughout the task. Although the higher-level analysis of overall differences in variance did not show any significant results of motivation, this approach allows for a finer-scale evaluation, and therefore a potential difference could potentially be found. In examining the curves, the group with lower motivation showed higher power across all frequencies as expected: their variance in RRT seemed higher (Figure 6.3, A). The functional t-test however, failed to reach significance at any point across the frequencies (Figure 6.3, B). No significant differences between the curves could therefore be found.

Figure 6.3
Functional data analysis of the RRT spectra in Study 7. A) shows the grand-average log-transformed PSD spectra for the two groups of individuals. These were calculated using the Fast Fourier Transform. B) reports the t-values of the functional t-test used to test differences between the groups. The curve represents the point-wise t-values, whilst the straight, dotted lines are the critical thresholds for significance. Since at any frequencies the t-values fail to cross the line, it can be concluded that no difference is found between the spectra.



- Attentional oscillations and motivation

6.3 Study 8

6.3.1 Method

The study continued Study 6, and details of the method including participants, design and data extraction and pre-processing can be found there.

6.3.1.1 Data analysis

The approach of analysis was equivalent to the one used in Study 7 and entailed extracting RT spectral curves from individual RT data.

6.3.1.1.1 Frequency analysis and functional data analysis

To obtain the Power Spectral Density (PSD) or RT data, a modified Welch method was used (Welch, 1967). For each individual, data was split into segments of 200 trials, with a 50% overlap. If a segment had more than 25 missing datapoints, it would be excluded. For each segment, missing points were filled with interpolated values, detrended, windowed using a Hamming function and zero-padded to 512 data-points. The squared amplitude of the FFT was then obtained and averaged across segments. Finally, the power was scaled accordingly to obtain the PSD. This procedure was repeated for each member of the two groups (rewarded, control). Individuals' data was then transformed into a functional data object using cubic splines with 35 knots (and 37 basis functions) (Ramsay & Silverman, 2005). The resulting smoothed curve was evaluated in the appropriate range of values corresponding to the original frequency range obtained from the FFT. A functional t-test was then calculated between the two groups, at each of the data-points in which the smoothed curves were evaluated. To assess significance, the obtained t-values were compared against the critical t-value calculated using alpha (0.05) and group sizes (n = (80,80)).

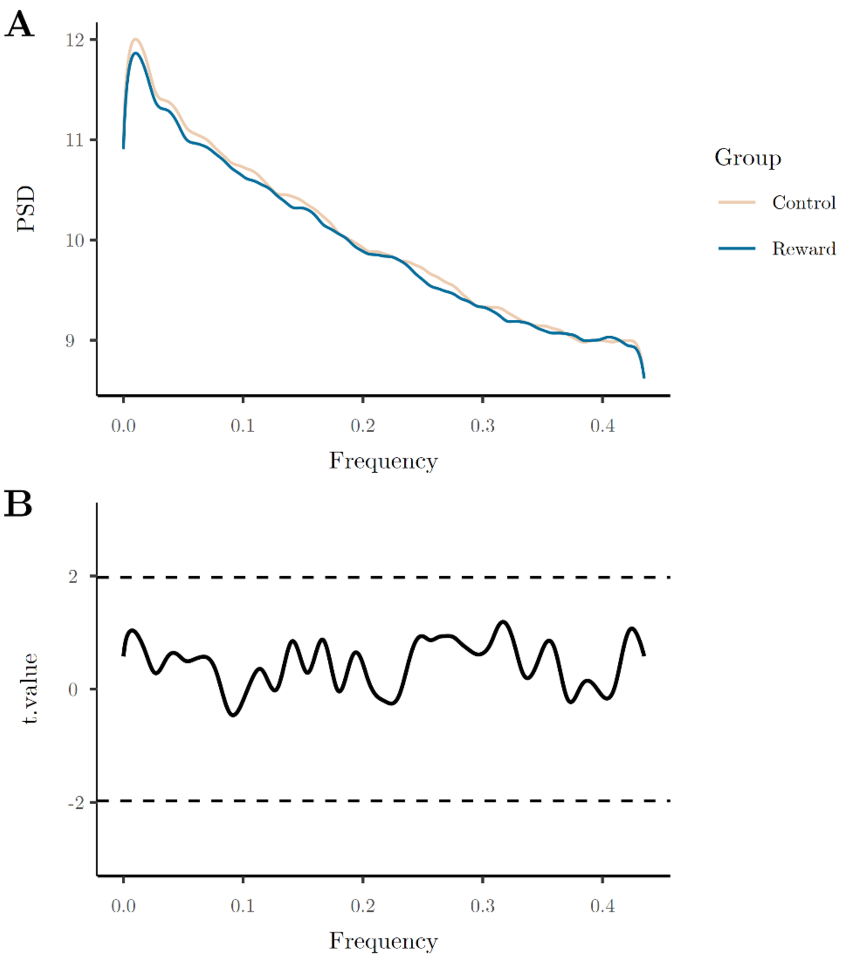
6.3.2 Results

6.3.2.1 Reaction time oscillations

Inspecting the PSD curves for the two groups (Figure 6.4, A), although the non-rewarded group seemed to show higher variance overall (higher area under the curve), there did not seem to lay any differences in specific frequency ranges. The functional t-test confirmed that: no significant differences were found between the two PSD curves (Figure 6.4, B).

Figure 6.4

Frequency analysis of RT data and the effect of reward in Study 8. A) Power Spectral Density (PSD) curves for the two groups. B) Functional t-test comparing the two averaged curves; if the solid line crosses the dotted lines, the difference is significant.



6.4 Discussion

In general, either intrinsic or extrinsic motivation did not seem to interact with RT oscillations.

6.4.1 Study 7

Contrary to the expectations, intrinsic motivation did not seem to interact with sustained attention in this particular instance, both in terms of overall performance and in RT oscillations.

- Attentional oscillations and motivation

Although the original publication used a different approach in the analysis of the data, it failed to find a significant effect of motivation on the RRT variability over time, as in the present study. The original paper, however, also tested the overall correlation between motivation and RRT, finding a positive, significant result. It might then be possible that in this particular task overall effects of motivation were facilitatory on RRT variability, however, including the effects of task over time, which showed a significant vigilance decrement, masked what effect motivation might have had on performance. These effects also proved to be non-robust as the authors discussed that significance of the correlation was found only testing a one-tailed hypothesis. An attempt to replicate the results of the original publication using a wider sample size also failed to see a link between RRT performance and motivation (Anderson et al., 2021).

It is relevant to mention that these studies included a measure of mind-wandering as their intention was to investigate both motivation and mind-wandering as recent theories suggest they might be underlying sustained attention performance (Thomson, Besner, et al., 2015). It was actually found that the more unintentional aspect of mind-wandering affected performance more heavily (Anderson et al., 2021). It might then be possible that the RRT task measured a quality of sustained attention that is not particularly susceptible to top-down attempts of the participants to control their performance, and therefore not directly affected by different levels of motivation. These results are also not in line with the findings of Study 4, where state intrinsic motivation predicted participant's RT variability. These differences in outcomes might support the view that these findings are task-specific. The RRT task is in fact different from any of the sustained attention tasks discussed so far, where it is missing any aspect of perceptual choice between a target and a non-target stimulus. These additional features found in the more traditional sustained attention tasks might interact with participants' task-engagement, allowing for higher top-down control and therefore higher susceptibility to motivation. The RRT task rather than relying on participants capabilities to detect and discriminate target stimuli, it requires participants to quickly learn a rhythm and rely on a more *internal* control, and thus potentially more vulnerable to unintentional mind-wandering (Seli, Cheyne, et al., 2013). However, a different investigation on the role of motivation in the RRT found that experimentally controlling motivation through reward differences in performance were found (Seli et al., 2019). Therefore, it is possible that the negligible effects in the present study could be explained by the type of motivation considered: state intrinsic motivation might be insufficient in determining an effect on performance variables, and reward manipulations are deemed necessary to exert a larger effect.

After investigating the linear relationship between performance variability and motivation, the focus was moved on testing differences in performance oscillations between groups with high and low motivation. Considering the results of the first step of the analysis, it was not expected to find any differences between the groups, and that was indeed the case. Referring to the Figure 6.3, it seemed that participants with high motivation consistently had lower power (less area under the curve) than the low motivation group across the length of the frequency range. In other words, the high motivation group seemed to produce lower variance than the low motivation group. This difference however was not statistically significant at any temporal frequency. Additionally, neither group showed a visible peak. This was however not true when individuals' curves were inspected separately, as each participant showed different peaks and areas under the curve. These differences were then lost in the group grand averages., indicating high inter-individual variation and that peaks of power were not reliable.

6.4.2 Study 8

Study 7 showed that intrinsic motivation did not lead to any differences in oscillatory behaviour of RT. Similarly, Study 8 failed to detect any effects of extrinsic motivation.

Although the results are similar to Study 7, it is important to consider methodological differences. The null results of Study 7 were potentially due to the task implemented, where performance was not predicted by individual differences in intrinsic motivation. Study 8, on the other hand, employed a task which was previously used in investigations of RT oscillations (K. A. Johnson, Kelly, et al., 2007). Additionally, CPTs have been frequently implemented to test the effects of reward on performance

(Esterman et al., 2016). This would indicate that extrinsic motivation might not be effective in driving changes in RT oscillations.

Additional research is however recommended. Study 6, in fact, showed that the reward manipulation implemented in the study design did not lead to improved performance, as motivated participants made more errors. As these results were not supported by the robust evidence of improvements in performance (Esterman et al., 2014; Massar et al., 2016), it might be possible that this specific dataset was not ideal to investigate the effects of reward on RT oscillations.

Chapter 7 - An application of frequency analysis to clinical data

7.1 Introduction

Study 9 aimed to examine the oscillatory behaviour of RT in mood disorders.

Study 7 and Study 8 utilised frequency analysis of RT data to investigate the effects of motivation on sustained attention. The two studies failed to highlight any effects on the spectral curves. However, the primary analyses on overall performance and performance changes over time also did not show any effects of motivation, potentially indicating shortcomings of the design. There is therefore not sufficient evidence to state with confidence that motivation should not affect RT oscillations. Nonetheless, it is also possible that individual differences in motivation and reward manipulations are not enough to elicit differences at the frequency levels, and it could only be seen in the presence of a dysfunctional cognition.

This research approach was in fact inspired by what has previously been described in the ADHD population, and the present study attempted to investigate the same phenomenon in different clinical populations. This study utilised the dataset already introduced in Study 1 (Gallagher et al., 2015): the sample included a group of controls representing the general population (control group), a group of patients with euthymic bipolar disorder (EBP), a group with bipolar disorder in a depressed state (DBP) and a group with major depression (medication-free) (MDD).

To reiterate (see more on this in the general introduction and in Study 7 and Study 8), previous research on the ADHD population showed an increase oscillatory behaviour in reaction times located around the frequency range of 0.02 and 0.07Hz (50-14s) (Hultsch et al., 2002). This increase in variability at this time-scale is believed to be associated with the inability to suppress the periodic intrusion of the Default Mode Network (DMN) to the activation of task-positive areas, which in turn causes behavioural lapses (Sonuga-Barke & Castellanos, 2007). This hypothesis is supported by the observation of dysfunctional regulation of the DMN in ADHD (e.g. Metin et al., 2015), and by the direct correlation between oscillations in DMN and attentional data (Zhang et al., 2022). Although qualitatively different, the conditions of ADHD, major depression and bipolar disorder share deficits in sustained attention, usually in the form of increased tendency of attentional lapses compared to the general population (Bora et al., 2006; Politis et al., 2004; Tucha et al., 2017; Van Der Meere et al., 2007). Additionally, dysregulation of the DMN has been found both in major depression (Marchetti et al., 2012), and in bipolar disorder (Rodríguez-Cano et al., 2017). In the latter, the extent to which the DMN regulation is shown seems to depend upon the clinical state of the bipolar condition (Martino et al., 2016). Considering the similar neurological phenomena found between ADHD, DBP, EBP and MDD, it might be possible to detect the same pattern of oscillatory behaviour, providing additional support to the idea that these behavioural observations are due to the dysregulation of the DMN activity during attentional tasks (Sonuga-Barke & Castellanos, 2007).

The present study investigated the oscillatory behaviour of RT data collected from a sustained attention task through spectral decomposition. Although using an exploratory approach, there were a few expectations: the clinical samples would differ in terms of overall levels of sustained attention variability; the differences would be concentrated in a frequency range comprised between 0.02 and 0.07Hz; differences would be present between the EBP and DBP groups.

7.2 Study 9

7.2.1 Methods

This study is based on the re-analysis of an existing dataset which has already been used in Study 1. The description of the methods will therefore report only information which has not been previously included. The reader is recommended to refer to Study 1, the introductory chapter and a recent publication based on the same dataset (Gallagher et al., 2015) for details on the participants, materials and procedure. The focus of this chapter will be the data analysis.

7.2.1.1 Participants

Although this dataset was used in Study 1, in this instance it included data from a total of 296 participants. This comprised 138 healthy controls (mean age = 40.50, SD = 12.50), 33 patients with bipolar disorder in a depressed episode (mean age = 47.00, SD = 8.64), 85 patients with bipolar disorder in a euthymic episode (mean age = 43.70, SD = 9.52) and 40 medication-free major depression patients (mean age 31.90, SD = 10.20).

7.2.1.2 Data analysis

The aim of the analysis was to investigate differences in attentional variability between different clinical populations. To do so, the first step of the analysis entailed the extraction of an index of reaction time (RT) variability, which corresponded to the coefficient of variation (CoV, standard deviation of RT divided by the mean RT). This was calculated for each individual separately using RT above 100ms obtained from correct responses, in 8 blocks of 60 trials. The CoV RT was then modelled using a mixed effect model that included the effects of grouping (Diagnosis) and time-on-task (Block). The model also included a random slope and intercept for each individual.

The following step of the analysis attempted to investigate whether differences in RT variance between the samples were located at specific time-periods by examining the group-averaged periodograms. These were derived from the responses of each individual, where RT for correct responses were extracted and detrended. Due to the task requirements of the Vigil CPT, the traditional frequency decomposition based on the Fast Fourier Transform was not possible. Due to the low target rate of the Vigil, the "sampling" of RT was in fact uneven, making it unsuited for the application of the FFT. As an alternative, the Lomb-Scargle method (Ruf, 1999) was implemented. This algorithm is suited for unevenly sampled data and returns the power at specific frequencies, similar to that derived with an FFT. Once the power was extracted for each individual, a functional data analysis approach was used to detect any differences between groups (Ramsay & Silverman, 2005). Firstly, each individuals' power curve obtained from the Lomb-Scargle periodogram was smoothed using a cubic spline with 46 basis (and 44 knots) (Figure 7.2, A). This value was selected to reasonably maintain each potential peaks in the curves. The functions were then evaluated at the appropriate range of frequencies (corresponding to maximum and minimum frequencies obtained from the frequency decomposition). To test differences, a functional ANOVA was computed at each data point (Figure 7.2, B). If any of the F-values surpassed the critical F-value, functional t-tests were then run between each sample to verify where exactly differences could be found. Two critical t-values were calculated for the present sample size, one uncorrected for more exploratory purposes and one Bonferroni corrected for a more conservative approach.

7.2.2 Results

7.2.2.1 CoV RT over time

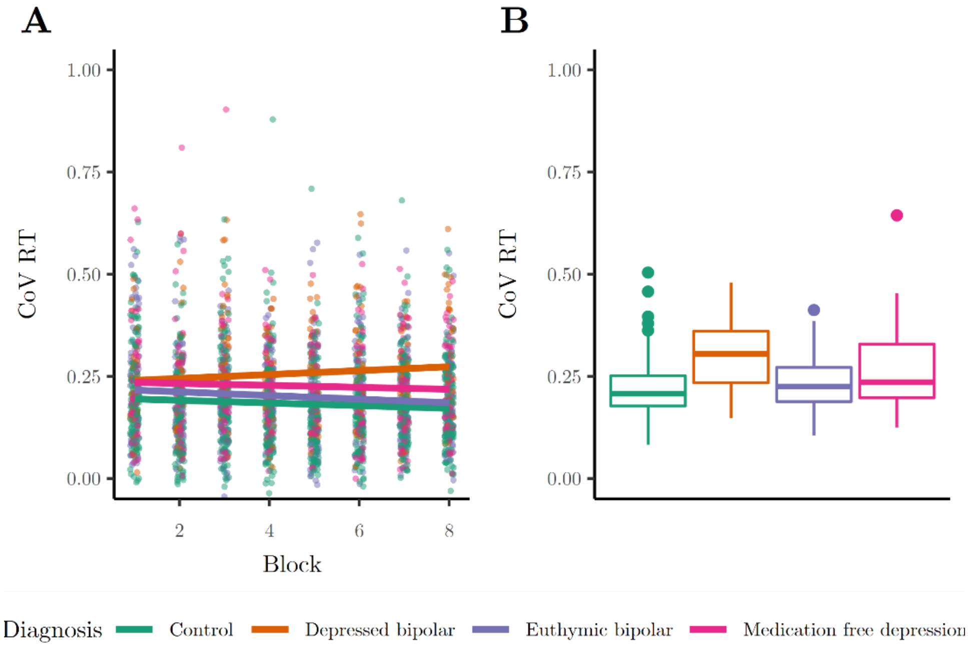
The mixed effect model (Figure 7.1) showed that grouping (Diagnosis) had an effect on the RT variability ($F(3, 271) = 3.16$, $p = 0.025$). Multiple comparisons showed that the depressed bipolar group had higher variability than the healthy controls ($p < 0.001$) and the euthymic bipolar group ($p < 0.001$). The medication-free depression group also showed higher variability than healthy control ($p < 0.001$). The interaction between diagnosis and time-on-task was also significant ($F(3, 280) = 3.72$, $p = 0.012$): the healthy controls showed less variability with time-on-task ($p = 0.006$) as well as the euthymic bipolar group ($p = 0.003$). The depressed bipolar group, on the other hand, had higher RT variability with time-on-task ($p = 0.048$).

7.2.2.2 Frequency analysis of RT

The functional ANOVA showed that there was a significant effect of diagnosis on the RT spectral curves ($F > 2.64$, $p < 0.05$) centred around the frequency corresponding to 0.064Hz (15.62 seconds), and within the range 0.076Hz (13.10 seconds) and 0.052Hz (19.23 seconds). Multiple comparisons between the groups (Figure 7.2, C, D and Table 7.1) within the frequency limits highlighted by the F-test using a conservative critical t-value showed that control group had lower spectral power than the medication-free depression group ($t(295) > 2.67$, $p < 0.05$); the euthymic bipolar group showed less power than the depressed bipolar group ($t(295) > 2.67$, $p < 0.05$), and the medication-free depressed group ($t(295) > 2.67$, $p < 0.05$). Using a more exploratory approach with the uncorrected critical t-score, the control group showed less spectral power than the depressed bipolar group ($t(295) > 1.97$, $p < 0.05$).

Figure 7.1

Differences in coefficient of variation (CoV) between groups in Study 9. A) CoV of reaction times modelled for the 4 groups and across blocks of trials. Dots represent the individual participants, whilst the lines are the model predictions. B) Coefficient of Variation by group.



7.2.3 Discussion

The present study set out to replicate previous findings on sustained attention impairment in mood disorder, and to investigate different pattern of oscillatory behaviour of reaction time due to neuropsychological dysfunction. Results showed mood-state-related effects on sustained attention variability, and that this variability was concentrated around the frequency of 0.064Hz (15.62 seconds). The analysis of sustained attention variability showed an impairment that was mediated by the current mood-state of the individuals, as only the MDD and DBP differed from the controls; this observation was supported by the finding that DPB and EBP also differed significantly. Examining the patterns of change of performance over time also provided an interesting and unexpected result: only the DBP showed a vigilance decrement (worsening of performance over time), whereas the controls and EBP tended to improve over time; the MDD, on the other hand remained stable.

These results partially replicate existing evidence of mood-related impairments in sustained attention in major depression and bipolar disorder (Gallagher et al., 2015; Martínez-Arán et al., 2004).

Figure 7.2

Frequency analysis of reaction time data and investigation of differences between the clinical groups in Study 9. A) averaged power curves for each experimental group. B) functional F-test between the power curves; the dotted line represents the critical F-value; greyed area is where the F-test is considered significant. C) functional t-tests following the significant F-test; the dotted horizontal line represents non-corrected critical t-value whilst the solid line is the Bonferroni corrected value; the comparisons are coded as follows: Cont = control group, Dep = depressed bipolars, Md = medication-free depressed; Eut = euthymic bipolars. D) average absolute power for each group within the frequency range where F-test was significant.

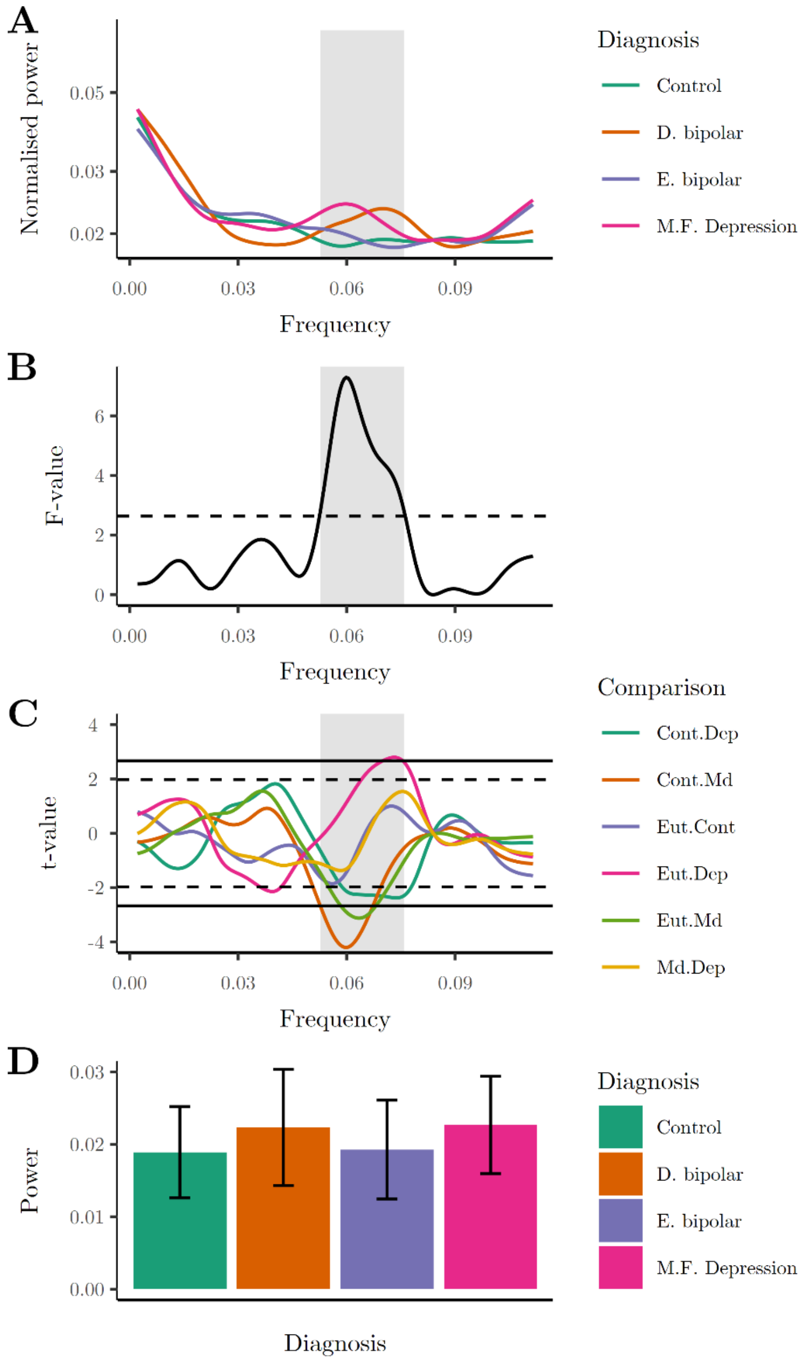


Table 7.1

Absolute power for each experimental group calculated within the frequency range where the F-test was significant.

	Normalised power	
	Mean	**SD**
Control	0.018	0.0063
Depressed bipolar	0.022	0.0077
Euthymic bipolar	0.019	0.0071
MDD	0.022	0.0066

Interestingly, previous research has found robust impairments in bipolar disorder even during an euthymic state (Clark et al., 2005). The absence of this phenomenon might be explained by the analysis implemented. The present study used an analytical approach not often implemented in clinical research where attentional data was examined not only between groups, but also across time-on-task. This approach has been recommended in ADHD research (Machida et al., 2022), as it provides a more complete profile of sustained attention performance in its different components (Esterman et al., 2014). The inclusion of time-on-task effects in the models might have reduced group differences that would have been present if simpler, more traditional approaches had been used. It was possible, in fact, that the EBP group might have had initial overall differences in sustained attention variability, but the differences were then reduced by their tendency of improving over time, similarly to the control individuals, possibly due to practice effects. These results challenge the idea of a trait-level sustained attention deficit in bipolar disorder, and highlight that the deficit might be moderated by the mood state (Clark & Goodwin, 2004).

The analysis of oscillatory behaviour provided an additional insight into the differences in variability performance found in terms of overall levels, and over time-on-task. More specifically, a group-effect was found within the frequency range of 0.076Hz (13.10 seconds) and 0.052Hz (19.23 seconds) and centred around 0.064 (15.62 seconds). Within this range, the controls and the EBP individuals both showed less spectral power than the DBP and the MDD individuals, again highlighting the importance of mood-state in explaining sustained attention performance. The frequency range in which differences were observed remarkably overlaps with what has been found in ADHD (Di Martino et al., 2008). These behavioural oscillations have been explained in terms of periodic intrusion of the default mode network (DMN), a circuit of areas usually active during resting-state and believed to be incompatible with effective sustained attention performance, during goal-directed action (Hultsch et al., 2002).

Remarkably, the DMN has been shown to fluctuate following the same time-signature as behavioural lapses in ADHD (Sonuga-Barke & Castellanos, 2007; Zhang et al., 2022). The present results could suggest that the same dysfunctional mechanism of DMN regulation found in ADHD might be present in mood disorder. Although speculative, if these behavioural patterns are underpinned by DMN activity, then this may suggest that euthymia might be characterised by a more ideal regulation of the DMN network compared to bipolars during a depressed state, in accordance to the idea of mood-state-related differences in DMN activity in bipolar disorders (Martino et al., 2016).

Chapter 8 - General discussion

The present section will provide a summary of the results from the empirical chapters and their implications, a discussion of the strengths and limitations of the project, and finally potential directions for future work.

8.1 Summary of the results

Chapter 3 addressed the gap in the literature of a validation of the multiple potential operationalisations of sustained attention, impacting the generalisability of method-specific results. The results suggested that, among the many methods which could be used to operationalise sustained attention, dprime and the Ex-Gaussian parameter tau seemed to be the more robust task-general facets in terms of nomothetic span, and convergent validity. These measures were in fact driven by the same underlying latent variable, regardless of the task used to obtain them.

Chapter 4 investigated the relationship between intrinsic motivation and sustained attention performance from a state and trait perspective, whilst addressing methodological inconsistencies of the existing literature. Study 3 found that higher trait motivation was correlated with a change (through the task) in strategy prioritising speed over accuracy of responses, whereas Study 4 showed mixed results regarding how state intrinsic motivation predicted performance: higher indices of intrinsic motivation measured after the task predicted higher accuracy and lower variability; pre task indices both predicted attentional lapses and accuracy.

Chapter 5 explored the effects of extrinsic motivation on sustained attention variables through reward manipulation, whilst controlling for individual differences in intrinsic motivation. Study 5 failed to detect any significant results due to either extrinsic or intrinsic motivation. Study 6, on the other hand, showed that the only detectable effect of reward on sustained attention performance was an increase in errors. Additionally, intrinsic motivation also predicted worse performance in terms of attentional lapses and number of errors.

Finally, chapter 6 investigated whether motivation would impact behavioural oscillations in the spectral curves of RT data. Both analyses failed to show any significant results.

- General discussion

8.2 Discussion and implications

8.2.1 The correct operationalisation

By investigating the factor structure of multiple sustained attention tasks, Study 1 and 2 showed that underlying performance measures there are multiple latent psychological constructs. Although these tasks were originally designed to recreate the subjective experience of sustained attention and provide an adequate, unitary measure, the presence of task-specific dimensions potentially hinders the generalisability of the results. A careful choice of which variables to use is hence required.

The present results follow the lines of evidence that showed that multiple facets of sustained attention can be derived from a single computerised task. For instance, Egeland and Kovalik-Gran, as previously discussed, demonstrated that within a CPT there are multiple underlying factors. Evidence also comes from other areas of research such as neurostimulation: Luna et al. (2020) applied transcranial direct current stimulation (tDCS) over two areas of the prefrontal cortex and found a dissociation between performance accuracy and reaction times: tDCS only mitigated the vigilance decrement in participants' accuracy but did not affect reaction times. Clinical research provides further evidence in showing that even though ADHD is a condition characterised by a deficit in sustained attention, only certain variables (mainly dprime, RT tau, commission errors) from a CPT are an adequate behavioural marker that separates it from the general population (Machida et al., 2022). Dissociations within task variables are observed also in motivation research (Esterman et al., 2014), and in studies on the effects of stimulants and exercise on performance (McIntire et al., 2014; Sanchis et al., 2020).

A potential approach to explain these dissociations within and across tasks and variables might be by considering sustained attention as a multifaceted construct. For instance, Luna et al. (2018) acknowledging the discordance in the theoretical models and in the experimental evidence, developed a new task, the Attentional Network Test for Interactions and Vigilance (ANTI-vea), to measure two different components which they termed: *executive vigilance*, defined as detection of infrequent targets and inhibition of frequent responses; *arousal vigilance*, related to sustaining fast reactions to stimuli.

- General discussion

Referring to the theories of sustained attention, this approach is particularly useful as it renders one perspective (e.g., overload or underload account) not necessarily exclusive of the other.

The issue with this approach, however, stems from the fact that the dissociations may be due to task-specific factors, and not different components of sustained attention. For instance, Sanchis et al. (2020) tested the effects of caffeine intake on RT in a sustained attention task and found no facilitation, directly contrasting positive effects on RT by a similar work (Hogervorst et al., 2008). An alternative approach to address these dissociations is asking whether the same types of variables obtained from different tasks are driven by the same underlying construct. The present results suggested that the better representation of sustained attention can be obtained using performance accuracy and attentional lapses. These measures proved valid in terms of nomothetic span, by showing correlations with other cognitive domains expected to be interrelated with sustained attention (Study 1) and in terms of generalisation across tasks (Study 2). In other words, lapses and accuracy were the only task-general measures among the multiple variables extracted.

The only study, to the author's knowledge, that ran a similar protocol was the one by Unsworth et al. (2021), in which it was found that attentional lapses of sustained attention measured across tasks were explained by a shared underlying factor. This work, however, only included two traditional sustained attention tasks (SART and PVT) and did not consider traditional vigilance tasks characterised by rare targets. The present results contribute to this by showing that an underlying, shared factor can be found even when including the Mackworth clock test and an additional CPT (TOVA), and that this factor might be represented by attentional lapses. Although the task-general factor explained attentional lapses in terms of RT, it also loaded on performance accuracy measured with dprime. This may still be considered a measure of lapses, as dprime is calculated by considering not only the number of correct responses but also the number of commission errors. The latter is, in fact, used as an alternative measure of lapses (Seli, Jonker, Solman, et al., 2013). Yet, it may still be argued that these findings are specific to the tasks included in the analysis. The choice of tasks was however driven by the degree of representation across theories of sustained attention and the tasks traditionally implemented. Granting that it is not possible to conclude that attentional lapses is the *only* task-general factor, the present results indicate that it may be the *most* generalisable.

From a different perspective, lapses are sometimes considered part of the wider construct of response variability (Yamashita et al., 2021). In fact, the Ex-Gaussian parameter tau represent not only the mean of the exponential distribution, but also its variability. Clinical research has shown that the slower component of variability represented by tau is particularly useful in differentiating the general population from mood disorders (Gallagher et al., 2015) and ADHD (Machida et al., 2022). Critically, differences between these groups were not present examining more traditional measures of variability such as standard deviation or sigma. Furthermore, the relevance of the measure of lapses can also be found in their ecological validity, in which failures of sustaining attention due to lapses are correlated with failures experienced in everyday life, across populations and contexts (Robertson et al., 1997; Smilek et al., 2010).

The present findings and the current literature from multiple areas and approaches therefore suggest that attentional lapses might not only represent the most robust operationalisation of sustained attention, but they have theoretical, ecological and clinical relevance. Utilising this measure would secure more robust and comparable results even at the application of different computerised tasks.

8.2.2 Motivation effects on sustained attention

In general, the results of the project do not provide a clear, unitary answer to how motivation influences sustained attention.

Focussing first on intrinsic motivation, in studies where the DSSQ was implemented, directly contrasting results were found in Study 4, in which success motivation measured before the task predicted higher accuracy whereas in Study 6 the same index predicted number of errors. Additionally, although the two studies utilised a similar task with similar length and demands, other findings of Study 4 were not replicated in Study 6. As discussed in the empirical chapter, the contrasting findings might be due to sample-specific factors such as the type of compensation they received: in Study 4, participants did not receive a monetary compensation whereas they did in study 6. The type of compensation received by the research subjects is indeed a known factor influencing performance (Tomporowski & Tinsley, 1996). Additionally, Study 5 did not find any significant results in terms of intrinsic motivation, even though the questionnaire utilised to measure it is known to be correlated with the indices used in the DSSQ (Neigel et al., 2017).

One question remaining is how should these inconsistent results be reconciled? Two observations might be relevant. Firstly, as discussed above, Study 1 and Study 2 showed that the only measures that were associated with a task-general construct related to attentional lapses. Secondly, measures of intrinsic state motivation obtained after the task with the DSSQ are considered more reliable and preferred over assessment pre-task (Matthews & Campbell, 2009). Adopting this perspective, the interpretation would focus only on post-task intrinsic items predicting lapses of attention. Study 4 showed that post-task intrinsic motivation predicted higher accuracy whereas post-task success motivation in Study 6 predicted higher attentional lapses. Considered together, these two opposing results could be the consequence of differing strategies, by which more motivated participants try to avoid missing target stimuli by a slowing of RT. However, for this to be the case, corresponding effects of response strategy should also have been detected in RT (in Study 4) and in accuracy (in Study 6).

A more probable interpretation entails the differences between the DSSQ indices of *success* and *intrinsic* motivation. The former refers to the willingness to perform well regardless of the activity; the latter concerns the enjoyment of doing. Interestingly, success motivation has been associated with factors known to negatively affect performance such as low self-esteem and task-unrelated thoughts (Matthews et al., 2001). This might explain how participants reporting higher success motivation showed higher tendency for attentional lapses. Intrinsic motivation, on the other hand, followed the predictions of both overload accounts and attentional allocation models: more motivated participants might have had a higher quantity of attentional resources, or might have been more capable in allocating them to the task at hand.

Which of the two is the more appropriate prediction? It is important to consider that both the DSSQ indices of intrinsic motivation and success motivation are used to calculate the task-engagement factor usually associated with attentional resources in an overload perspective (Matthews, 2021). The present findings, however, showed that the two indices had opposite predictions of performance, therefore not aligning completely with the overload predictions. Attention allocation accounts explain the role of motivation in terms of perceived costs and benefits (Kurzban et al., 2013; Thomson, Besner, et al., 2015). This perspective allows a more flexible interpretation of the results: success motivation might not have been effective in increasing the benefits of the task, especially if participants disliked the activity; intrinsic motivation, on the other hand, as it is related to enjoyment, might have represented a good indicator of the participant's ability to shift costs and benefits and allocate resources more appropriately.

Although this theoretical framework at least partially explained the findings regarding intrinsic motivation, it could not account for the reward-manipulation results. In fact, while no significant effects were seen in Study 5, Study 6 showed that the only aspect of performance which was affected by a reward manipulation was the number of commission errors, which increased. Extrinsic manipulation is the dimension that should most easily be interpreted in a resource-allocation perspective, however, its effects did not follow any of the potential predictions. It is possible that these results might be due to the "chocking under pressure" phenomenon (Mesagno & Beckmann, 2017), which states that sometimes participants might perform worse due to the increased pressure caused by the potential additional reward. From this point of view, the results might support an overload account which highlights the role of state factors in leading to worse performance (Warm et al., 2008). If that was the case, however, different rates of vigilance decrements should have also been found, as higher pressure would have led to a faster depletion of resources. Yet, no effects of reward on performance over time were found.

Looking at both dimensions of motivation, the results unexpectedly showed that intrinsic motivation was the more effective factor in predicting better performance. The outcome does not follow what Gilliland and Landis (1992) predicted in terms of task requirements: sustained attention tasks require a lengthy and monotone performance, and therefore focus on quantity rather than quality. In these cases, extrinsic motivation should be more effective than intrinsic motivation in improving performance (Cerasoli et al., 2014). The findings seem to align with a theoretical model of motivation referred to as Self Determination Theory (Ryan & Deci, 2000b) which states that extrinsic manipulation of motivation through reward might undermine the positive link between intrinsic motivation and performance (Deci, 1972). Here intrinsic motivation was indeed related to higher performance, whereas reward led to worse. It might then be possible that when presented with the possibility of obtaining additional compensation contingent on performance, participant's intrinsic motivation was reduced, and worse performance followed. It is interesting to see matching effects of extrinsic motivation and the DSSQ item of success motivation on performance, potentially because they are both related to being motivated to do well, rather than enjoy the activity.

8.2.3 Attentional oscillations and motivation

If the effects of motivation on traditional measures of sustained attention were not consistent, or straightforward to interpret, the effects on attentional oscillations were consistently null. In fact, in both Study 7 and Study 8 where behavioural oscillations were examined based on levels of intrinsic and extrinsic motivation respectively, no significant differences were detected. Although the present results do not seem to support the hypothesis of the Default Mode Network interfering with task-directed attention (Sonuga-Barke & Castellanos, 2007), effects of motivation on behavioural variability were not detected even in previous analysis. It is therefore not possible to conclude with certainty that motivation does not interact with oscillatory behaviour.

What the present study consistently found was a phenomenon referred to as pink noise, or 1/f function which entails a negative slope found in the spectral curves of RT data (K. Clayton & Frey, 1997). Frequently found in many tasks which require speeded responses, it indicates serial correlations between consecutive trials distributed across multiple scales (both high and low frequencies). This coherence is usually interpreted in term of coordination of healthy cognition (Kello et al., 2007), intended as a self-organising complex system (Van Orden et al., 2003). The peaks of power located at frequencies $<.01$ found in ADHD might be present only because of a dysfunctional regulation of the DMN (Hultsch et al., 2002), and it might be found only in *unhealthy* cognition. Recent research has in fact showed that the same oscillations can be detected in other clinical conditions such as in TBI patients (traumatic brain injury) with frontal lesions (Gazzellini et al., 2017) (see Study 9 as well). It could then be that the general population might not be susceptible to motivation in oscillatory behaviour.

8.3 Strengths and limitations

The project has the advantage of addressing the validation of multiple operationalisations of sustained attention and in finding an appropriate set of measures which refer to a task-general construct. In doing so it provided guidance on interpreting the results of the subsequent analyses by selecting the appropriate variables. Additionally, it contributed to the debate regarding which operational definition is more robust for generalisable results. Nonetheless, different factors limited the two studies. Firstly, in place of an aggregated measure of performance accuracy such as dprime, raw measures might have been more appropriate to address the research questions. In fact, some tasks might prioritise specific aspects of performance (missing rare targets or failing to inhibit for frequent non-targets) (Mackworth, 1948; Seli, Jonker, Solman, et al., 2013), rather than relying on a general measure of accuracy. Including raw indices might have provided a clearer picture in terms of factor structure. Another limitation regards the so-called Common Method Variance (Kock et al., 2021; Podsakoff et al., 2003), which warns that variance might be due to the method employed rather than the construct of interest, and could appear when multiple variables are derived from the same task. Although multicollinearity was examined prior to both factor analyses, a more critical approach could have been used to counteract the risk more effectively. Finally, regarding mostly Study 2, a higher number of participants would've been beneficial in improving on non-ideal indices of data adequacy and factor model fit.

Regarding the following part of the project, methodological strengths are found in the complete treatment of sustained attention variables both in terms of overall levels, and in changes over time, by utilising modern, non-traditional approaches in obtaining and analysing data and by employing large datasets insuring adequate statistical power. From a theoretical standpoint, the project provided a thorough examination of the influence of motivation on sustained attention while addressing gaps in the literature. A clear limitation of the project, however, regards the effects of reward on task performance. Whilst the present results provided an alternative view on the topic with interesting implications, it is also possible that the form of reward implemented was not adequate to elicit performance differences, as the study failed to replicate robust effects found in the literature (Esterman et al., 2014, 2016). This would also potentially explain the null results in attentional oscillations. A different type of reward, perhaps including an estimation of subjective costs (Massar et al., 2016) would have provided more reliable results.

From a theoretical standpoint, motivation provides a useful tool to test predictions across different models of sustained attention. The more recent attentional allocation accounts hypothesise that attentional lapses are due to a reallocation of resource to alternative tasks, while overload accounts state that while sustaining attention, resources are depleted. Effects of motivation are expected to be found on behavioural variables of task performance (such as variability, and accuracy). These variables, however, do not assess *where* attention is allocated, hence a measurement of whether the participant was focussed on the task or to something else perhaps utilising thought-probes, would have been particularly useful in determining which models explained the evidence in a more effective way. In particular, mind-wandering is a concept very frequently associated with sustained attention (Neigel, Claypoole, Fraulini, et al., 2019) and motivation (Kawagoe et al., 2020). Recent evidence showed that mind-wandering might mediate the effects of motivation on sustained attention (Brosowsky et al., 2020). Including a measure of mind-wandering might have provided an explanation to the inconsistent results found here.

8.4 Future directions

The present study advised on a robust operationalisation of sustained attention. The first step for future work might be a re-evaluation of the large existing literature using the perspective obtained here that highlighted the importance of attentional lapses. The contrasting results might in fact be due to findings based on task-specific components that are not generalisable across different methods. Moving forward, the role of motivation is yet to be adequately understood in the context of sustained attention performance. Addressing the limitations discussed above and the methodological advances implemented here would provide useful evidence regarding both intrinsic and extrinsic motivation. A further novel element of the present work was assessing how trait motivation relates to performance, but further research is needed.

Another step to consider would be implementing physiological measures as the present study only relied on behavioural data. Existing research has in fact attempted to implement measures from pupillometry (Unsworth & Robison, 2018), eye tracking (L. Wang, 1998) or skin conductance (Gergelyfi et al., 2015) which would provide additional insights on constructs like arousal, engagement, mind-wandering, compared to only behavioural measures from computerised tasks. These measures would inform more effectively on the underlying mechanisms supporting sustained attention performance and which of the theoretical frameworks is more aligned.

Behavioural oscillations also require further investigation with the combination of behavioural and physiological data using for instance EEG (Electroencephalography). Since the implementation here was based on the potential application of a hypothesis that is believed to be based on neurophysiological phenomena, ascertaining the link between behaviour and brain would widely increase the understanding. Recent research has attempted to do it while using fMRI (Zhang et al., 2022), however methods such as EEG with higher temporal resolution would be even more appropriate to investigate time/oscillatory behaviour. Additionally, the line of research looking at attentional frequencies $>$ 0.01Hz (VanRullen, 2016) provides behavioural tasks that offer denser recording which would allow the investigation of a larger range of frequencies, potentially linking behaviour to faster functionally relevant brain frequency ranges such as theta (4-8Hz) and alpha (9-12Hz) (Helfrich et al., 2018; Kienitz et al., 2021).

To conclude, the present work contributed to the literature of sustained attention by providing guidance on conducting research with generalisable findings, through careful design and choice of methods. Additionally, it showed that among the multiple facets of motivation, the aspects most effective in predicting performance was intrinsic motivation: in order to perform well in difficult and long task, it is essential to find enjoyment in the activity, rather than in performing well or in an external incentive. Finally, Study 9 provided an application of how the new methods of analysis may be used in other areas of research in exiting new directions, to better understand sustained attention in clinical groups.

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