Trade-offs between focused and distributed temporal attention

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Humans and other animals are faced with a continuous trade-off between exploiting the current task goal and continuing to explore or monitor their environment to identify new opportunities or threats. The exploitation-exploration dilemma has been investigated in a broad range of fields from animal foraging to machine learning to human decision-making. Often, trade-offs in human behaviour occur on a moment-by-moment basis, between focusing one's attention and distributing one's attention. Although it has been traditionally believed that attention is 'good' when selective and focused, it is increasingly becoming acknowledged that this is not always the case and that there are occasions when distributed attention is optimal instead.

This thesis develops the Attentional Blink – Illusory Conjunctions paradigm as a new experimental context to study distributed and focused attention in time comparatively in visually identical tasks. The thesis sets out to investigate trade-offs between focused and distributed temporal attention using the novel paradigm in a series of 9 experiments. To test how attention states trade off, manipulations known to either enhance attentional focus or to broaden attention are used. Furthermore, the dissociable association between mind wandering and focused vs. distributed temporal attention is analysed in a series of experiments. The neural correlates of the focused-distributed attention trade-off are also investigated using electroencephalogram (EEG) methods.

A key strand of work in this thesis investigates how attention trades off in terms of individual differences. The hypothesis that some people have a more focused attentional style and others have a more distributed attentional style is tested both in the blocked version of the Attentional Blink - Illusory Conjunctions paradigm used throughout the thesis, as well as in a non-blocked version introduced in the final experiment. The non-blocked paradigm variation that concludes the thesis provides a context to analyse how attentional states fluctuate, and furthermore exemplifies the potential of the Attentional Blink – Illusory Conjunctions paradigm as an experimental context that can be flexibly adapted to test a wide range of hypotheses regarding trade-offs in temporal attention.

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Table of contents

Chapter 1. Introduction.....1

The exploitation–exploration dilemma.....1

Foraging 1

Decision-making: how to solve the dilemma?.....2

Cognitive control: how does the brain solve the dilemma?.....3

An exploration bias?.....5

The Locus Coeruleus – Noradrenaline system.....9

Decision-making or attention?.....13

Trade-offs in attention.....16

Traditional view of attention: Goal-driven selective behaviour.....16

Capture of attention by orienting.....18

Focused and distributed attention in space.....20

Focused attention helps to avoid illusory conjunctions.....21

Distributed spatial attention.....22

Trade-offs in temporal attention.....25

Endogenous and exogenous temporal orienting.....25

Failures of focused attention in time.....30

Mind wandering.....31

The Attentional Blink.....34

A reflection of limited capacity or a case for distributed attention.....35

Alternative accounts of the Attentional Blink.....38

Preliminary evidence for trade-offs in temporal attention.....41

A way forward: Illusory Conjunctions within the Attentional Blink task..45

Aims of the thesis.....48

Chapter 2. Exploring the Attentional Blink – Illusory Conjunctions paradigm.....53

Introduction.....53

Trade-offs and the AB-IC paradigm.....54

Individual differences in the temporal attention trade-off.....59

State fluctuations in temporal attention.....61

Trade-offs in temporal attention within participants.....63

Method.....64

Results.....68

Quantifying AB and IC task errors.....68

Individual differences in the temporal attention trade-off……73
Individual differences in mental state and attentional trade-offs……76
Within participant factors affecting the temporal attention trade-off……77
Effects of foreperiod length……77
Salience of T1……79
Discussion……82
The AB-IC paradigm……82
Individual differences in temporal attention……84
Dissociable effects of intrinsic variation in task design……85

Chapter 3. Effects of temporal orienting on the temporal attention trade-off……89
Introduction……89
Orienting attention using exogenous and endogenous cues……90
Orienting attention in time: exogenous……92
Orienting attention in time: endogenous……93
Speed of presentation and the temporal attention trade-off……95
Experiments 2-4……96
Experiment 2: Exogenous cueing of attention in time……97
Method……97
Results……98
Discussion……100
Experiment 3: Endogenous cueing……101
Method……102
Results……104
Between-experiments comparison……109
Discussion……110
Experiment 4: Effects of speed of presentation on the temporal attention trade-offs……113
Method……113
Results……113
Discussion……115
General Discussion……117

Chapter 4. Distributed attention in time……121
Introduction……121
Mind wandering……122
Divided attention……125
Distributed attention in space……127
Experiments 5-7……131

Experiment 5: Mind wandering and temporal attention trade-offs.....132
Method.....132
Results.....133
Discussion.....137
Experiment 6: Dual tasking and temporal attention trade-offs.....139
Method.....140
Results.....142
Discussion.....144
Experiment 7: Spatial attention scope and temporal attention trade-offs.....146
Method.....147
Results.....148
Discussion.....151
General Discussion.....153
Irrelevant mental activity affects the temporal attention trade-off.....153
Distributed attention in time, in space and beyond.....156

Chapter 5. EEG correlates of the temporal attention trade-off.....159
Introduction.....159
Event-related potentials and the temporal attention trade-off.....159
EEG oscillations and focused vs. distributed attention in time.....163
Alpha.....164
Theta.....167
Beta.....168
Gamma.....169
Method.....171
EEG Acquisition and Preprocessing.....171
EEG Data Analysis: ERPS.....173
EEG Data analysis: oscillations.....175
Results.....177
Behavioural results.....177
Event-related potentials.....177
Neural oscillations.....184
Alpha.....185
Theta.....187
Beta.....187
Slow Gamma.....188
Discussion.....190
Event-related potential analysis.....190

Neural oscillations……193
Neural correlates of temporal attention states……196

Chapter 6. Individual differences and fluctuations in temporal attention trade-offs……197
Introduction……197
Individual differences in attention style……198
Fluctuations in attention states……199
Experiments 1-8……200
Experiment 9……203
Method……203
Results……205
Individual differences in attention style……206
Fluctuations in attention states in relation to mind wandering……207
Fluctuations in attentional states: further findings……210
Discussion……216
Individual differences in attention style……216
Fluctuations in attention states……218

Chapter 7. Discussion. The focused-distributed temporal attention trade-off and beyond……223
The AB-IC paradigm……224
The temporal attention trade-off: strategy, state and trait……229
Characteristics of focused and distributed temporal attention……234
Characteristics of focused temporal attention……234
Characteristics of distributed temporal attention……236
Object-based vs. Broader scope……238
Temporal attention trade-offs and the exploration–exploitation dilemma……240
Conclusions……245

Chapter 1

Introduction

Trade-offs in exploitation-exploration and in focused-distributed temporal attention

From simple organisms to complex humans, all intelligent life navigates its environment and, driven by its goals, selects what information to act upon. Conversely, the organism needs to continue to monitor its surroundings and quickly change its behaviour if a threat or a more rewarding stimulus appears. The organism is faced with a continuous trade-off due to the need to balance exploration and exploitation, while it is able to only perform one of the two at any given time. The following sections will describe this trade-off between exploitation and exploration in a number of different domains of research, leading up to the domain of attention in time, which is the focus of the research reported in this thesis.

The exploitation–exploration dilemma

Foraging

Exploitation and exploration trade-offs have been widely researched in zoology. One conceptualisation by Charnov (1976) explains the foraging dilemma as follows: if an animal can feed on only one patch at a time and patches differ in their payoff, how does the animal decide how long to feed on one patch before exploring new ones? At any given moment, the animal faces the trade-off between

on the one hand the possibility to exploit the current patch which has a certain known payoff associated and the possibility to explore other patches which may or may not yield greater payoffs.

Decision-making: how to solve the dilemma?

The "Gittins index" has been developed as a means of calculating the optimal strategy for choosing between a number of options with unknown but stationary probabilities for reward (Gittins & Jones, 1974; Gittins, 1979). The strategy involved a series of decisions about which option to choose next based on the probabilities of reward of available options, taking into account that each decision was based on more information than the previous one. In practice, the Gittins index was successfully used, for example, to predict the time when birds would stop exploring their environment and exploit a certain feeding post (Krebs, Kacelnik & Taylor, 1978).

Research on how the dilemma is solved has been conducted both in the field of machine learning (how to teach computers to solve it) and in human cognitive neuroscience (how people do it). Much of the research in both of these fields has used the Multi-armed Bandit problem: a gambling problem where one has to decide for how long to play a certain arm before switching to another one, if the arms have unknown reward probabilities. Using this problem, machine-learning theorists attempted to improve algorithms (Kaelbling, Littman & Moore, 1996) for reinforcement learning (learning which takes place through receiving negative and positive feedback). In fact, it was in the context of computational sciences that the phrase "exploitation–exploration dilemma" was coined. One of the problems of the Gittins index was that it only addressed the Multi-armed Bandit problem in stationary environments. By contrast, in nature, environments are changing. For example, reward distributions for stimuli and actions (akin to bandit arms in the formal setting) may change over time.

To investigate the dilemma in the described non-stationary case, Daw et al. (2006) observed how human participants behaved in the Multi-armed Bandit task, recorded the neural correlates of behaviour and compared this to simulated models. They compared three models of how exploitation–exploration decisions are computed in non-stationary environments: a) the epsilon-greedy algorithm which predicts that generally the options with greatest rewards will be chosen while preserving a fraction of random exploratory choice (Sutton & Barto, 1998); b) the "soft max" rule predicting that usually the maximum reward is chosen but with a ratio of next-to-best options being taken into account; c) the same "soft max" rule but additionally unselected options are boosted by an uncertainty bonus. Despite other accounts which favoured the uncertainty bonus schemes especially in machine learning (e.g. Kaelbling, 1993), the "soft max" computational model fitted behavioural data best in Daw et al.'s study. In practice, participants alternated between periods of exploitation when they chose the option with the best known value, and periods of exploration when the next-to-best options were chosen. The study shows several things: that people face a dilemma between exploration and exploitation decisions, that they solve this dilemma by taking reward probabilities into account, and that they alternate between periods of exploitation and periods of exploration.

Cognitive control: how does the brain solve the dilemma?

Following up on research in animal foraging (e.g. Charnov, 1976), Kolling, Behrens, Mars and Rushworth (2012) looked at the neural mechanisms behind exploration and exploitation decision-making in humans. The authors argue that much of the work in human neuroscience has looked into competition between available options, whereas the exploitation–exploration dilemma rather refers to a choice of whether or not to engage with options as they continuously become available.

This decision depends on how rewarding the encountered option is, but also on how rich the environment is and thus how likely it is to encounter a more advantageous option (the value of continuing to search). In an imaging study, Kolling et al. (2012) contrasted brain activity during foraging (exploration) and decision (exploitation) during a task where participants continuously had to choose whether to search or commit to deciding between current options. During the decision phase, the activity in the ventromedial prefrontal cortex reflected the difference in value between the chosen and unchosen options. On the other hand, anterior cingulate cortex activity reflected the richness of the environment (the value of exploration) during both foraging and decision. By contrast, Shenhav, Botvinick and Cohen (2013) reviewed a long strand of research into the role of the dorsal anterior cingulate cortex which suggests the structure is activated by the strength of incentives to exercise cognitive control over a current task, and also activated by the costs of doing so, such as task difficulty and performance decrements (e.g. Kouneiher, Charron & Koechlin, 2009; Kool & Botvinick, 2014; Kool, McGuire, Rosen & Botvinik, 2010). Based on such evidence, Shenhav et al. (2013) propose that the dorsal anterior cingulate cortex represents the expected value of control, accounting for both incentives and costs of exercising control. The viewpoints of Kolling et al. (2012) and Shenhav et al. (2013) are similar in that they both postulate that the anterior cingulate cortex computes costs and rewards, but while the first refers to these two in relation to search, the second group argues it is about control over the current task. While it is beyond the current scope to compare these theories, it is worth noting that the result of both positions is that depending on the computation of the anterior cingulate, the current behaviour (either exploitation or exploration) may either continue or it may discontinue in favour of the other.

Does the brain always get the decision right? Fallon and Cools (2014) explain that we continuously need to perform current tasks using our working memory while

also integrating incoming information about new motivationally salient events. On the other hand, the novel information should not disrupt us from performing the current task unless necessary. This creates a conflict between the stability of working memory representations and the flexibility of incorporating new information. The authors report that when participants experienced an unexpected financial gain, brain activity in the prefrontal cortex and ventral striatum was associated with increased ability to ignore distractors but decreased ability to flexibly update working memory. This suggested that unexpected gains could, possibly through dopamine-related changes (Schott et al., 2008), induce a brain state that was beneficial for exploitation but not for exploration. By contrast, Froeber and Dreisbach (2016) showed that the expectation of receiving a higher reward on the next trial not only benefitted flexibility by reducing the reaction time costs of switching, but furthermore it increased the frequency of voluntary task switching. These results support the argument that trade-offs between exploitation and exploration states exist in human behaviour and that experimental manipulations can affect the trade-off in either direction. Crucially, inducing either state comes at a cost to the other type of behaviour: inducing stability by giving unexpected gains was detrimental to updating working memory, whereas inducing flexibility by giving increased reward opportunities could lead to decrements in reaction time.

An exploration bias?

Failures in performance might not necessarily always reflect failures of control or errors in choosing between stability and flexibility. When performance on the current task decreases (e.g. decreases in vigilance observed over time), this decrease is associated with a subjective feeling of mental effort or fatigue. Previously, mental effort was perceived as a result of depletion of available mental resources, in particular attention capacity (Kahneman, 1973). However, there are a number of problems with the resource depletion interpretation. First,

as noted by Navon (1984), resource theories may become unfalsifiable because any result can be interpreted within the theory (e.g. any decrease in performance as an indication of limited resources), as long as resources cannot be measured independently. To give some examples, a good performance can be seen as evidence that the task demand was within capacity; but when there is poor performance on the same task, it may be attributed to lack of motivation, rather than seeing it as evidence against resource limitations. Similarly, when two concurrent tasks cause interference, this may be interpreted as a limitation of parallel processing capacity, while if two tasks do not cause interference, it may be interpreted as showing that they depend on two separate resources, rather than calling capacity limitations into question (Navon, 1984).

There are further problems with the resource theory. For example, a self-control task such as suppressing emotion or choosing to eat radishes over chocolate has been shown to lead to decrements in performance on a subsequent task such as an anagram or a puzzle (Baumeister, Bratslavsky, Muraven & Tice, 1998). The self-control task is believed to deplete the ego or the available resources and decrease performance on subsequent tasks. However, if positive affect is induced in between, the depletion does not happen (Tice, Baumeister, Shmueli & Muraven, 2007). This cannot be explained if the mental resource is a physical property of the system. Often, resources are linked to glucose, with the argument that the brain uses up available glucose for difficult tasks (Gailliot & Baumeister, 2007) but on the other hand performance in mental tasks is improved by physical exercise, which is known to consume glucose significantly (Tomporowski, 2003). Moreover, resource theories struggle to explain “learned industriousness” as well as reversed ego-depletion for participants who believe that self-control is beneficial, in both cases performance being better after more taxing tasks (Converse & DeShon, 2009; Savani & Job, 2017). Finally, there is much evidence to suggest that increasing participants’ incentives makes performance better, which

suggests that motivation, rather than resource, drives performance (Baumeister & Vohs, 2007).

If mental fatigue is not explained by a depletion of resources, Kurzban, Duckworth, Kable and Myers (2013) propose instead that fatigue reflects an opportunity cost. The theory rests on the assumptions that the brain is organised for adaptive behaviour (Tooby & Cosmides, 1992) and that the role of experience is to motivate behaviour that will solve adaptive problems (Tooby et al., 2008). According to Kurzban et al. (2013), one crucial adaptive problem is "simultaneity", that the organism cannot do everything at once, and the solution to the simultaneity problem is prioritisation (the choice of one action over alternative ones). Thus, the value of the current goal pursuit is monitored in comparison to alternatives (Hockey, 2011), and mental effort signals the opportunity cost associated with it (Kurzban et al., 2013). When the subjective experience of mental effort occurs, it is a signal that it is becoming more advantageous to switch to exploration rather than to continue exploiting the current task. In addition, as the authors argue, at times the same mental effort feeling may reflect an adaptive built-in bias towards exploration, which would lead to performance decrements over time in any task.

Is there evidence to support the existence of an exploration bias? Daw et al. (2006) did not observe an uncertainty bonus in their study using the multi-armed bandit task. Periods of exploration were still present in the best-fit model, the 'soft-max', through the occasional choice of next-to-best options, but they did not reflect a bias. However, other accounts of the exploitation–exploration dilemma in the context of the same task, but in the domain of machine learning, did posit such a strategic bias (e.g. Kaelbling, 1993). The difference may be due to the specific context of the task used by Daw and colleagues. When participants are faced with financial decisions, as is the case in this task, they tend to prefer a more certain option when the discriminability of its certainty is high (e.g. 100%

versus 80%), even if the certain option has a lower expected payoff than the less certain one (Kahneman & Tversky 1979; Hertwig, Barron, Weber & Erev, 2004; Shafir et al., 2008). On the contrary, when overall uncertainty is high (20% and 25% probabilities), people choose less certain options that may yield higher payoffs.

An interesting hypothesis is that the exploration bias is necessary particularly in the early stages of cognition, when there is a need to form multiple associations (McClure et al., 2006). As the authors explain, in the field of machine learning, one issue is how to implement reinforcement learning for multiple associations. If a first association is strongly learnt, then adapting to a change of association will be difficult. By contrast, if there is a weaker learning initially then change can be more easily learnt. Thus in order to limit the strength of the initial learning, an annealing mechanism can be implemented, which adds noise to the system so that random exploration of new associations is favoured (Cohen, McClure & Yu, 2007). Once exploration is over, noise is reduced again to strengthen the formed associations.

There are several candidate neural correlates of an exploration bias. First, McClure et al. (2006) propose a neural model in which on the one hand reward learning is computed through a dopaminergic system, while on the other hand there is an annealing mechanism reliant on frontal regions but also on the locus-coeruleus noradrenergic system (LC-Na), a system often described as being involved in the exploitation–exploration trade-off (e.g. Aston-Jones & Cohen, 2005). With regard to dopamine, there is indeed evidence not only that dopamine mediates reward-seeking behaviours, but that novelty is often a reward in itself, and thus that dopamine may be linked to a bias for novelty-seeking (e.g. Bardo, Donohew & Harrington, 1996; Kakade & Dayan, 2002). Finally, there is another brain system that might mediate an exploration bias: the default mode network, a brain network which is active during rest but also during internal mentation

including mind wandering, for example in the form of imagining future scenarios and simulating, or mentally exploring alternative options (e.g. Buckner, Andrews-Hanna & Schacter, 2008; Andrews-Hanna, 2012; Mason et al., 2007). These strands of research do not necessarily clarify whether the human brain is equipped with an exploration bias active at all times, but they do testify that such a bias occurs at least in some circumstances.

The Locus Coeruleus – Noradrenaline system: a candidate mediator of the exploitation – exploration trade-off?

As seen in the previous sections, it is very important to decide on whether at any specific point it is better to exploit or explore. This can be done through various computations: the Gittins index, the "soft max" rule (Daw et al., 2006), computing the search value (Kolling et al., 2012), the expected value of control (Shenhav et al., 2013) or the opportunity cost (Kurzban et al., 2013). At times, the decision can go wrong leading to distraction (Fallon & Cools, 2014) but poor performance and mental fatigue might also have an adaptive value in signaling the need to end exploitation and begin to explore (Kurzban et al., 2013). Perhaps to avoid such opportunity costs, people alternate between periods of exploitation and periods of exploration (Daw et al., 2006). It is also worth noting there are reasons to believe that human behaviour is characterised, at least in some situations, by an exploration bias (e.g. McClure et al., 2006).

While these summarised findings shed light on how the exploitation–exploration dilemma might be solved, they reveal comparatively less about the mechanisms that mediate such behaviours. Multiple strands of research suggest that the human brain can be in two different operating modes or states, one of which favours exploitation and the other exploration. The fluctuation between these two states, in terms of behavior and neural correlates, was highlighted by Daw et al. (2006). Some candidate neural correlates were revealed by Kolling et al. (2012)

who dissociated between the ventromedial prefrontal cortex, which may compute the value of exploitation, and the anterior cingulate cortex, which reflected the value of exploration. Similarly, Fallon and Cools (2014) showed that financial gain can induce a brain state that favours exploitation by activating the prefrontal cortex and ventral striatum, possibly by modulating dopamine (Schott et al., 2008). A further theory proposed by McClure et al. (2006) was that exploitation may depend on dopamine, while exploration and the interplay between the two states may be mediated by the locus–coeruleus noradrenergic system (LC-Na). Indeed, an involvement of the LC-Na system in the exploitation – exploration trade-off has been proposed by several researchers (e.g. Usher et al., 1999; Aston-Jones & Cohen, 2005).

The locus coeruleus, a nucleus in the dorsal pons, is the main source projecting noradrenaline throughout the brain, forming the LC-Na neuromodulatory system (Jones & Moore, 1977). It has been documented that LC neurons have three tonic firing modes. During periods of sleep and disengagement the LC exhibits a low firing mode (Aston-Jones & Bloom, 1981; Foote, Aston-Jones & Bloom, 1980). Conversely, when a monkey or a rat is presented with visual stimuli in different modalities and responds to these, the LC exhibits a moderate tonic firing as well as phasic responses to stimuli. One of the first theories proposed that the LC-Na system regulated arousal (Berridge & Waterhouse, 2003). However, as highlighted by Aston-Jones and Cohen (2005), theories linking the LC-Na system to arousal have not clearly defined either arousal itself or the neural or computational mechanisms involved in LC-Na's moderating role. Furthermore, arousal theories did not fully account for the utility of tonic firing periods.

Instead of reflecting arousal, there is strong evidence that phasic firing reflects task engagement. When a stimulus is presented repeatedly, the LC phasic response is present for as many instances as an orienting response to the stimulus appears (Foote et al., 1980). The same phasic response coupled with

moderate tonic firing appears in response to targets but not distracters during periods of good performance in a perceptual discrimination task (Aston-Jones, Rajkowski, Kubiak & Alexinsky, 1994; Usher et al., 1999). Finally, there is some evidence that the role of the LC-Na system is causal, because the phasic bursts occurred at short latencies, prior to the monkeys' behavioural response (Aston-Jones et al., 1994; Usher et al., 1999), because LC activity was linked to RT variability rather than stimulus onset (Rajkowski, Majczynski, Clayton & Aston-Jones, 2004), and optogenetic manipulation of LC firing affected behaviour of mice (Schwarz & Luo, 2015).

While phasic firing appears to be related to task engagement or, in other words, task exploitation, on the other hand tonic firing may relate to exploration. In a perceptual discrimination task, high levels of tonic firing were observed during periods of distractibility, when monkeys made more frequent false alarm errors that involved responses to distracters, and additionally the animals had decreased ability to discriminate targets from distractors (Usher et al., 1999; Aston-Jones et al., 1994; Rajkowski, Kubiak & Aston-Jones, 1994). Interestingly, during tonic firing periods monkeys also exhibited more visual scanning of the environment (Rajkowski et al., 1994). When the stimulus-response contingency was reversed such that targets became non-targets, LC exhibited an increase in tonic activity immediately after reversal (Aston-Jones, Rajkowski & Kubiak, 1997), suggesting that LC tonic activity may boost responses to novel stimuli and play the role of an annealing mechanism as proposed by McClure et al. (2006).

A similar but alternative account is that the LC-Na system mediates task switches or reorienting (e.g. as proposed by Yu & Dayan, 2005; Bouret & Sara, 2005; Sara & Bouret, 2012; Corbetta, Patel & Schulman, 2008). Indeed, switching was facilitated by pharmacological stimulation of the LC-Na system (Devauges & Sara, 1990) and was disrupted by deafferentation of noradrenergic neurons (McGaughy, Ross & Eichenbaum, 2008). As an interesting parallel, in crustacean

species the brains' central oscillatory patterns are flexibly re-configured by neuromodulators to serve different functions depending on the environmental demands (Simmers, Meyrand & Moulins, 1995), similarly to how the LC-Na facilitates transitions between sleep and wake (McCormick, 1989). The problem with the reset or reorient theories of LC-Na function is that they do not account for the involvement of phasic LC bursts in task-relevant activity, and thus do not fully explain the duality of the LC system.

Results showing that the LC-Na system is involved in both task engagement and reorienting are in line with the adaptive gain theory of LC-Na function (Aston-Jones & Cohen, 2005), which posits that noradrenaline regulates behavior along a continuum between exploitation and exploration. The way the LC-Na was suggested to optimize behaviour on this dimension was through adjusting the adaptive gain of cortical circuits phasically or tonically. In other words, shifts between high and moderate tonic firing rates would reflect transitions from exploration to exploitation. Computational studies support a role for phasic firing in focused attention and a role for tonic firing in behavioural flexibility (Aston-Jones, Rajkowski & Cohen, 1999) and furthermore suggest that such transitions are gradual, along a continuum of tonic and phasic activity and a continuum in terms of efficiency of responding to stimuli (e.g. Usher et al., 1999).

A direct test of the hypothesis of LC-Na involvement in exploitation-exploration is pending in human research, partly due to difficulties in recording LC activity. However, researchers have looked at a proxy of LC activity: pupil dilation, which is believed to co-vary with LC-Na activity (Murphy et al., 2014). In a tone discrimination task, pupil dilation was greatest, reflecting a tonic LC firing mode, just before the participant abandoned the current series of discrimination trials and went on to try the next one, as reported by Aston-Jones and Cohen (2005). Pupil dilation was associated with transitions between exploitation and exploration behaviours in the multi-arm bandit gambling task (Gilzenrat,

Nieuwenhuis, Jepma & Cohen, 2010; Jepma & Nieuwenhuis, 2011) and between periods of exploration and exploitation in an analogic reasoning task (differentiated on the basis of participants' think-aloud patterns that reflected when they were exploring options or exploiting a solution; Hayes & Petrov, 2016). On the other hand, there was mixed evidence that pharmacological manipulations of noradrenaline impact behavior within the gambling task (Jepma et al., 2010; Warren et al., 2017). This latter finding may not affect interpretation, since pharmacological manipulations do not directly modulate tonic or phasic LC firing. Overall, there is accumulating evidence for an association between the exploitation–exploration trade-off and the LC-Na system.

The exploitation–exploration dilemma: decision-making or attention?

Further to arguing for a mediating role of the LC-Na system in exploitation and exploration, the adaptive gain theory proposes that the LC-Na system mediates the decision making trade-off through a temporal attention filter (Aston-Jones & Cohen, 2005). The authors make the case for this proposal by referring to drift diffusion models of decision making. Within these models, evidence for each decision option accumulates stochastically and a decision is made when the difference in evidence reaches a certain threshold (Ratcliff & McKoon, 2008). However, evidence accumulation takes place in a complex system, on several layers from a task-specific level to a response level (e.g. Schall, 2003). As such, it becomes inefficient to compute this threshold on a layer-by-layer basis. As Aston-Jones and Cohen propose, the role of the LC phasic response is to signal the time when task-level decision is reached and to rapidly transmit this information throughout the whole system. Conversely, top-down signals in brain regions such as the orbitofrontal cortex announce that the value of a choice has changed (e.g. Wallis & Kennerley, 2011), and because these brain regions project to the LC (e.g. Schwarz & Luo, 2015), the LC tonic activity is proposed to then spreads gain throughout the whole system, mediating an exploration state. Furthermore,

performance decrements associated with tonic LC mode are interpreted as reflecting local consequences of longer-term adaptive mechanisms meant to change from current task focus to explorative behaviours. In this proposed view, LC-Na is a temporally-specific but spatially global attentional filter, within which the phasic bursts act to enhance task-relevant selectivity of attention. Moreover, a specific phenomenon in temporal attention that has been linked to the LC adaptive gain theory is the Attentional Blink, as will be discussed further below (Nieuwenhuis, Gilzenrat, Holmes & Cohen, 2005).

Within and beyond the adaptive gain theory, attention in time may play an important role in the exploitation–exploration trade-off. Aston-Jones and Cohen (2005) propose this role in gating neural signals to aid decision making. However, even if this theory was proven wrong there still remain reasons why attention may be important in exploitation–exploration trade-offs. Cohen et al. (2007) note in their review of the field of exploitation–exploration in cognitive neuroscience that there are multiple scales of the dilemma: from moment–by–moment trade-offs (e.g. concentrating on writing a paper in the face of distracting noise vs. noticing the sound of the fire alarm when it goes off) to complex dilemmas such as life choices (e.g. continue dating new people or commit to a partner). According to Cohen et al. (2007) some of the more complex dilemmas actually involve multiple levels of 'exploitation' behaviours. In a stable or predictable environment, optimal strategies (e.g. the Gittins index) involve choosing between options in a context such as the multi-arm bandit task. Because of the deterministic and strategic nature of this choice, Cohen et al. (2007) argue that in this case the 'exploration' behaviour i.e. shifting to the next arm of the bandit, would actually be a more complex form of exploitation. To a degree, this might also be the case in unpredictable environments, where 'exploratory' behaviours involve computing the value of a few sub-optimal options and trying these (e.g. Daw et al., 2006). To better understand the psychological and neural mediators of exploitation and exploration while avoiding confounds, research would benefit

from looking into exploitation and exploration at a lower-level scale, isolating simple exploitation and exploration behaviours, rather than a composition of multiple levels of exploitation decisions. One candidate for studying such lower-scale exploitation and exploration states is the field of attention, as attention is one of the most basic cognitive mechanisms at the intersection between perception and cognition.

Recently, a dissociation between two states of attention has been increasingly gaining support. Traditionally, attention is seen as a mechanism aimed at selecting sensory information to be further processed, based on task requirements, utility or salience. Conceptually, this parallels definitions of exploitation behaviours. In this case, attention is seen simply as a means to choose targets for exploitation and to remain committed to them. Often, periods when attention was not efficient in selectivity were deemed to reflect distraction and failure of attention (e.g. James, 1890). More recently however, there has been increasing support for the view that attention is not only about selection, but also shows a duality and a trade-off between periods of focused, selective attention and periods of broad, distributed attention (e.g. Navon, 1977), and that the latter may also prove adaptive in certain circumstances. In this case, exploitation–exploration trade-offs become relevant within the domain of attention.

Beyond this conceptual connection, Manohar and Husain (2013) recently proposed that attention acts as a teleforaging mechanism, with trade-offs between foraging for information (exploring) and foraging for reward (exploiting). Their experiment supported this view, such that participants started off spatially broadening their attention to explore various options for gambling until they later fixated on the gamble that they were going to choose. In what follows, the literature on trade-offs in attention will be discussed, starting with spatial attention, which has been the subject of traditional investigations in

attention and continuing into the more recently expanding field of temporal attention.

Trade-offs in attention

Traditional view of attention: Goal-driven selective behaviour

Beginning with the early days of researching attention, it was considered that a focused, selective attention is adaptive to human behaviour.

> *"Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called distraction." (William James, 1890).*

As the quote suggests, the idea that attention is defined as a selective process is deeply rooted in folk psychology. Building on this interpretation, the first systematic studies of human behaviour supported the same view of attention. Psychologists studied limitations of human performance and found decrements in performance when switching from one task to another (task switching, Jersild, 1927), when exposed to interference (the Stroop effect, Stroop, 1935) and immediately after processing a stimulus (psychological refractory period, Telford, 1931). Similarly, early cognitive psychology experiments suggested that a focused attention was optimal, for example in order to select information for further processing and make a conversation possible during a noisy cocktail party (Cherry, 1953).

The first theories of attention aimed to explain what makes a 'good' performance possible. Researchers proposed various mechanisms by which attention could focus and select particular information while rejecting distracting irrelevant information. One mechanism was an 'attentional bottleneck' that filters information based on its relevance for behaviour or its physical properties (Broadbent, 1958; Treisman, 1964). Another proposed mechanism was a spatial 'spotlight' which favours processing of items at a specific location (Eriksen & Hoffman, 1973; Posner, 1980) or nearby through a zoom lens (Eriksen & Yeh, 1985) or Gaussian gradient (Downing & Pinker, 1985).

While theories of attention all highlighted the importance of selection, neural findings supported this. Desimone and Duncan (1995) proposed that at a neural level, selective attention was mediated by a biased competition between visual stimuli for neural representation. Indeed, visual stimuli are represented hierarchically throughout the brain, starting from sensory organs and continuing in early visual cortices and finally in higher-order visual cortices. Within this visual stream, in early cortices there are neurons that respond selectively to a small region of space through their receptive fields (Ungerleider & Mishkin, 1982; Desimone & Ungerleider, 1989; Kanwisher, McDermott & Chun, 1997). While this demonstrates spatial selectiveness at a neural level, the competition can be biased through top-down signals that originate in higher-order cortices and modulate visual cortices (Felleman & Van Essen, 1991). An intention to direct spatial attention to a location containing a stimulus enhances the response of visual cortex neurons responsible for that location (Heinze et al., 1994). Furthermore, this enhancement is accompanied by suppression of neural response to competing stimuli located elsewhere (Rees, Frith & Lavie, 1997). What all of this shows is that there is a complex neural hierarchy responsible for selection of some stimuli at the expense of other stimuli, through focused attention.

Capture of attention by orienting: a building block for selective attention, or more?

In both 'spotlight' as well as biased-competition theories of spatial attention, a crucial building block of selective attention is orienting of attention to a location, such that stimuli at that location can be prioritised for further processing and goal-directed actions. Orienting of attention has been extensively studied within the 'Posner paradigm'. Posner (1980) showed that participants were better at detecting a target visual stimulus on the screen if they had been cued with regard to its location. Central arrows were believed to guide attention in a top-down, endogenous manner while peripheral salient cues presented at the future location of the target or at incongruent locations were believed to draw attention through bottom-up, exogenous mechanisms. Both benefited performance when they were valid while harming performance when invalid. By improving stimulus processing, both types of spatial orienting acted to shift the cognitive state towards a more focused attention.

Apart from being a building block of selective attention through triggering a focused mode, the two types of orienting might also be informative with regard to the trade-off between exploitation and exploration in terms of attention. One theory is that while top-down cues guide attention voluntarily following a clear task exploitation goal, on the other hand bottom-up cues may sometimes have a role in breaking the current task circuit to rapidly draw attention to a new task priority (e.g. Corbetta et al., 2008). Indeed, evidence showing that reduced reaction time to targets could be observed earlier following salient peripheral cues than central symbolic cues indicates that bottom-up cues act earlier than top-down cues in the benefit of target detection (Posner & Cohen, 1984; Muller & Rabbitt, 1989). Moreover, peripheral cue effects interfered with effects of voluntary symbolic cues, even in trials when peripheral cues were not predictive

of target location (Muller & Rabbitt, 1989), supporting a potential role for bottom-up orienting in task circuit breaking.

Neuroscientific evidence also supports the dissociation between goal-driven orienting, which has been associated with a dorsal network, and circuit-breaking re-orienting, associated with a ventral neural network (Corbetta et al., 2008). To begin with, various human fMRI and PET studies found that activity in the intraparietal sulcus (part of the dorsal stream) increases during tasks requiring voluntary orienting of attention (Corbetta, Miezin, Shulman & Petersen, 1993; Nobre et al., 1997; Corbetta et al., 1998). Moreover, the role of the intraparietal sulcus in goal-driven orienting was highlighted by a study finding increased activity during the period when attention was guided by a cue, but not during target detection. On the other hand, the right temporoparietal junction (part of the ventral network) increased activation when a target was detected, especially for targets detected at unattended locations, for which participants had to re-orient in a bottom-up way (Corbetta, Kincade, Ollinger, McAvoy & Shulman, 2000). Additionally, lesions to the temporoparietal junction have been found to be associated with failures to detect stimuli in the visual field contra-lateral to the lesion unless the locations of the stimuli were cued beforehand (Posner, Walker, Friedrich & Rafal, 1984; Friedrich, Egly, Rafal & Beck, 1998). Temporoparietal junction lesions also disrupted detection of novel, infrequent targets (Knight & Scabini, 1998; Daffner et al., 2000), suggesting that the role of the ventral network is not specific to spatial attention, but mediates a more general re-orienting mechanism (Corbetta et al., 2008).

Overall, the two types of orienting are informative in two ways. First, they show that a focused and selective attention state, in which visual stimuli are better processed, can be induced. The fact that a selective, focused attention can be experimentally induced provides a context to analyse it further and compare it with a different, distributed state. Second, the difference between the two types of

orienting as well as the two neural networks described above lends more support to the existence of trade-offs in attention. Particularly, the evidence supporting a re-orienting mechanism, potentially mediated by the ventral neural network highlights the fact that focusing on a stimulus location or exploiting a task is not optimal at all times. Rather, there are occasions when it is necessary to break the current task, for example by means of a salient bottom-up stimulus which draws attention to a new priority or which enables a new explorative state. Nevertheless, it is important to note that while bottom-up salient cues can at times re-direct attention, they are often congruent with current task goals and with top-down intentions, as for example in congruent trials of the Posner paradigm (Posner, 1980), in which case bottom-up cues remain tools for focusing attention towards exploiting the current task goal.

Focused and distributed attention in space

The research reviewed so far has described the perspective that attention serves for goal-directed action, as a selection mechanism, and that orienting cues can improve the ability to select stimuli efficiently. On the other hand, the potential role of bottom-up cues as circuit-breakers suggests that trade-offs in spatial attention (and possibly beyond it) exist and that a mechanism to counteract a too-focused attention may exist in the brain. If circuit-breakers prevent a too-focused attention state and promote a more exploratory attention state, on the other hand it remains unclear what the mechanisms of an exploratory attention state are. In what follows, a different line of research into spatial attention will be presented, which portrays a dissociation between focused attention as locally-centered, a mode that favours expoitation of task goals; and distributed attention which is globally-spread and may serve for exploration purposes (Treisman, 2006).

Focused attention helps to avoid illusory conjunctions

In space, focused attention is most often portrayed as locally-centered, as reflected by the 'spotlight' theories. The Feature Integration Theory of visuospatial attention (Treisman & Gelade, 1980) goes beyond this to propose that focused attention, centered on a location in space, is essential for binding visual features and perceiving coherent objects. The theory is based on the neuroscience of the visual system. Besides the re-orienting role described above, the ventral stream has also been described as the 'what' neural pathway (Ungerleider & Mishkin, 1982). It includes the V1, V2, V4 visual cortices and the inferior temporal cortex and it responds to identification of objects. A property of neurons in V1 primary visual cortex is that they respond to features such as orientations of light bars (Hubel & Wiesel, 1959) or colours (Thorell, De Valois & Albrecht, 1984) rather than to full objects. Moving higher in the ventral pathway, neurons respond to increasingly complex stimuli. But if different features of a visual object are represented separately in the brain, how are these coordinated in order to form a single coherent object? This 'binding problem' of perceptual features is, as proposed by Treisman and Gelade, solved through focused attention. The key idea is that when attention is adequately focused, attended features are bound together in a coherent 'object file'.

Conversely, when attention is not focused, illusory conjunctions may occur, which means that features belonging to different objects may be incorrectly bound together. As evidence for this hypothesis, Treisman and Schmidt (1982) showed participants three coloured letters presented together in the same visual display, while asking them to attend to distractor flanking digits. Participants made many illusory conjunctions, reporting for example a red E and a green T when the stimuli were a red O, a blue T and a green E. Similar results were found by other researchers, making the 'illusory conjunctions' a well-documented illustration of how spatially focused attention can fail (e.g. Houck & Hoffman, 1986).

Distributed spatial attention

While the characteristics of a focused attention in space have been widely studied, distributed spatial attention has been less well-described. However, several lines of research reveal the existence of distributed attention in space as distinct from focused attention in space. One of the early lines of investigation compared local and global visual attention. Navon (1977) looked into the perception of large visual shapes composed of smaller shapes, for example large letters composed of smaller letters. A trade-off was observed: the instruction to concentrate on the global created interference with perceiving the local (smaller) letter, and the reverse (Hoffman, 1980; Miller, 1981; Pomerantz, 1983). Moreover, the idea of a trade-off was further supported by evidence that instructions from the previous trial, and thus the previous attention state, influenced performance in the current trail (Ward, 1982). A global bias that reminded of the exploration bias was observed: large letters are responded to more quickly, suggesting that they are represented earlier (Navon, 1977). Global letters also created more interference with speed of responding to local letters, compared to the reverse (Hoffman, 1980; Miller, 1981; Pomerantz, 1983). Importantly, top-down orienting through cueing the level at which participants needed to attend benefitted performance for both local and global targets (Robertson, Egly, Lamb & Kerth, 1993). Thus, the trade-off in attention could be experimentally manipulated.

While the Navon paradigm supported the existence of trade-offs between local and global attention, it remained unclear whether the paradigm tapped into more general spatial attention trade-offs. Dale and Arnell (2013a) investigated associations between three tasks: the Navon local–global letters task; a task containing hierarchical shapes in which the global shape could match the shape of some but not other lower level stimul, and a spatial frequency task presenting hybrid face stimuli composed of one face stimulus of a high spatial frequency, and

a second face stimulus of a low spatial frequency. The authors did not find that the global and local biases were correlated across tasks, suggesting that these tasks might tap into distinct global-local trade-offs. However, the study looked at individual differences, i.e., whether the degree of preference towards distributed or focused attention was consistent between tasks. This is not necessarily informative with regard to whether the tasks have a common cognitive substrate.

A series of experiments looking at focused and distributed spatial attention in a within-participants design was conducted by Chong and Treisman (2005a; 2005b). In these experiments, the authors induced a focused attention state through a difficult search task requiring selective processing: looking for a closed circle in an array of circles with gaps. By contrast, a distributed attention state was induced through an easy, pop-out search task: searching for a circle with a gap in a display of closed circles. To validate the manipulation of attentional states, authors showed that the closed circle search took longer in a 12-item array than in a four-item array, while the gap circle search did not. The experimental task involved either reporting the mean size of circles (statistical processing) or the size of a random individual item (focus of attention). Performance of individual item size reporting was better after a focused mode was induced, while statistical processing was better in the no-focus mode. Further experiments also linked global and local attention to this dissociation. Again, the authors manipulated attention experimentally. Global attention was induced by asking participants to report the orientation of a rectangle surrounding a display, while local attention induction asked for the orientation of a rectangle at the center of the display. Again, the two manipulations affected statistical processing and individual item processing in opposite ways. A third manipulation used parallel processing for broader attention and serial processing for increasing focus, to the same effect. Finally, Chong and Treisman observed that processing of individual items was affected by performance of a concurrent task, while statistical processing was not. The interpretation was that statistical processing takes place

automatically, resembling the global precedence or the exploration bias described previously. Overall, the work of Chong and Treisman supported the idea of a spatial attention trade-off which can be experimentally manipulated and which appears to generalise over multiple types of broad or distributed and local or focused attention, the latter involving an increased perceptual acuity for individual items.

The interesting dichotomy between processing of individual items or statistical processing was more recently investigated by Summerfield, Behrens and Koechlin (2011) in a perceptual discrimination experiment. The researchers showed that when having to report the average orientation of a series of visual gratings presented to them, participants switched between using two strategies, as revealed by two computational models which best fitted the behavioural data. At times, participants used a working-memory strategy of remembering the individual items presented last (attention was focused on a few items), while there were also periods when a Bayesian strategy involving statistical processing was used (attention was distributed). There are three key differences between this work and that of Chong and Treisman. First, Summerfield et al. used a single task and was able to observe both types of behaviour within it, whereas Chong and Treisman did not use identical visual tasks for comparing the two attention states. Such differences may lead to visual processing confounds. On the other hand, Summerfield et al. were only able to identify the two types of behaviours retrospectively rather than by instruction or experimental manipulation. Finally, in Summerfield et al.'s study, participants focused or distributed their attention in time, between visual items that were presented serially. Thus, the study highlighted a trade-off in perceptual decision making, in the time domain.

Trade-offs in temporal attention

As Summerfield et al. (2011) observed, trade-offs take place in perception across time. The authors argued that we experience the world continuously and make decisions based on perceptual information accumulating in time, which is also highlighted by drift diffusion models. The importance of the temporal domain was highlighted by Aston-Jones and Cohen (2005) in the adaptive gain theory. They proposed that temporal attention gates accumulating information to aid a decision for exploiting a certain task goal or exploring further. Thus, the authors linked temporal attention to the trade-off in exploitation and exploration and to the mediating LC-Na neural system. Moreover, temporal attention also appears important to the exploitation–exploration trade-off at a face value, because of the momentary nature of these two states. Indeed, attention is continuously captured by different stimuli either endogenously or exogenously (Munneke, Hoppenbrouwers & Theeuwes, 2015), which means that on a moment-by-moment basis, attention changes between various exploitation and exploration states. The experimental evidence for dissociable focused and distributed states in the time domain, and for their trade-off, will be discussed in the following sections.

Endogenous and exogenous temporal orienting: mechanisms for selective temporal attention

In temporal attention, like in spatial attention, focused modes have been more widely studied. Particularly, focused attention in time has been studied through orienting manipulations. Early on, Wundt (1887) reported that a warning signal presented before a target increased reaction time to target, even if not conveying information about the target location or time of presentation. As further research observed, warning signals were most effective when the foreperiod to target onset was short (Woodrow, 1914; Zahn & Rosenthal, 1966; Mattes & Ulrich,

1997), perhaps because shorter time spans are estimated more accurately, enabling more response readiness (Grondin, 2001; Allan & Gibbon, 1991; Wearden & Lejeune, 2008). An additional observation made by Woodrow (1914) was the sequential effect: responding to a target was influenced by the foreperiod lengh of previous trials. A neural signature of this automatic preparation effect, the contingent negative variation, was observed even in trials when attention was cued to a different foreperiod length (Los & Heslenfeld, 2005). Despite the strength of such preparation, it is unclear whether warning cues act to increase attentional focus. Indeed, after an auditory warning cue, researchers found an increased global bias in Navon tasks (Weinback & Henik, 2011; Van Vleet, Hoang-duc, DeGutis & Robertson, 2011). In light of this uncertainty with regard to warning cues, the following section will review whether endogenous and exogenous cueing experiments were more successful in inducing a focused attention in time.

To begin with, endogenous cueing has been increasingly investigated in the temporal domain. Symbolic instructions were first given by Kingstone (1992) who showed participants the letters S (instructing a short delay to target), L (instructing a long delay) and N (neutral instruction). Coull and Nobre (1998) used a temporal version of the Posner cueing paradigm. In their experiment, participants were instructed with regard to the moment in time when the target will appear: 'early' (400 ms SOA) or 'late' (1600 ms SOA). Instructions were valid in 80% of trials and results showed that RTs were indeed speeded in the short delay after the 'early' cue. The temporal orienting effect at short delay was subsequently replicated (Naccache, Blandin & Dehaene, 2002; Nobre, 2001). An explanation for the lack of such results in the long delay (although Correa, Lupianez, Milliken & Tudela, 2004 also found the effect for the 'late' cue) was that targets always appeared at short or long delays, and thus even if participants had prepared for the short foreperiod, they would have time to re-orient and be prepared when the target appeared at a long delay. Nevertheless, in the field of

temporal attention, the 'late'/'early' instruction paradigm has become established as he most common way to measure endogenous orienting.

While endogenous orienting in time takes place through symbolic cueing, a number of studies have also looked at exogenous orienting in time. The most common method for exogenous orienting in time is rhythmicity, either perceptual rhythmicity induced through presenting stimuli at regular intervals, or motor rhythmicity induced through response patterns (Praamstra, Kourtis, Kwok & Oostenveld, 2006; Martin et al., 2005; Coull & Nobre, 2008; Mathewson et al., 2010; Sanabria, Capizzi & Correa, 2011). Both of these types of rhythmicity improved reaction time to targets as well as accuracy. In a more naturalistic experiment, Doherty, Rao, Mesulman and Nobre (2005) guided temporal attention through the trajectory of a ball on the screen. When the trajectory was predictable, the reaction times to a target were speeded when the target re-appeared after occlusion. Moreover, a similar experiment showed that rhythmicity cues were beneficial to perceptual discriminations regarding the ball (Rohenkohl, Coull & Nobre, 2011). While exogenous cueing using rhythmicity was dissimilar to spatial attention experiments, on the other hand, salience, which has been used to cue exogenous attention in space (e.g. Posner, 1980) can also be used to cue attention in time. For example, Lawrence and Klein (2013) manipulated the intensity signal of a cue independently of the predictive value of the temporal expectation. There was evidence that saliency of the warning cue enhanced the benefit of temporal orienting. Thus, attention in time could be cued exogenously through both rhythmicity as well as salience.

To exercise caution, it is important to review the literature on what types of performance can benefit from temporal orienting. First, selective processing does benefit, because having an expectation of the time of onset of a target leads to a more rapid and more selective encoding of the target stimulus in short-term memory, with reduced memory for distractors (Sorensen, Vangkilde & Bundesen,

2015). Apart from selectivity, a focused attention mode in space is associated with enhancement of perceptual processing, for example as reflected in the avoidance of feature binding errors (Treisman & Gelade, 1980). However, early experiments in the temporal domain found that orienting benefits occur at later processing stages involving motor control, as shown by modulations of late neural potentials associated with motor control (Niemi & Naatanen, 1981; Coull & Nobre, 1998; Miniussi, Wilding, Coull & Nobre, 1999; Coull, Frith, Buchel & Nobre, 2000; Hackley, 2009). On the other hand, neural correlates of attention were also modulated, for example the P3 event-related potential was enhanced in amplitude and peaked earlier for temporally cued targets (Miniussi et al., 1999). Furthermore, later experiments also found modulations of early visual processing potentials such as the N1 (Griffin, Miniussi & Nobre, 2002; Faugeras & Naccache, 2016) or P1 (Correa, Lupianez, Madrid & Tudela, 2006a), suggesting that orienting benefitted perceptual processing.

A benefit of orienting to perceptual discrimination was especially reported in tasks that were more perceptually difficult, including: feature detection (Griffin et al., 2002), luminance threshold, perceptions of orientation, stereoscopic perception (Lasley & Cohn, 1981; Westheimer & Ley, 1996; Rolke & Hofmann, 2007), or perceiving the correct order of consecutive stimuli in a serial presentation (Correa et al., 2006b; Bausenhart, Rolke & Ulrich, 2008). Finally, Correa, Lupianez and Tudela (2005) observed that cueing the temporal position of a target within an RSVP (rapid serial visual presentation) stream, in which several stimuli are presented sequentially with short inter-stimulus intervals, was particularly beneficial to perceptual discrimination when the response to the target was unspeeded. Thus, perceptual discrimination benefits occurred particularly in more difficult perceptual tasks and in unspeeded tasks.

One challenge to studying temporal attention is the current lack of knowledge of the neural substrate of time representation. First, it is not yet clear how the brain

keeps track of time (Muller & Nobre, 2014). Despite this, our ability to estimate time has been found to be quite reliable, apart from circumstances when a research participant is engaged in both duration estimation and a concurrent difficult secondary task (Brown, 1997). On the other hand, Nobre (2010) noted that preparing attention for a specific moment in time is not as straightforward as orienting spatial attention to a certain location. While there are specific cells selectively coding for a spatial location, there are no specific cells coding for a moment in time. Rather, time and temporal expectancy is coded in neural networks (Nobre & O'Reilly, 2004; Karmarkar & Buonomano, 2007; Buonomano & Maass, 2009) and thought to involve brain oscillations (Cravo, Rohenkohl, Wyart & Nobre, 2011) in frequency bands such as theta (4-8 Hz, Parker et al., 2014) or alpha (10-12 Hz, Oprisan & Buhusi, 2014).

Because of such distributed coding of temporal expectancy, activity in specific neurons cannot be enhanced, but instead there might be a phasic enhancement of widespread neural activity, as Nobre (2010) noted. Indeed, Fischer, Plessow and Ruge (2013) found that temporally-predictive cues yield task-unspecific brain readiness. Such task-unspecific brain readiness might be detrimental in some cases. One such case could be response conflict tasks. As Correa, Cappucci, Nobre and Lupianez (2010) observed, cueing the time of onset of a display was detrimental to performance in a response conflict task where participants had to report the direction of an arrow flanked by distractor arrows. On the other hand, perceptual discrimination tasks appear to remain unaffected. Effects of temporal orienting on perceptual discrimination of various types have been well-documented, as previously reviewed. To highlight this dissociation, Jepma, Wagenmakers and Nieuwenhuis (2012) experimentally observed that temporal orienting benefits perceptual processing, but not response conflict. Therefore, there is strong evidence to suggest that a state of focused attention in time exists, that this state is associated with enhanced perceptual processing and that it can be experimentally manipulated through orienting in time.

Failures of focused attention in time

As is the case in the spatial attention literature, in the time domain a distributed attention mode has been little researched. To understand trade-offs in temporal attention better, it is worth looking first at failures of attention in time or over time. If authors such as Kurzban et al. (2013) argue that cognitive failures such as fatigue may reflect the cost of continuing to exploit a current task at the expense of other opportunities, then failures of attention in time may be similarly informative.

One common way in which failures of attentional performance take place over time is through lapses in vigilance. These become problematic for example for air traffic monitoring or even during driving on long stretches of highway. One common way to investigate vigilance experimentally is within the Sustained Attention to Response Test (Robertson et al., 1997), which requires participants to respond regularly to non-target stimuli and withhold their response to infrequent targets. Decrements and fluctuations in vigilance within this task or across tasks have been observed over the course of hours or minutes (Weissman, Roberts, Visscher & Woldorff, 2006; Macdonald, Mathan & Yeung, 2011).

Despite being generally considered failures of attention, these lapses have also been suggested to play an adaptive role in making sure we continue to monitor what happens in our environment outside our current task, or continue to explore (Robertson & O'Connell, 2010). In support of this idea, a link between vigilance and the exploitation-exploration trade-off might relate to noradrenaline. A genetic study showed that individuals whose genotype was linked to a slow rate of dopamine to noradrenaline conversion, and thus comparatively lower levels of noradrenaline in the cortex, were more likely to make errors of vigilance (Greene, Bellgrove, Gill & Robertson, 2009). Moreover, Smith and Nutt (1996) showed that suppression of noradrenaline decreased vigilance. Thus, although lapses in

vigilance are seen as a failure of attention over the course of time, they may in fact relate to a trade-off between contrasting needs. While this potential relationship is relevant to the understanding of exploitation-exploration dilemmas, on the other hand it remains unclear how vigilance can be mapped onto the focused-distributed temporal attention trade-off.

Mind wandering

Failures of attention over time, reflected in lapses in vigilance, have also been associated with periods of mind wandering (Smallwood et al., 2004; Macdonald et al. 2011). Mind wandering is defined as a drifting away from the current task to thoughts that are self-generated, unrelated to external events and that often occur spontaneously (Smallwood & Schooler 2015; Smallwood 2013, although as noted by Seli, Risko & Smilek, 2016 mind wandering can also occur deliberately). Episodes of mind wandering are typically measured by experience sampling, in which participants are periodically probed to rate their level of task focus (Kahneman et al. 2004; Smallwood & Schooler 2006), or by retrospective self-reports (Smallwood et al. 2012). A high frequency of mind wandering episodes is associated with decrements in performance in many tasks, including comprehension during reading (McVay & Kane 2012) and sustained attention (Smallwood et al., 2004). A reason for this may be that mind wandering involves perceptual decoupling (Kam & Handy 2013; Schooler et al., 2011), while perceptual processing is important for facilitating action during external goal-driven activities (Posner & Petersen 1990). Furthermore, the tendency to mind wander during working memory and intelligence tests has been shown to correlate with poorer performance in SAT exams (Mrazek et al. 2012), suggesting that mind wandering is detrimental to achieving one's goals. The conclusion that mind wandering is not beneficial is also supported by research showing that it is associated with feeling unhappy (Killingsworth & Gilbert, 2010). Thus, there appear to be strong reasons to believe that an unfocused state reflected in mind

wandering is to be avoided, while a focused attention state is optimal, as has been long believed by psychologists (e.g. James, 1890).

Despite the reasons why mind wandering appears to be maladaptive, on the other hand the research reviewed so far in the domains of attention and performance suggest that focused attention is not optimal in all task contexts (e.g. Chong & Triesman 2005a, 2005b) and that even seemingly negative phenomena such as mental fatigue may have benefits to avoiding the cost of missed opportunities (Kurzban et al. 2013). The fact that people engage in mind wandering about 25-50% of their waking time (Kane et al., 2007; Killingsworth & Gilbert, 2010) suggests that mind wandering may have a role in adaptive behaviour rather than always being detrimental. Mind wandering has been associated with a number of positive or adaptive outcomes (Smallwood & Andrews-Hanna 2013). The tendency to mind wander during periods of low external attention demand has been associated with more patience in delaying gratification (Smallwood, Ruby & Singer, 2013, Bernhardt et al., 2014). Individuals' tendency to mind wander is also related to their performance in a divergent thinking task (Baird et al. 2012). One key role that has been proposed for mind wandering is in future planning, because much of the content of mind wandering is biased towards future thinking (Baird, Smallwood & Schooler, 2011; Smallwood, Nind & O'Connor, 2009) and when this is the case, mind wandering tends to be associated with a positive mood rather than the negative mood involved in thinking about the past (Poerio, Totterdell & Miles, 2013; Ruby, Smallwood, Enger & Singer, 2013; Smallwood & O'Connor, 2011). Prospective thinking is believed to be an adaptive process, because simulating and mentally exploring potential courses of action can help us prepare for future events and achieve goals (Schacter, Addis & Buckner, 2007). The conclusion is on the one hand that mind wandering does have benefits, and on the other hand that these may relate to a type of mental exploration.

As the overview shows, mind wandering has both costs such as being associated

with lapses of vigilance (e.g. Smallwood et al., 2004) as well as potentially important benefits such as exploration of future courses of action (Smallwood & O'Connor, 2011; Schacter et al., 2007). Crucially for the current thesis, mind wandering reflects a trade-off in human behaviour that shows similarities to the trade-off in exploitation-exploration. Indeed, research shows that individuals may vary in their ability to calibrate their mental state along such a trade-off by mind wandering when it is appropriate to do so. Good cognitive control has been associated with limiting one's mind wandering levels during a demanding external task (Kane & McVay, 2012; Unsworth & MacMillan, 2013). On the other hand, individuals with good cognitive control abilities mind wander more than others when the external environment does not necessitate their attention, possibly reflecting a better ability to plan for the future at appropriate moments (Levinson, Smallwood & Davidson, 2012; Rummel & Boywitt, 2014; Smallwood & Andrews-Hanna, 2013) although it should be noted that Robison and Unsworth (2017) did not find the same association between having a higher working memory capacity and a tendency to mind wander more when not engaged in a task. In addition to individual differences in cognitive control, an important factor that modulates mind wandering is motivation, such that financial rewards associated with the exploitation of current task goals decrease levels of mind wandering (Mrazek et al., 2012) while preoccupation with goals outside of the current task increases levels of mind wandering (Klinger, 2013). Overall, there is evidence that mind wandering reflects a trade-off in human behaviour, which is both relevant for the exploitation-exploration dilemma, as well as being intrinsically related to how people deploy their attention in time to the present moment or outside of it.

The Attentional Blink

Although both lapses of vigilance and mind wandering appear to be relevant for the exploitation-exploration trade-off, neither can be directly mapped onto the focused-distributed attention distinction, while on the other hand there may be a different example of attentional failure that reflects the need to distribute attention. This is the Attentional Blink (AB), a widely researched phenomenon in the attention literature. After some early observations of the phenomenon (e.g. Broadbent & Broadbent, 1987), the AB effect was named by Raymond, Shapiro and Arnell (1992) in an experiment showing participants a rapid serial visual presentation (RSVP) stream of stimuli. Two target letters were presented within the stream: the first target (T1) was a white letter and the second target (T2) was a black X letter, which appeared in 50% of trials. All other RSVP stimuli were distracter black non-X letters. Participants were asked to identify which letter was presented as T1 and whether T2 was present or not. The authors found that when the first target (T1) is correctly identified and when the second target (T2) is presented shortly after T1 (between 200 ms and 500 ms, commonly at a lag of 2-3 items after T1) with one or more distractor items in between, then T2 is often missed, compared with trials when T2 is presented later in the stream (500 to 800 ms after T1, commonly at a lag of around 6 items after T1). Following these initial results, the AB paradigm was used on many occasions to study limits and mechanisms of visual perception, attention, memory, and consciousness (Shapiro & Raymond, 2010). Different versions of the task use objects, words, faces or other stimuli, including cross-modal stimuli. Nevertheless, most commonly the AB is studied using letters and digits presented at a rate of about 100 ms/stimulus.

The Attentional Blink: a reflection of limited capacity or a case for distributed attention

Early theories of the AB argued that the blink was due to capacity limitations of attention. First, Raymond et al. (1992) argued that the AB effect was an attentional process rather than purely perceptual, because it was only observed when participants were asked to identify the T1 item, and not when they were merely visually exposed to it. After establishing that the performance failure was of attentional nature, it was proposed that the cause was that attention was a limited resource. Within its limited capacity, attention was unable to process the T2 item while it was engaged with T1. According to Chun and Potter (1995) target processing involves two stages: an unlimited initial processing stage and a second, limited-capacity stage involving further processing within a short-term memory store. The limitation causing the AB effect was believed to occur at the level of the second stage, which was occupied with T1 processing (Jolicoeur & Dell'Acqua, 1998; Arnell & Jolicoeur, 1999). In line with the two-stage account, some early processing of T2 was found even in error trials: for example, T2 had been processed enough for it to act as a prime influencing further behaviour (Shapiro, Arnell & Raymond, 1997).

Another important characteristic of the capacity limitation theories was the involvement of distractors. The AB only occurred when a distractor was presented between T1 and T2, while there was a sparing of the second target when occurring at lag 1 (Potter, Chun, Banks & Muckenhoupt, 1998; Visser, Bishof & Di Lollo, 1999). To explain this finding, researchers proposed that there was a process of inhibition to block the first distractor, which also blocked T2 (Raymond et al., 1992) by triggering a bottleneck of attention (Chun & Potter, 1995). Alternatively, the distractor was believed to interfere with T2 retrieval or conscious processing (Shapiro, Raymond & Arnell, 1994; Dehaene, Sergent & Changeux, 2003). Finally, in Di Lollo et al.'s "temporary loss of control" theory (Di

Lollo, Kawahara, Ghorashi & Enns, 2005), the appearance of a distractor caused a change to the state of the system in order to filter out the item. Because of the sudden exogenous influence caused by the distractor, there was a temporary loss of endogenous control over a 'central executive' mechanism (e.g. Baddeley, 1996), and this loss of control led to the blink. Although Di Lollo et al. (2005) argued that the "temporary loss of control" theory avoided resource explanations, Olivers and Meeter (2008) observed that the central executive postulated by Di Lollo et al. needs to have a limited capacity if its control is to be temporarily lost.

The sparing of targets at lag 1 is a challenge for explanations involving a limited capacity. It is unclear how another item is permitted in when there is already a limited capacity that is filled after processing of T1. The filter theories presented above may help explain the lag-1 sparing effect, but it has also been observed that items can be spared up to lag 5 when no distractors are presented in between (Di Lollo et al., 2005; Kawahara, Kumada & Di Lollo, 2006; Olivers, van der Stigchel & Hulleman, 2007; Nieuwenstein & Potter, 2006). One possibility is that the limit of capacity is extended, but as Di Lollo et al. (2005) observed, this makes the postulated limitation of capacity underspecified. One potential final resort for the resource theories is that multiple items get chunked together. Indeed, in the case of lag 1 sparing, the two targets appear to be integrated into a single perceptual episode, which can lead to illusory conjunctions such as perceiving both as a single contour (e.g. Akyurek et al., 2012) or mis-reporting their order (Olivers & Nieuwenhuis, 2006; Spalek, Lagroix, Yanko & Di Lollo, 2012). Nevertheless, there remains a more fundamental problem with resource theories. As was mentioned in a previous section, Navon (1984) noted that capacity-limitation or resource theories easily become unfalsifiable: as long as resources cannot be independently measured, any findings could be interpreted within these theories. For these theoretical reasons and for experimental reasons such as the lag 1 sparing, the endorsement of limited-capacity theories has been decreasing.

An interesting alternative to the limited-capacity theories is that the attentional

blink occurs because attention is overinvested in T1 processing (Olivers & Nieuwenhuis, 2006). First, it was observed that manipulations to distract attention, such as listening to music or being asked to think about one's holiday during AB performance decreased blink rates (Olivers & Nieuwenhuis, 2005). These counterintuitive findings suggested that distraction was beneficial to the AB, although distraction, such as thinking task-unrelated thoughts, is generally detrimental to tasks that require focused attention or goal-directed behaviour (e.g. Smallwood & Schooler, 2006). A second study confirmed that the AB effect was reduced when participants were asked to concentrate less on the AB task or to perform a concurrent secondary task involving the maintenance of a visual pattern in memory (Olivers & Nieuwenhuis, 2006). These results suggested that not only distraction, but a less focused attention and even a divided attention benefitted the AB. The authors proposed that in fact, the optimal attention state in the AB task was a distributed one, as opposed to an overinvested one.

Evidence in favour of the distributed attention interpretation has been accumulating. For example, merely presenting sounds during T2 occurrence reduced or even eliminated the AB effect (Olivers & Van der Burg, 2008; Kranczioch & Thorne, 2015). Similarly, presenting visual distraction during the RSVP, such as a visual background of flickering dots, reduced the size of the AB effect (Arend, Johnston & Shapiro, 2006). The same happened when participants detected a peripheral red dot while performing the AB task (Taatgen et al. 2009; Wierda, van Rijn, Taatgen & Martens, 2010). Furthermore, the size of the effect is also reduced by the performance of more demanding concurrent tasks such as estimating time intervals (Lapointe-Goupil, Fortin, Brisson & Tremblay, 2011). Thus, the overinvestment theory has been gaining support, suggesting that the AB task might in fact measure a distributed attention in time.

Alternative accounts of the Attentional Blink and their relation to the overinvestment hypothesis

The following will describe three alternative accounts of the Attentional Blink that might shed more light on the phenomenon without contradicting the overinvestment theory. First, Olivers and Meeter (2008) propose the Boost and Bounce theory in order to reconcile two lines of evidence. On the one hand, they refer to findings regarding attentional enhancement. For example, Reeves and Sperling (1986) showed that if participants are presented with two concurrent visual streams and they have to switch to the second stream in response to seeing a specific cue in the first stream, then their accuracy in reporting multiple digits presented in the second stream is transiently enhanced for a period of 250 to 600 ms after cue. Such results are difficult to explain within a limited capacity account. Conversely, an attentional blink is often observed even when the amount of information competing for a potential 'limited store' is scarce, for example within a skeletal version of the AB task which presents two targets that are both immediately followed by masks (Ward, Duncan & Shapiro, 1997).

Within the Boost and Bounce theory (Olivers & Meeter, 2008), the selection of information to process takes place via boosting the relevant representations through neural excitatory mechanisms and through "bouncing" irrelevant representations through inhibitory feedback. For example, in an RSVP stream in which letters are targets and digits are distractors, only letter representations will receive excitatory modulation. However, the process has its constraints: it depends on a working memory store estimated to have a capacity of around five items (e.g. Cowan, 1995); and its boost and bounce modulations are imprecise, accidentally boosting distractors or affecting targets because of the time it takes for neural enhancement to take place (i.e. in the authors' view, that would be around 100 ms after target onset).

The Boost and Bounce theory explains many findings, but leaves room for the

involvement of additional mechanisms. To exemplify, the theory explains attentional enhancement: the phenomenon may take place due to a boost in response to relevant items. By contrast, attentional blinks occur even in skeletal task versions because of the bounce in response to the mask item. Moreover, lag 1 sparing is explained since there are no distractors to cause a bounce. Additionally, if working memory has a capacity of five items, sparing up to lag 5 can also be explained (Di Lollo et al., 2005; Kawahara et al., 2006; Olivers et al., 2007; Nieuwenstein & Potter, 2006). The time-dependent boost extension explains why sparing can occur for T2s even after distractors, in the case of speeded streams (Bowman & Wyble, 2007). Despite this, the boost and bounce mechanisms do not explain why the attentional blink only occurs on some trials, as observed by Cohen, Cavanagh, Chun and Nakayama (2012). As Olivers and Meeter explain, the intensities of the boost and bounce responses depend on the current state or current level of excitation of the system. This observation accommodates the distributed attention explanation (Olivers & Nieuwenhuis, 2006) such that a distributed state may decrease boost to T1 along with the corresponding bounce, thus allowing for T2 detection.

A further theory of the Attentional Blink, which may explain the dependency on the state of the system, is the LC-Na theory. According to Nieuwenhuis, Gilzenrat, Holmes and Cohen (2005), a phasic response of the LC noradrenergic neurons is necessary for detection of T1. This phasic signal is followed by a refractory period, which causes the T2 target to be missed. The authors propose that lag 1 sparing is due to residual Na still existing in the system after the phasic firing. On the other hand, during a period of tonic firing of the LC neurons, phasic responses to T1 are less strong, which is beneficial to the AB task. In terms of evidence supporting the theory, monkey studies show that LC activity peaks at 100 ms post-stimulus, followed by a refractory period of Na depletion between 200 and 400 ms post-stimulus (Usher et al., 1999), corresponding to the time course of the AB.

While LC activity remains difficult to directly measure in humans, indirect tests using pharmacological manipulations have been conducted. A study that used clonidine to attenuate noradrenaline levels did not find any impact on the attentional blink, although T1 processing was impaired as expected (Nieuwenhuis, van Nieuwpoort, Veltman & Drent, 2007). On the other hand, De Martino, Strange and Dolan (2008) did find that manipulating noradrenaline levels using propranolol impaired both T1 and T2 detection. The findings regarding pharmacological effects on the AB are not conclusive regarding the LC-Na theory, because these manipulations do not directly affect the phasic and tonic firing modes of the LC.

Although more research is needed to understand the role of the LC in the attentional blink, it is interesting to note that the LC-Na theory draws a connection between the attentional blink and the exploitation–exploration dilemma, which is also proposed to depend on the LC system according to the adaptive gain theory (Aston-Jones & Cohen, 2005). One possibility is that the attentional blink is part of the temporal gating mechanism proposed by the adaptive gain theory. Most importantly, the LC-Na theory sheds more light on the AB phenomenon as an interesting starting point for further understanding a trade-off in temporal attention.

While the Boost and Bounce theory and the LC-Na theory support the interest in the Attentional Blink as an appropriate context for studying distributed attention in time, there is a third account that calls for more caution. This is the alpha entrainment hypothesis, which argues that blinks occur because of an entrainment of brain oscillations to the rate of presentation of stimuli within the RSVP stream. Indeed, cortical oscillations have been observed to synchronise to the rhythm of presented visual stimuli (e.g. Muller, Teder & Hillyard, 1997) and the oscillations' amplitude increases when the stimuli are attended to (Muller & Hillyard, 2000). Most AB experiments present stimuli at 100 ms per stimulus, which corresponds to an alpha frequency of 10 Hz. Moreover, alpha oscillations

entrainment during the AB task was higher for participants whom had been previously characterised as 'blinkers' based on a large size of the AB effect that they displayed (Martens, Munneke, Smid & Johnson, 2006). Similarly, if at the time of T1 presentation the alpha oscillation was entrained to the RSVP rhythm, attentional blinks were more likely to occur (Keil, Ihssen & Heim, 2006; Keil & Heim, 2009; Petro & Keil, 2015). Such findings call for caution in interpreting data from AB studies that use a presentation rate falling within the alpha frequency band, although they are less relevant for experiments using a different presentation rate. Furthermore, even at presentation rates falling within the alpha band range, the overinvestment theory of the AB is not contradicted. This is because when a concurrent task was performed along with the AB task, promoting a distributed attention state, alpha entrainment was found to decrease at the same time as the size of the attentional blink (Wierda et al., 2010). Therefore, irrespective of any involvement of alpha entrainment in the AB, the likelihood that attentional blinks occur remains dependent on the attentional state, making the AB task a candidate context for investigating temporal attention trade-offs.

Preliminary evidence for trade-offs in temporal attention within the Attentional Blink task

As the previous sections have highlighted, there are reasons to believe that the Attentional Blink task is best performed in a state of distributed attention. This was proposed by the overinvestment theory (Olivers & Nieuwenhuis, 2006) based on findings that distraction, less concentration and a divided attention all improved AB performance (Olivers & Nieuwenhuis, 2005; 2006). The same findings challenged earlier theories that the attentional blink is the product of a limited capacity (e.g. Raymond et al., 1992; Chun & Potter, 1995). On the other hand, the idea that the AB is best performed under a distributed attentional state was compatible with other theories of the Attentional Blink phenomenon, such as the Boost and Bounce theory (Olivers & Meeter, 2008) which proposed that

blinks occur due to a bounce that follows a boost in processing T1. As a result of a distributed attention, boost signals are attenuated and hence bounce signals are also attenuated, reducing attentional blink rates. Moreover, distraction benefits AB task performance even in circumstances when brain oscillations are entrained to the alpha rhythm of presentation of stimuli (Wierda et al., 2010). This makes the AB task an interesting context for studying distributed attention in time.

As a task measuring distributed attention in time, the AB creates an opportunity to further understand trade-offs. Interestingly, the attentional blink has been indirectly linked to the exploitation–exploration dilemma. The LC-Na theory of the AB argued that blinks occurred during a refractory period of noradrenergic neurons (Nieuwenhuis et al., 2005). On the other hand, the LC-Na has also been argued to be involved in the exploitation–exploration trade-off (Aston-Jones & Cohen, 2005). Preliminary evidence supports the association of the LC-Na system with both the exploitation–exploration trade-off (Gilzenrat, Nieuwenhuis, Jepma & Cohen, 2010; Jepma & Nieuwenhuis, 2011; although Jepma et al., 2010 did not find the effect) as well as the attentional blink (De Martino et al., 2008), although evidence is not yet conclusive. Apart from the association with the LC-Na system, attention and particularly temporal attention have been directly proposed to be involved in the exploitation–exploration trade-off. First, Manohar and Husain (2013) portrayed attention as a teleforaging mechanism mediating both exploitation and exploration. Similarly, Aston-Jones and Cohen (2005) argued that temporal attention gates decision-making within the exploitation–exploration dilemma. To investigate this potential role of temporal attention, the trade-off between distributed and focused temporal attention needs to be investigated. As a task that is believed to capture a distributed attention in time, the AB provides a starting point.

Several lines of research provide preliminary evidence for trade-offs within the Attentional Blink task. To begin with, as has been highlighted, there is accumulating evidence that distraction or dual task performance improves AB

performance, probably because these induce a distributed attention (Olivers & Nieuwenhuis, 2005; 2006). The same benefits were found as a result of visual distraction (Arend et al., 2006) as well as auditory distraction such as music played during the task (Olivers & Van der Burg, 2008; Kranczioch & Thorne, 2015; Ho, Mason & Spence, 2007). Concurrent tasks improved performance in the AB (Taatgen et al. 2009; Wierda et al., 2010; Lapointe-Goupil et al., 2011). The same improvements were found after inducing a positive mood by showing participants photos with positive valence (Olivers & Nieuwenhuis, 2006). Indeed, positive affect has been associated with broad cognitive states that favour exploration (Ashby, Isen & Turken, 1999; Frederickson, 2001; Frederickson & Branigan, 2005; Carver, 2003), while negative affect is generally believed to prompt a narrowing of focus in order to increase chances of survival under threat (Ashby et al., 1999; Storbeck & Clore, 2005). In line with this, Jefferies, Smilek, Eich and Enns (2008) found that inducing a specific mood through music and recalling memories affected the AB. Negative affect and high arousal (anxiety) induced the largest AB, positive affect (calm and happy) induced an intermediate AB, and finally negative affect with low arousal (sad) induced the smallest AB. Furthermore, Rokke, Arnell, Koch and Andrews (2002) found that severely depressed participants had a larger AB than non-depressed participants. Besides showing an interesting relation between affect and attention state, these findings highlighted a trade-off in attention within the Attentional Blink task.

While inducing broader attentional states had an impact on the AB size, blink sizes were also modulated by dispositional cognitive states. Dale and Arnell (2010) found that dispositional diffusion of attention as measured through a precedence of global stimuli in the Navon task predicted smaller attentional blinks. By contrast, participants showing less interference on local Navon stimuli, a marker of a more locally focused attention, had larger attentional blinks. The same finding was later replicated using multiple measures of local and global preference, such as hierarchical shapes, which were found to predict the size of

the AB (Dale & Arnell, 2015). Indeed, individual differences in the size of the attentional blink are an interesting example of trade-offs. It has been repeatedly observed that people vary in their tendency to produce attentional blinks (Willems & Martens, 2016). In fact, as already mentioned, researchers have been able to divide people roughly into 'blinkers' and 'non-blinkers' on the basis the size of their attentional blinks (e.g. Martens et al., 2006).

A further trade-off has been observed in terms of the relationship between the P3 event-related potential and the size of the AB. The P3 is a neural potential occurring in response to target detection and is believed to reflect stimulus processing (e.g. Vogel & Luck, 2002). It was found that an enhanced P3 potential in response to T1 was associated with more attentional blinks, while 'non-blinkers' tended to display smaller and earlier P3 potentials (Martens et al., 2006). Together, the associations between the AB on the one hand and both the P3 as well as local/global task performance on the other hand provide preliminary evidence for a dissociation between focusing attention and distributing attention within the Attentional Blink task.

An additional line of evidence for the effects of focused attention on the AB comes from difficulty manipulations. Various experimental manipulations of the difficulty of processing T1 have increased blink rates. For example, when T1 was a less frequent word from the vocabulary (Burt, Howard & Falconer, 2011), or when T1 was perceptually more difficult such as an inverted target (Martens, Korucuoglu, Smid & Nieuwenstein, 2010), participants made more attentional blinks. A potential interpretation of these findings is that T1 difficulty required a more focused attention to enable processing, which led to less distribution of attention to capture both T1 and T2 (as per the overinvestment theory, Olivers & Nieuwenhuis, 2006).

Apart from manipulations of difficulty that may or may not increase focus to T1, there have been studies that directly use exogenous cueing to increase focus to

T1, leading to larger attentional blink sizes. In an early experiment, Weichselgartner and Sperling (1987) increased the salience of a target presented within a RSVP through highlighting or boxing the stimulus. As a result, participants were poor at detecting the next items up to 300 ms after T1. A similar finding was reported using the AB task. Increases of T1 contrast improved T1 detection while negatively affecting T2 detection (Chua, 2005). Apart from perceptual salience, behavioural relevance is also known to attract attention (e.g. Posner, 1980; Duncan & Humphreys, 1989). Indeed, even if no response to T1 was required, an attentional blink was still observed if T1 shared features with relevant targets from previous trials (Thompson, Underwood & Crundall, 2007). The importance of these findings is that they complement above-presented effects of distraction, by showing that inducing a focused attention to T1 is detrimental to AB task performance.

A way forward: Illusory Conjunctions within the Attentional Blink task

The section above has described several lines of preliminary evidence for trade-offs between focused and distributed attention within the Attentional Blink task. Manipulations to diffuse, divide or distract attention reduce the attentional blink size, while increasing T1 difficulty or salience increased attentional blink size. Mood inductions shifted the size of the AB in both directions, while global and local Navon task performance predicted smaller or larger attentional blink sizes. Finally, the size of the P3 neural response to T1, believed to reflect T1 processing, also dissociated between 'blinkers' and 'non-blinkers'. Overall, these findings show that more focus to T1 or enhanced processing of T1 was detrimental to the attentional blink. Although this may reflect a trade-off between focused attention and distributed attention, alternatively the findings can be explained as a mere trade-off between processing of T1 and T2. By contrast, good performance within the AB task involves processing of both T1 and T2. In its current form, the AB task can only measure a distributed attention that allows processing of both targets. On the other hand, tasks that measure a focused temporal attention have been

described in earlier sections as involving the processing of a target in time, but also making perceptual discriminations regarding that target (Coull & Nobre, 1998; Griffin et al., 2002; Correa et al., 2005; Rolke & Hofmann, 2007). Consequently, in order to investigate the trade-off between distributed and focused attention in time, there is a need for matched tasks measuring, on the one hand, the detection of two targets and, on the other hand, the detection of one target that is processed in depth and based on which perceptual discriminations can be made.

Interestingly, the key to creating such matched tasks may in fact be found amongst findings regarding the attentional blink. To begin with, as has been previously mentioned, the phenomenon of lag 1 sparing comes with a drawback. Detecting two targets when they occur at a lag of 1 can lead to illusory conjunctions such as perceiving both targets as a single visual object (e.g. Akyurek et al., 2012) or mis-reports of their order (Olivers & Nieuwenhuis, 2006; Spalek et al., 2012). By contrast, Raymond et al. (1992) argue that T1 opens an 'attentional gate' to enable its processing, but when a distractor occurs between T1 and T2, the 'attentional gate' closes when the next distractor is encountered. The need to close the attentional gate when distractors are encountered is supported by other findings. In an RSVP containing a red letter embedded in distractions of different colours, the identity of a nearby letter was sometimes mistakenly reported (McLean, Broadbent & Broadbent, 1983). Similarly, if instructions were to report the colour of a digit presented within a stream of letters, errors included reporting the colour of items adjacent to the target. Such errors have also been observed in the AB task. Instead of reporting the T1 letter, participants often mistakenly report the four nearest-to-target items (Vul, Hanus & Kanwisher, 2008a; Vul, Nieuwenstein & Kanwisher, 2008b). Moreover, participants often erroneously bind the target with a range of features of nearby distractors. For instance, the identity of T1 can be mistakenly bound to the orientation of nearby items (Corballis, Armstrong & Zhu, 2007). Frequently,

binding errors occur between the identity and the colour of stimuli. In an experiment by Popple and Levi (2007), T1 and T2 were red letters while the rest of the RSVP items were gray letters. In this case, when T1 was mis-reported, an incorrect letter-to-colour matching took place. Thus, illusory conjunctions within the AB task appear to be a robust phenomenon.

The fact that illusory conjunctions occur within the Attentional Blink task may provide an opportunity for studying focused attention in time. As reviewed above, focused attention in the spatial domain has been described as essential for binding features in a coherent visual object (Treisman & Gelade, 1980) and avoiding illusory conjunctions between features of nearby objects (Treisman & Schmidt, 1982). This suggest an interesting possibility: that while a distributed attention in time helps avoid attentional blinks, on the other hand a focused attention in time may help avoid illusory conjunctions.

Aims of the thesis

Within the larger framework of exploitation-exploration trade-offs, the current thesis aims to investigate the existence of trade-offs between focused and distributed attention in time. Research in attention suggests the existence of trade-offs between focused and distributed states, which have been compared in spatial attention (Chong & Treisman 2005a; 2005b), while in temporal attention most research has looked either at a focused attention (e.g. Coull & Nobre, 1998) or at lapses in sustained attention over time (Macdonald et al., 2011) and how the latter are related to another marker of unfocused attention: mind wandering (Smallwood & Schooler, 2006; Smallwood et al., 2004). The idea of trade-offs between focused and distributed attention in the temporal domain has yet to be clearly articulated in current theories of temporal attention, which do not link explicitly to theories about the exploitation-exploration trade-off.

There are no well-established experimental paradigms for studying the focused-distributed temporal attention trade-off. As described, there is preliminary evidence that a range of factors affect the size of the attentional blink, including individual differences (Willems & Martens, 2016) but also experimental manipulations that on the one hand induce a divided attention, less concentration on task or a positive mood (e.g. Olivers & Nieuwenhuis, 2005; 2006; Arend et al., 2006) or on the other hand increase the salience of T1 (Weichselgartner & Sperling, 1987; Chua, 2005). If the AB phenomenon is interpreted within the overinvestment theory (Olivers & Nieuwenhuis, 2006), such findings reflect the way in which a distributed attention varies. However, in order to test the existence of trade-offs between distributed and focused attention in time, the effects of these factors on the attentional blink need to be compared with effects on a matched task that measures focused attention.

The current thesis aims to provide evidence for the existence of trade-offs between focused and distributed attention in time, and develop a method for studying these trade-offs. To this end, we identify an opportunity that has not yet been explored as a reflection of an unfocused attention: the occurrence of illusory conjunctions between features of RSVP items within the AB task (e.g. Corballis, Armstrong & Zhu, 2007). In spatial attention, illusory conjunctions have long been believed to reflect an unfocused attention (Treisman & Gelade, 1980; Treisman & Schmidt, 1982).

Chapter 2 introduces a novel paradigm for studying the temporal attention trade-off between focused and distributed states: the Attentional Blink – Illusory Conjunctions paradigm. The experiment reported in this chapter focuses on the idea of individual differences in the trade-off, such that some people tend to have a focused attention style and others tend to have a distributed style. Furthermore, the chapter investigates the relationship between the two attention states and mind wandering.

Chapter 3 aims to use the Attentional Blink – Illusory Conjunctions paradigm to investigate whether manipulations that increase attentional focus affect focused and distributed temporal attention in dissociable ways. This chapter and the next explore the theoretical boundary conditions of what is meant by 'focused' and 'distributed' attention. The experiments in Chapter 3 investigate two standard manipulations that, as reviewed above are expected to increase attentional focus: exogenous and endogenous cueing (cf. Posner, 1980; Coull & Nobre, 1998; Rohenkohl et al., 2011; Chua, 2005). The chapter also looks at the dissociable effects of the rate of presentation on focused and distributed attention in time.

Chapter 4 aims to investigate whether manipulations that distract or broaden attention affect focused and distributed temporal attention in dissociable ways, by contrast to the manipulations investigated in Chapter 3. Extending on previous

findings of effects of task-unrelated thinking and divided attention on the attentional blink (Olivers & Nieuwenhuis, 2005; 2006) as well as associations between global/local attention in space and the attentional blink (Dale & Arnell, 2015), Chapter 4 investigates how these three factors relate to the trade-off between attentional blinks and illusory conjunctions within the novel paradigm. Furthermore, Chapter 4 explores whether 'focused-distributed' manipulations are necessarily temporal in nature, or relate to a wider concept of broad cognitive states, which includes mind wandering and global spatial attention.

Chapter 5 focuses on the neural correlates of temporal attention trade-offs within the Attentional Blink – Illusory Conjunctions paradigm using electroencephalography (EEG). The chapter investigates how the amplitude of the P3 event-related potential to T1 is dissociable in relationship to focused and distributed attention states, following on from previous research that associates the P3 to attentional processing (Vogel & Luck, 2002), focused attention in time (Miniussi et al., 1999) and to the size of the attentional blink (Martens et al., 2006), but not yet to the trade-off between focused and distributed attention in time. Chapter 5 also takes an exploratory approach to looking at the relationship of pre-trial neural oscillations to performance in focused and distributed attention, in light of their proposed important involvement in temporal attention (e.g. Nobre, 2010; Cravo et al., 2011). Investigations focus on alpha, theta, beta and gamma frequency bands, some of which have previously been investigated in the context of temporal attention (e.g. Parker et al., 2014; Oprisan & Buhusi, 2014; Macdonald et al., 2011) and of the attentional blink task (MacLean & Arnell, 2011; Ronconi et al., 2016; Glennon, Keane, Elliott & Sauseng, 2016; Nakatani, et al., 2005; Gross et al., 2004), but not in the context of trade-offs in attention in time.

Finally, Chapter 6 introduces a variation to the Attentional Blink – Illusory Conjunctions paradigm using a non-blocked task design. The chapter continues

the investigation of individual differences in attention style, expanding on previous research looking at individual differences in the attentional blink (Willems & Martens, 2016), and following on from the experiment reported in Chapter 2. Furthermore, Chapter 6 returns to an investigation of fluctuations between focused and distributed attention states and how these relate to mind wandering, in light of previously observed fluctuations in sustained attention that have been associated with mind wandering (Smallwood et al., 2004; Macdonald et al., 2011).

To summarise, the thesis develops a novel paradigm for the study of trade-offs between focused and distributed attention in time. Trade-offs are investigated in terms of individual differences in attention style and in terms of variations in attention states. Trade-offs in attention states are studied in several ways: in terms of how the effects of manipulations believed to induce attentional focus or distributed attention differentially affect the two states; in relation to their neural correlates; and finally in the way they fluctuate in their own right and in relation to mind wandering.

Chapter 2

Exploring the Attentional Blink – Illusory Conjunctions paradigm

Introduction

Chapter 2 aims to explore and validate the novel Attentional Blink – Illusory Conjunctions paradigm as a measure of distributed and focused temporal attention. In the first experiment we tested the hypothesis that there are individual differences in attentional style, with some people being more focused and others more distributed. Furthermore, the relationship between attentional trade-offs and cognitive states (affect and mind wandering) was analysed. Finally, we investigated how variations in design parameters known to influence focused attention impacted on the two tasks.

Trade-offs and the Attentional Blink – Illusory Conjunctions paradigm

In this chapter we propose the Attentional Blink – Illusory Conjunctions paradigm, which has its roots in the view that temporal attention, as well as attention and human performance more broadly, are subject to trade-offs between the competing needs to narrow or enlarge the scope of cognitive processing. It is a frequent observation in psychology that human performance is limited, as reflected for example in lapses of sustained attention in the case of air traffic monitoring (Mackworth, 1948; Weissman et al., 2006). It is often believed that such failures of performance, along with feelings of mental effort, are due to limitations of capacity (Kahneman, 1973). However, one more recent view is that lapses or mental effort might both reflect a conflict between performing the current task and exploring one's environment (Robertson & O'Connell, 2010; Kurzban et al., 2013). Similarly, a recent theory sees human attention as a tele-foraging mechanism shifting between periods of information-seeking exploration and periods of reward-seeking exploitation (Manohar & Husain, 2013).

Trade-offs have been considered in the domain of visual attention. A focused attention in space benefits processing of information within a 'spotlight' (Eriksen & Hoffman, 1973; Posner, 1980), while the lack of a focused attention could lead to illusory conjunctions due to poor integration of visual features into a coherent object (Treisman & Gelade, 1980). Due to such evidence of the importance of focused attention, researchers have employed orienting manipulations through salient bottom-up or symbolic top-down cues in order to increase focus (Posner & Cohen, 1984; Muller & Rabbitt, 1989). On the other hand, there is evidence that in some cases, a broad and global attention mode is beneficial for statistical processing or processing of a visual scene as a whole (Treisman, 2006; Chong & Treisman, 2005a; 2005b), although this distributed mode is also more prone to distraction.

As is the case for spatial attention, trade-offs are also important in temporal attention. Focused temporal attention, manipulated through warning signals (Woodrow, 1914; Zahn & Rosenthal, 1966), implicit rhythmic cues (Doherty et al., 2005; Martin et al., 2005; Coull & Nobre, 2008; Mathewson et al., 2010; Sanabria et al., 2011) or explicit instructions (Kingstone, 1992; Coull & Nobre, 1998) aids in detecting targets that appear after a certain interval. However, focus is hard to maintain because attention waxes and wanes continuously (Macdonald et al., 2011) as the mind wanders (Smallwood & Schooler, 2006). One phenomenon that has long been considered to reflect a failure of temporal attention is the Attentional Blink (AB, Raymond et al., 1992), the difficulty in perceiving a second target (T2) when it immediately follows a first target (T1) within a rapid serial visual presentation (RSVP) of distractors (Broadbent & Broadbent, 1987). The traditional interpretations of the Attentional Blink are that it reflects limitations of attentional capacity (Raymond et al., 1992; Chun & Potter, 1995; Arnell & Jolicoeur, 1999). On the other hand, Olivers and Nieuwenhuis (2005; 2006) reported that distractions of various forms, from a secondary concurrent task to asking participants to think about their recent holiday or playing music to participants all reduce the attentional blink. In the authors' interpretation, this is evidence that the AB task is optimally performed in a state of distributed attention, rather than one in which attention is overinvested or overfocused on the first target. As an extension of the overinvestment theory on a neural level, Nieuwenhuis et al. (2005) portrayed the attentional blink as being related to the locus-coeruleus noradrenergic system (LC-Na), a brain system previously shown to be involved in attention regulation (e.g. Usher et al., 1999). According to the authors, the attentional blink corresponds to a refractory period of the LC-Na neurons, after a phasic firing in response to T1. Thus, if less attention is invested in T1 and the phasic response is decreased, the blink can be avoided. While this hypothesis remains to be experimentally tested, the overinvestment theory of the attentional blink is in line with the concept of

trade-offs in temporal attention: a focus on T1 is associated with the cost of distributing attention across timepoints to detect further targets.

Despite findings that AB performance can be improved by distraction, such results are not sufficient to conclude the existence of two different attentional modes for focused and distributed attention respectively, each of which is optimal in different circumstances. Instead, there could be alternative explanations for the existing data. Filtering theories might argue that distraction merely helps set attention in an optimal filtering mode in which distractors can be filtered out and targets can be filtered in (Di Lollo et al., 2005). Yet another explanation could be that merely increasing the difficulty of the AB through a secondary task somehow benefits T2 processing, in accordance with the cognitive load theory and findings that increases in load improve cognitive performance and prevent distractor processing in some contexts (Lavie, 2005).

In the face of such alternative explanations, one needs to seek further support for the existence of two attention modes that trade off. Nevertheless, the ongoing debate around the AB task results, as well as the robustness of the task, make it an appropriate starting point for further research into temporal attention trade-offs. In the domain of cognitive neuropsychology, it is often considered that in order to distinguish between two different cognitive modules (Fodor, 1983) one needs to provide a 'golden standard' double dissociation such that a specific manipulation selectively affects one of the functions and a different manipulation selectively affects the other (Teuber, 1955; Patterson & Plaut, 2009). Although in the present case we seek to distinguish two cognitive functional modes rather than separate modules, a double dissociation would indeed provide valuable support. To achieve this, a basic requirement would be to have parallel tasks that emphasise focused and distributed attention, and a desideratum is that they are otherwise well matched. These two tasks would enable the study of dissociable effects of different manipulations on focused and distributed temporal attention respectively.

In the quest to design a task that is visually equivalent to the Attentional Blink but in which a focused attention is optimal rather than a distributed attention, specific findings from the AB paradigm are revealing. One key observation from AB experiments is that when participants are asked to detect a target letter of a specific colour embedded within a stream of letter distractors of a different colour, often the participants mis-report the identity of letters near the target (Raymond et al., 1992; Popple & Levi, 2007). This 'illusory conjunctions' (Treisman, 1996) phenomenon occurs across a range of different features, for example mistakenly binding the identity of the target stimulus and the colour or orientation of nearby stimuli (Corballis et al., 2007).

Despite the robust observation of illusory conjunctions within the AB paradigm, the phenomenon has been little studied in its own right in this context. The occurrence of binding errors has been taken as evidence that an 'attentional gate' needs to shut when the first distractor after T1 occurs in the RSVP, in order for the T1 stimulus to be accurately processed (Raymond et al., 1992; Shapiro & Raymond, 2010). Indeed, if T2 is presented at lag 1 after T1 and there are no distractors in between, conjunctions occur between T1 and T2, such that for example their order is mis-reported, or they are perceived as a single object (Olivers & Nieuwenhuis, 2006; Spalek et al., 2012; Akyurek et al., 2012). Thus, in studies of the AB phenomenon it is held that a filtering out or inhibition of irrelevant post-T1 stimuli needs to occur in order for the T1 to be processed without illusory conjunctions occurring. It is rather unclear how this filter or inhibition explanation sits with the findings that illusory conjunctions frequently occur with the four nearest-to-target items, which includes items presented before T1 in the RSVP (Vul et al., 2008a; 2008b).

On the other hand, in the spatial attention literature, illusory conjunctions and feature binding errors have been classically reported and are considered to be effects of unfocused attention (Treisman & Gelade, 1980; Treisman, 1996). If

attention is prevented from focusing on each item in turn or it is for instance divided between the items and another object, illusory junctions are more likely to occur (Treisman & Schmidt, 1982; Treisman & Paterson, 1984). On the other hand, manipulations that increase attentional focus to the location of a stimulus prevent conjunctions with features of items nearby (Cohen & Ivry, 1989) and improve conjunction item performance more than they improve simple detection (Prinzmetal, Presti & Posner, 1986). Therefore, a focused attention mode might be beneficial for the processing of T1 without any illusory conjunctions occurring. If this is the case, then a dissociation emerges such that a focused attention mode benefits T1 processing without binding errors, while a distributed attention mode benefits dual target processing.

Based on the above assumptions, the current experiment set out to design a task that is visually equivalent to the Attentional Blink task but in which a focused attention mode is beneficial. Because in the Attentional Blink task two items are to be reported, in the new task there are also two requirements: to report both the identity of the T1 item as well as its colour. We call the new task the Illusory Conjunctions task (IC), and we call the composite task alternating between traditional AB instruction and the new IC instructions the AB-IC paradigm. Within the paradigm, we use coloured letters as T1 and T2 and coloured digits as embedding distractors. Therefore, the instruction in the AB task is to report the two letters, while in the IC task participants are required to report the first letter and its colour. The prediction is that when attention is not sufficiently focused, illusory conjunctions will occur such that the colours of nearby digit distractors are reported instead of the T1 colour.

The key aim of the first experiment was to validate the two tasks and provide initial evidence that the paradigm captures the distinction between focused and distributed attention. Additionally, being an exploratory study, the experiment also looked into three ways that the temporal attention trade-off manifests. We

investigated the hypothesis that there are individual differences in attentional style, such that some people tend to be more focused and others more distributed. Moreover, we looked at how current state (in terms of affect and mind wandering) influences the temporal attention trade-off. Finally, we were interested in how factors built into the design, which have been previously shown to affect the focus of attention, differentially influence the two tasks.

Individual differences in the temporal attention trade-off

The first key hypothesis of Experiment 1 was that there are individual differences in temporal attention. This is partly based on findings that people differ in their ability to report the second target in an Attentional Blink task, and can be divided into 'blinkers' and 'non-blinkers' reliably, such that two such groups defined within a testing session remain in the next session (Martens et al., 2006; Klein, Arend, Beauducel & Shapiro, 2011; Willems & Martens, 2016). For example, one experiment divided people into 'blinkers' who showed 20-30% difference in accuracy between T2 at short and long lags, and 'non-blinkers' showing less than 10% difference between lags (Martens et al., 2006).

Within the framework of viewing attention as a trade-off between focused and distributed modes, these findings suggest that some people are more prone to function in a focused and others in a more distributed mode. It has been previously proposed that the Attentional Blink is neurally mediated by the mechanisms of the locus-coeruleus noradrenergic system (Nieuwenhuis et al., 2005). Indeed, one possibility is that the two firing modes (phasic and tonic) mediate the two attentional states of focused and distributed. Thus, individual differences might reflect the LC-Na's tendency to function more in one or the other of its firing modes. As previous studies showed (e.g. Usher et al., 1999), neural activity seems to reflect a continuum between tonic and phasic firing rather than two discrete modes. In the case of individual differences in behaviour, we propose that focused and distributed modes are also on a continuum. However, both in the form of a

continuum as well as discrete modes, individual differences would predict a negative correlation between performance in the Attentional Blink and the Illusory Conjunctions tasks.

Despite a general tendency for cognitive tasks to positively correlate with each other, there are strong reasons to expect a negative correlation in this case. Although there is a positive correlation between T1 detection and AB performance (Arnell, Howe, Joanisse & Klein, 2006), commonly-used measures of cognitive ability do not seem to predict individual differences in the Attentional Blink. Indeed, intelligence or working memory tend to predict overall rates of T1 and T2 detection but not the size of the attentional blink which is measured as the differences in reporting T2 at long and short lags (Martens & Johnson, 2009; Arnell & Stubitz, 2010, but Colzato, Spape, Pannebakker & Hommel, 2007; Klein et al., 2011). There was more support for mental speed being related to reduced AB, although findings with regard to this were also mixed (Visser & Ohan, 2012; Wagner, Rammsayer, Schweizer & Troche, 2014; but Arnell et al., 2006). On the other hand, the size of participants' attentional blinks is more reliably predicted by their tendency to respond more rapidly to global versus local features of a visual stimulus in a spatial attention task (Dale & Arnell, 2015). This global versus local spatial attention preference itself is a stable individual trait (Zmigrod, Zmigrod & Hommel, 2015; Dale & Arnell, 2010) that reflects a similar trade-off.

Even though research shows that individual differences in the Attentional Blink are unlikely to be due to cognitive ability, the latter might still be a confounding factor of common variance between Attentional Blinks and Illusory Conjunctions. Thus, we included measures of intelligence and mental speed as covariates in investigating the negative relation between the tasks. Because most of the sample was recruited from a population of Oxford students, a high-end intelligence test of deductive reasoning, the AH5 (Heim, 1968), was used to avoid ceiling effects. With regard to mental speed, this was measured using the Digit Symbol task that is part

of the Wechsler Adult Intelligence Scale WAIS-III and has been repeatedly found to mainly capture mental speed (Wechsler, 1997; Joy, Kaplan & Fein, 2004). The Digit Symbol test was also chosen due to its short administration time, helping to keep experimental time low.

State fluctuations in temporal attention

To seek further support for the idea that focused and distributed temporal attention trade off, and that these trade-offs are reflected in the AB-IC paradigm, it was examined how states which are known to relate to narrow or broad cognitive modes and focused and distributed attention influence temporal attention in the current study. The finding that blinks only occur in around 50% of trials has been recently interpreted in the view of attentional states; i.e., that there are spontaneous fluctuations in the attentional state of a participant, as reflected for example in how the brain oscillations fluctuate from trial to trial in an AB experiment (Cohen et al., 2012). It was found that the brain state and brain oscillations occurring before the presentation of stimuli influence subsequent AB performance (Pincham & Szucs, 2012; Nakatani et al., 2005; MacLean & Arnell, 2011; MacLean, Arnell & Cote, 2012), supporting the idea that the AB is state-dependent.

One state measure repeatedly shown to relate to broad and narrow cognitive modes is affect. Generally, positive affect appears to relate to broader cognitive styles, perhaps as a motivation for exploration behaviours (Frederickson, 2001; Frederickson & Branigan, 2005; Carver, 2003). Induced positive affect was also found to benefit the AB (Olivers & Nieuwenhuis, 2006). On the other hand, negative affect is often associated with a narrow, more focused cognitive style (Ashby et al., 1999; Storbeck & Clore, 2005) and was found to relate to a larger blink (MacLean, Arnell & Busseri, 2010). The current study used the Beck Depression Inventory (Beck, Steer & Brown, 1996) to examine individual differences in negative affect,

with the prediction that negative affect would relate to better IC performance while increasing the attentional blinks rates.

As a second measure of the relationship between state and attention trade-offs, the current study used a self-report questionnaire about how much people mind wandered during the AB and IC tasks, with the prediction that mind wandering would relate positively to AB performance and negatively to IC performance. In recent years there has been increasing interest in mind wandering and its association to the default mode network of the brain (Buckner et al., 2008) and how mind wandering during a task, i.e. thinking about something other than what one is currently doing, decreases task performance (Smallwood & Schooler, 2006; Smallwood & Schooler, 2015). A wide range of research suggests that mind wandering decreases performance in attention tasks, working memory tasks as well as daily endeavours (e.g. Smallwood et al., 2004; McVay & Kane, 2012; Kane & McVay, 2012; Smallwood, McSpadden & Schooler, 2008). Moreover, individual differences in propensity to mind wander were linked to distractibility in task performance (Forster & Lavie, 2014). Conversely and counter-intuitively, people who report that they mind wander frequently both during a task and in their daily lives have recently been found to have smaller attentional blinks (Thomson, Ralph, Besner & Smilek, 2015). This is in line with previously mentioned findings that asking participants to think about their holiday improves attentional blink performance (Olivers & Nieuwenhuis, 2005). Therefore, there is evidence to suggest that while mind wandering is generally detrimental when focus is necessary, it can also be beneficial in the context of the Attentional Blink task. Our study further investigates this by comparing the relationship of mind wandering to focused and distributed attention in our matched AB and IC tasks. Due to the exploratory nature of the current experiment, we used a post-task self-report, as has been previously used in studies of mind wandering (e.g. Smallwood et al., 2012), although it has been acknowledged that this self-report may be subject to

forgetting or differences in people's ability to reflect on their inner states (Schooler, Reichle & Halpern, 2005).

Trade-offs in temporal attention within participants

While individual differences and state measures investigated how between-participants factors affected the temporal attention trade-off, we also looked at trade-offs across trials within individuals. The prediction was that any factor known to focus attention to the T1 timepoint would reduce illusory conjunctions while increasing attentional blink errors. Intrinsic fluctuations in task design allowed for investigating the effects of foreperiod length and T1 salience.

The first factor we investigated was foreperiod length. In keeping with previous AB task designs (e.g. Raymond et al., 1992), the position of T1 was varied from trial to trial in order to prevent participants from being able to predict precisely when T1 will occur. In the temporal attention literature it has been found that short foreperiods between a cue announcing that a target will appear and the actual target onset are most beneficial for target detection (Woodrow, 1914; Zahn & Rosenthal, 1966), presumably because they help attention to focus. On the other hand, previous research in the AB task found that long preparation times benefit the AB (Badcock, Badcock, Fletcher & Hogben, 2013). Therefore, we expected a dissociation, with longer foreperiods benefitting the AB task while being detrimental to IC task performance.

The second factor we analysed was T1 salience, exploiting the natural differences in relative salience in our colour and letter stimuli. We hypothesised that salient T1 stimuli would focus attention and reduce illusory conjunction rates while increasing attentional blinks. There are fragments of evidence in support of this. In an RSVP study, Weichselgartner and Sperling (1987) showed that presenting a boxed, more salient T1 stimulus improved its processing, at the expense of later

targets. Chua (2005) found that a salient T1 captures attention to the detriment of T2 processing.

Method

Participants

Because we were interested in individual differences, we recruited a reasonably large sample of 52 participants. Participants were recruited in Oxford and included both students at the University of Oxford and participants from the general population. Three participants were excluded from the analyses because their T1 detection accuracy was lower than 55%. Of the remaining 49 participants, 35 were female and 14 were male. The mean age was 24 and the age range was 18 to 40. None of the participants were self-reported as colour blind and all had normal or corrected-to-normal vision. All participants were fluent in English and none of them was on any psychoactive medication at the time of the study. The experiment received ethical clearance from the University of Oxford Central University Research Ethics Committee. All participants received course credits or payment of £8 for their participation.

Procedure

The Attentional Blink – Illusory Conjunctions paradigm

We designed the Attentional Blink – Illusory Conjunctions paradigm (Figure 1), which contrasted an AB task hypothesized to emphasise distributed attention with a novel IC task that was hypothesized to depend on focused attention. The AB and IC tasks were completed in separate blocks. In both tasks, each trial involved a rapid serial visual presentation (RSVP) of 18 coloured stimuli on a grey background, presented for 80 ms each. Stimuli were alphanumeric characters: 8 digit distractors, each shown twice, and two letter targets, T1 and T2. In the AB task (Figure 1A) participants were instructed to report both letter targets. In the IC task

(Figure 1B), they were instructed to report the first letter and its colour. Within the RSVP stream, T1 appeared at positions 4-9 equally often, while T2 appeared with equal frequency at lag 2 (with one distractor digit separating it from T1) and lag 6 (five distractors in between). Each pair of two different letters appeared equally often as targets. In the interval between positions -2 and +6 relative to T1 there were no colour repeats. The RSVP stream used the letters A C D H K Q R T U, chosen because they were visually dissimilar to each other. The digits used were 2 to 8, because 1 was too easily confused with letter I. Colours were chosen on the ground of being dissimilar to each other: dark green, dark purple, dark blue, red, green, yellow, light blue, orange, brown. Each trial started with a fixation cross appearing for 400 ms. Stimuli subtended approximately 1.5° by 1.5° of visual angle.

Multiple choice responses were made at the end of each trial, 400 ms after the last RSVP item. Participants were prompted to indicate the identity of T1, followed by either the identity of T2 (AB task) or the colour of T1 (IC task). Each response screen contained a central fixation point where the mouse cursor was positioned and 9 response boxes corresponding to the 9 possible letters or colours, arranged in a circle around the central point. Response options were randomly located in response boxes on each trial. Participants chose a response by mouse-clicking on the corresponding response box. Participants were not asked to make speeded responses, but instead to respond as accurately as possible. After the second response there was an interval of 1000 ms before the next trial began.

The experiment comprised a total of 12 blocks of trials, of which 6 were Attentional Blink blocks and 6 were Illusory Conjunctions blocks, arranged in repeating XYYX order and counterbalanced across participants. Each block comprised 36 trials, such that the experiment contained 432 trials in total. The experiment began with two practice blocks (one of AB, one of IC) of 12 trials in total. In the practice blocks participants were given feedback after each trial, but in the experimental blocks feedback was given only after each block. The task was performed in an isolated

room, on a computer screen with the refresh rate of 75 Hz. The duration of performing the AB-IC paradigm was approximately one hour.

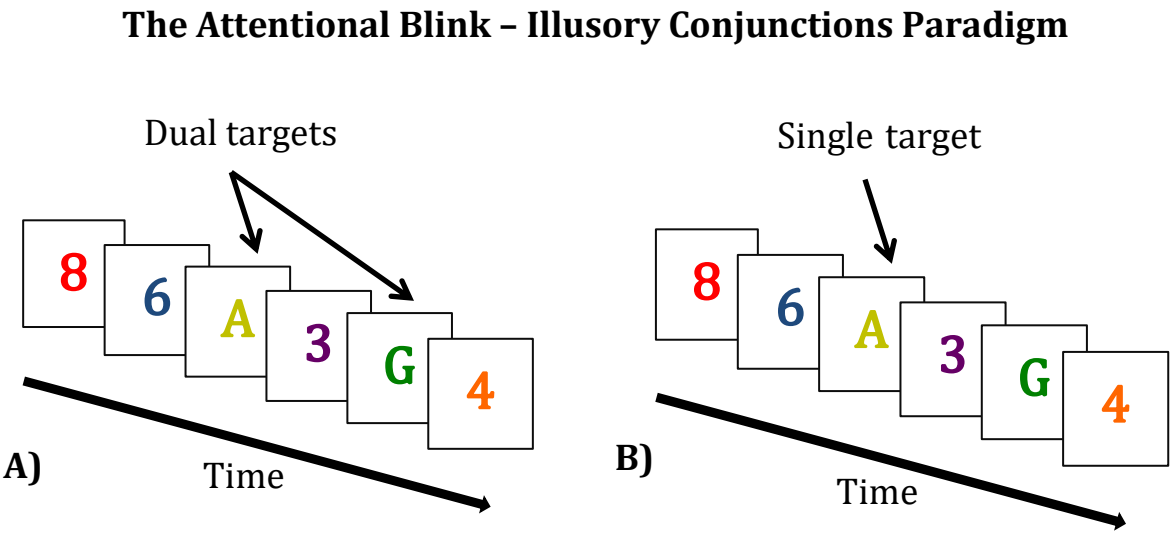

Figure 1. (A) The Attentional Blink task requiring the report of two letters in a stream of distractor digits. **(B)** The Illusory Conjunctions task requiring the report of the first letter and of its colour.

Other measures

Following the AB-IC task, participants proceeded to complete a number of pen and paper tasks with a total duration of half an hour. They began with tests of cognitive ability. The first was the AH5 general intelligence test (Heim, 1968), of which only Part 1 was used. This measures verbal reasoning (directions, analogies, series and similar relationships) and results are generally consistent with Part 2. The test lasted 20 minutes. Example items are presented in Appendix A. The second cognitive task we used was the Digit Symbol test of mental speed. The task is part of the Wechsler Adult Intelligence Scale WAIS-III and has been repeatedly found to capture mental speed (Wechsler, 1997; Joy et al., 2004). Participants had 1.5 minutes to complete the test, which required them to match as many digits as

possible to paired symbols. Example items are presented in Appendix A. Both the Digit Symbol test and the AH5 tests of cognitive abilities were used to control for common variance between distributed and focused attention that can be attributed to general ability or motivation rather than individuals' attentional style.

Next, participants completed two measures of mental state. The first was the Beck Depression Inventory (BDI II, Beck et al., 1996) measuring depression symptoms in the past two weeks including the day of testing (example item in Appendix A). Second, participants were given a self-report questionnaire to measure how much they mind wandered during the recently completed AB-IC task, similar to how other studies measured mind wandering (e.g. Smallwood et al., 2012). Mind wandering was rated on a scale of 1 to 5 in 7 different questions with a total score of 35 (example questions in Appendix A).

Results

Quantifying AB and IC task errors

We began by analyzing basic performance in the AB and IC tasks, in order to establish suitably robust measures of performance for the subsequent planned comparisons. Accuracy of detecting T1 was similar across the AB and IC tasks (18.6% and 19.3% error rates, respectively, $t < 1$), suggesting that the tasks were similarly demanding. In trials where T1 was correctly reported, participants were more accurate in reporting the second RSVP target in the AB task (21.0% errors) than they were in reporting the colour of the first target in the IC task (49.1%), $t(48) = 10.8$, $p < .001$. This comparative difficulty in reporting T1 colour is similar to the findings of McLean et al. (1983), who reported a 58-65% accuracy in reporting the colour of a specific item presented in an RSVP stream.

Because of the low colour detection rates, an analysis was conducted to investigate whether some specific colours were responsible. There were indeed significant differences in the accuracy with which different colours were detected, $F(8, 384) = 16.186$, $p < .001$, although follow-up pairwise contrasts revealed that the only reliable difference between individual colours was that brown (26%) was detected less reliably than all the others ($p < .02$, bonferroni corrected; Figure 2A). Since most colours proved relatively similar in detection accuracy, we had a reasonable degree of confidence in the results.

For comparison, a corresponding analysis was conducted to look at the accuracy of reporting each letter when presented as T1. A one-way ANOVA showed that letter identity had a main effect on T1 detection ($F(8,384) = 41.6$, $p < .001$), such that some letters were consistently better detected than others, with means ranging from 62% (“C”) to 86% (“Q”). Only letter “C” was consistently less frequently detected than all other letters ($ps < .001$, Figure 2B), while the differences in detection frequency between all other T1 letters were more gradual, with the

letters being more or less frequently detected than some letters but equally often detected as other letters.

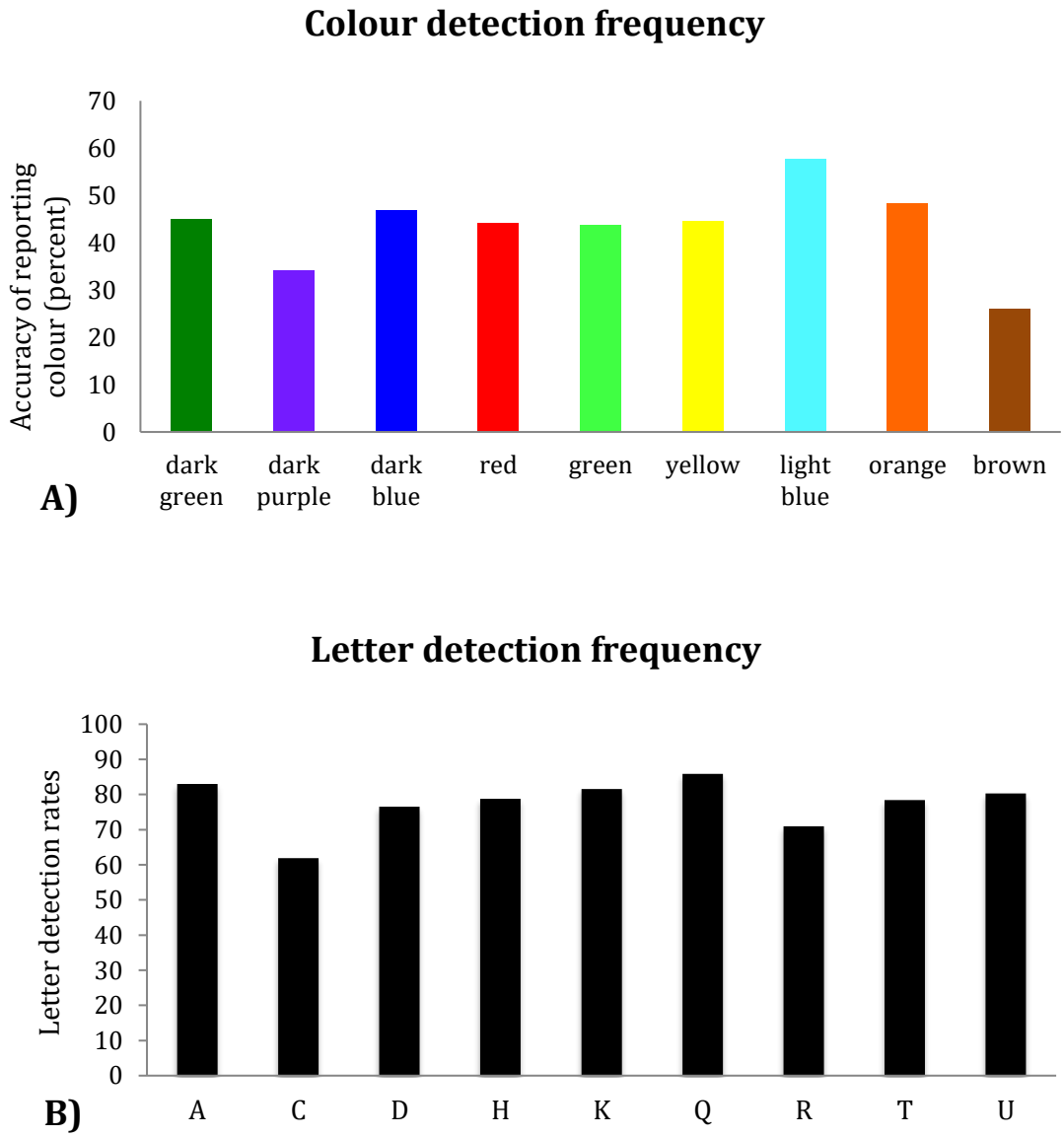

Figure 2. (A) Accuracy of reporting each colour when T1 identity was correctly reported; **(B)** Accuracy of reporting each letter as T1.

Proceeding with individual task accuracy, results in the AB task replicated standard findings (e.g. Raymond et al., 1992), in that the error rates for detecting T2 were reduced when T2 followed T1 quickly (lag 2, 29.4%) than when T2 occurred later in the stream (lag 6, 13.8%), $t(48) = 8.5$, $p < .001$. It is common for

the attentional blink to be calculated as the difference in accuracy between long and short lags. However, in our data this measure was relatively unstable across participants, with low correlations of accuracy in odd versus even-numbered trials, $r(49) = .60$, or in trials in the first and second half of the experiment, $r(49) = .50$. Thus, we chose an alternative computation of attentional blink error scores, as the difference between lag 2 accuracy and an average of lag 6 accuracy and T1 accuracy. This measure showed greater reliability for both odd-even trial splits, $r(49)= .70$, and first vs. second half trial splits $r(49) = .67$. Thus calculated, the attentional blink effect ranged from -10% to 49% across participants, with a mean of 13%.

With regard to illusory conjunctions, we observed that these errors varied as a function of position relative to T1 (Figure 3A). Interestingly, there was little evidence of increased likelihood of reporting the colour of the second letter in the RSVP stream (which was irrelevant in the IC task, but critical in the accompanying AB task): Participants were not more likely to report the colour of items at the +2 position (Lag 2) than at the -2 position (in fact, the opposite was true: $t(48) = 3,13$, $p = .003$), and they were not more likely to report the colour of +6 than +5 items ($t < 1$). Overall, the accuracy in reporting the correct T1 colour (position 0) varied substantively across participants (27% - 76% errors). Nevertheless, there was a general tendency for participants to mis-report the colour of distractor digits near to T1 in the RSVP, as shown by a reliable effect of position on reporting rate ($F(7,336) = 173.8$, $p < .001$). Illusory conjunctions were significantly more likely to occur in the four positions nearest to T1 (positions -2, -1, 1, 2, mean illusory conjunction rate = 9%) than in the four distant positions (3-6, mean illusory conjunction rate = 3%), $t(48) = 31.7$, $p < .001$. These results replicated previous findings that the four nearest-to-target items are the most likely source of illusory conjunctions (McLean et al., 1983; Vul et al., 2008a; 2008b).

Observing that the above-presented relationship between colour reporting and item position was consistent across participants, we sought to describe it as a function. As seen in Figure 3, there was a fit for a function capturing the cumulative probability of missing versus reporting the colour of each position. The function worked in the following way: if p is the probability of correctly reporting T1 colour (position 0), then for the immediately neighbouring item the probability is p multiplied by the probability of missing the T1 colour, i.e. $p(1\text{-}p)$. Following the same logic, the probability of reporting the next item would be $p(1 - (p + p(1 - p)))$, and this is continued until position 6. Whenever $p < 1$, the sum of probabilities across positions 0-6 was less than 1, therefore the remainder was treated as a guessing rate and distributed evenly across positions. We compared these modelled values with the observed reporting rates, after averaging observed rates for positions -1 and +1, as well as -2 and +2, so that the function monotonically decreased as a function of position. In order to fit the model function onto our data, for each participant we chose the p value that minimised least squared error between modelled and observed reporting rates, across positions. Function fits were reasonable across the range of participants' performance, from low to high accuracy participants as shown by Figure 3B-C. Although other functions might have provided an equally good or better fit, the measure we chose was simple and intuitive. Moreover, it showed very good reliability across participants, for odd and even trial splits, $r(49) = 0.92$, and first vs. second half trial splits, $r(49) = 0.91$. These reliability values were better than those of simple T1 detection rates ($r(49) = 0.92$ odd vs. even, $r(49) = 0.78$ split half) or the difference in reporting the colour of near versus far distractors ($r(49) = 0.15$ odd vs. even, $r(49) = 0.26$ split half). Therefore, we hereafter present and analyse the fitted model values as the error rates for the Illusory Conjunctions task. We treat this as a percentage, for symmetry with the Attentional Blink error rates. Thus calculated, the error rate in the illusory conjunctions task ranged from 22% - 80% across participants, with a mean of 47%.

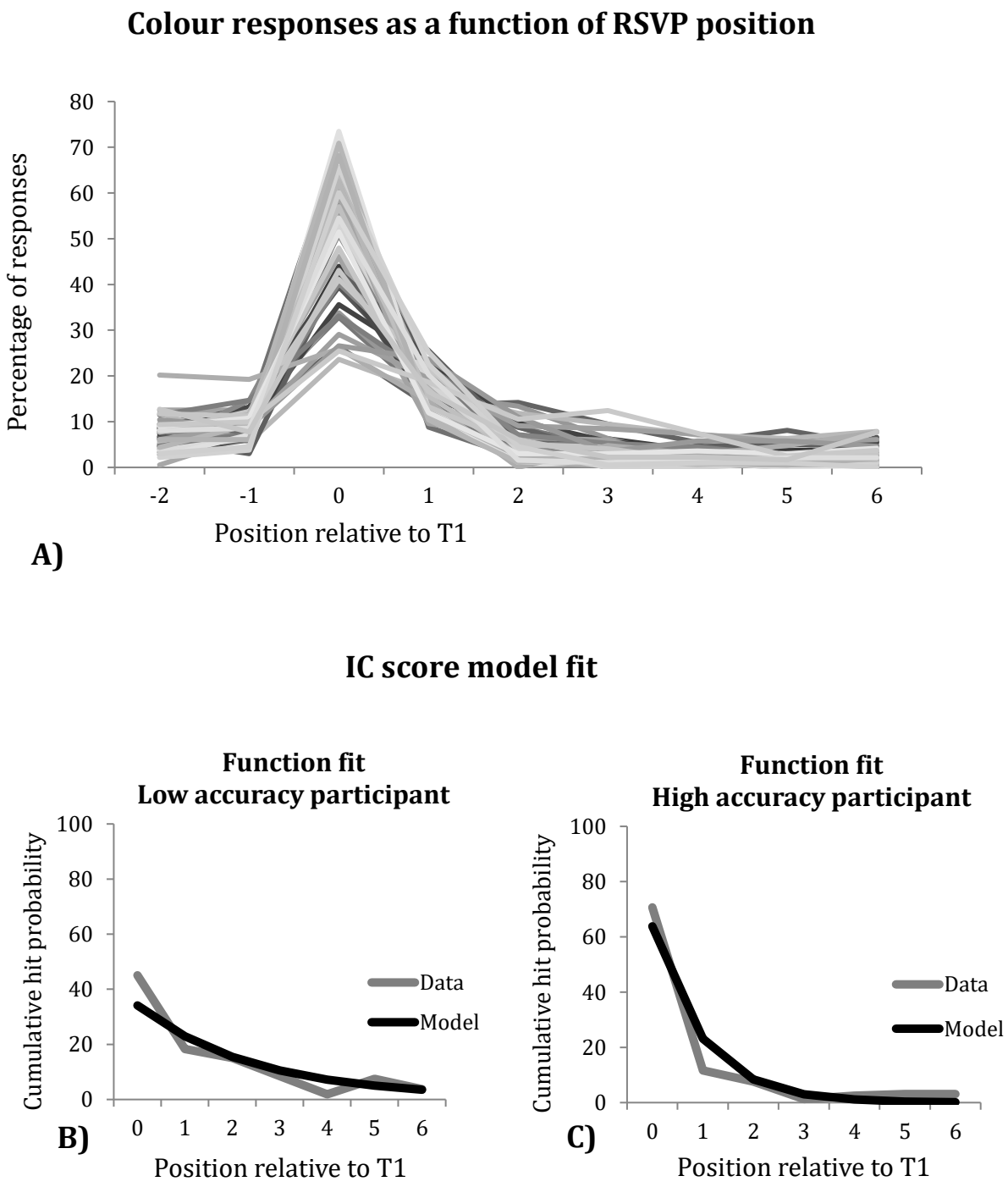

Figure 3. (A) Spread of colour reports and mis-reports over RSVP positions relative to T1, across all participants (separate lines). **(B)** IC score model fit for a low accuracy participant and **(C)** IC score model fit for a high accuracy participant.

Individual differences in the temporal attention trade-off

The first hypothesis was that there are stable individual differences in attentional style, with some people being more distributed and others more focused, leading to a negative correlation of attentional blink and illusory conjunction error rates. As can be seen in Figure 4, the correlation was negative overall but not reliably so ($r(49) = -0.15$, $p > .1$), and this remained true even when partialling out cognitive ability scores measured through the AH5 and Digit Symbol tasks ($r(49) = -0.23$, $p > .1$). Thus, we did not find support for the individual differences hypothesis, although previous studies reported individual differences in attentional blink size (Martens et al., 2006; Klein et al., 2011; Willems & Martens, 2016).

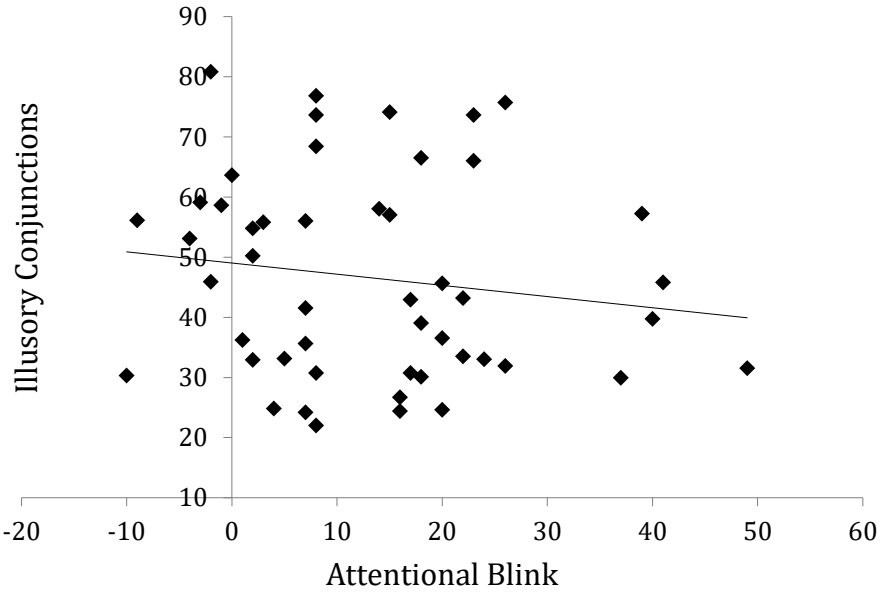

Figure 4. Correlation between Attentional Blink and Illusory Conjunctions error rates across participants.

As Experiment 1 had an exploratory approach, we looked further into the two measures of cognitive ability. With average scores of 13.92 for AH5 (of 36) and 73.63 for Digit Symbol (of 115), the measures did not show ceiling effects, but were able to capture individual differences. The two measures were positively related, but not reliably so (r = .26, p = .07). Interestingly, while a higher AH5 score predicted fewer Illusory Conjunction errors, albeit not significantly so (r(49) = -.27, p = .06, Figure 5A), AH5 scores were unrelated to AB size (r(49) = -.07, p = .62, Figure 5B), similarly to previous findings linking intelligence to target accuracy but not blink size (Colzato et al., 2007). On the other hand mental speed reliably predicted smaller attentional blinks (r(49) = -.33, p = .02, Figure 5D), but was unrelated to IC scores (r(49) = -.18, p = .21, Figure 5C), in line with studies showing that mental speed predicted AB (Wagner et al., 2014; but Arnell et al., 2006). Nevertheless, the differences in how IC and AB correlated to each of the two cognitive measures were not significant (Fisher's Z < 1), limiting its interpretation.

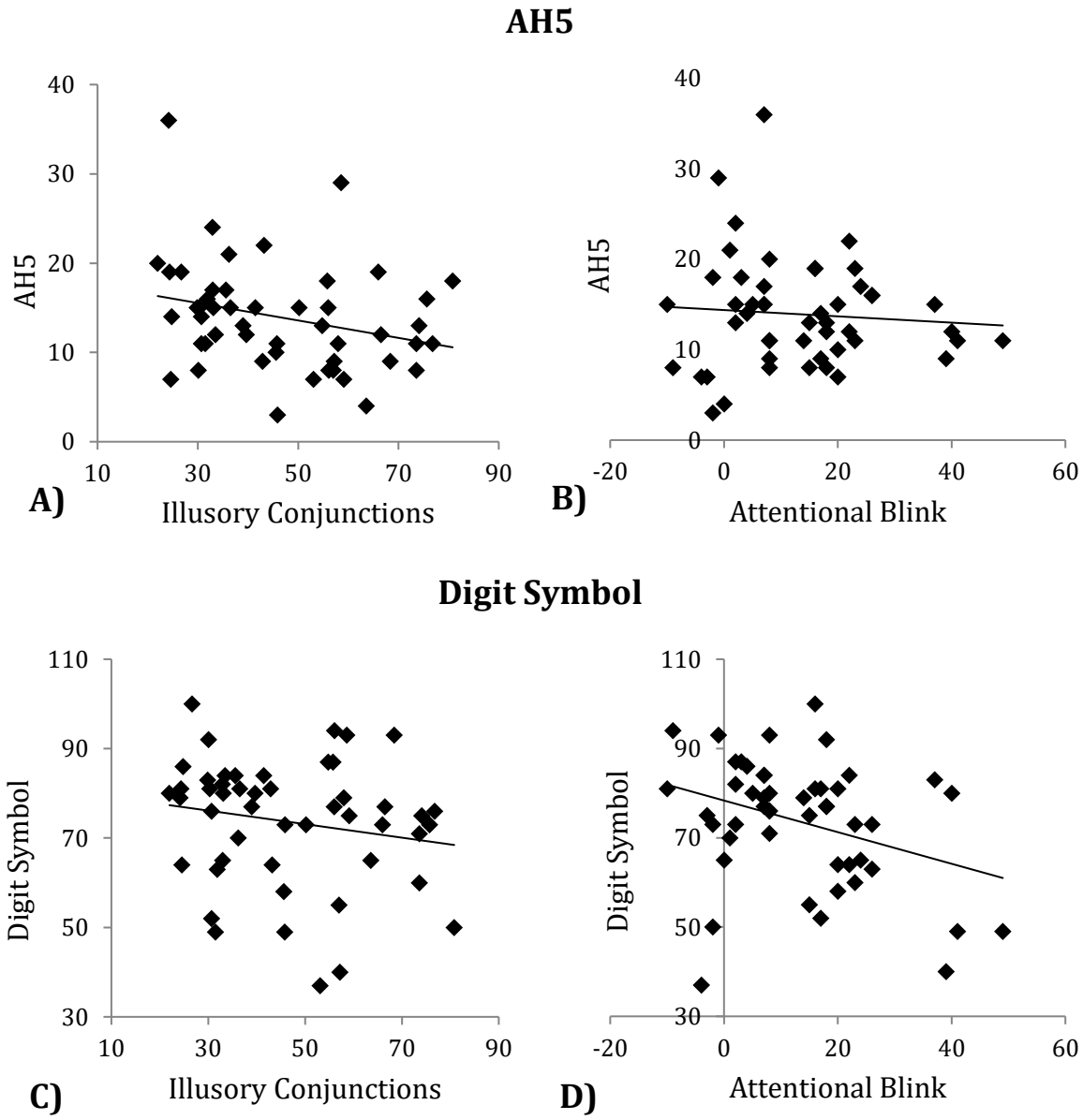

Figure 5. Differences in how Illusory Conjunctions and Attentional Blinks correlate to AH5 and Digit Symbol cognitive abilities measures.

Individual differences in mental state and attentional trade-offs

Having investigated individual differences in the temporal attention trade-off, we looked at whether the trade-off was influenced by individual differences in mental state. Despite previous findings linking positive and negative affect to distributed and focused attention respectively (Gasper & Clore, 2002; Storbeck & Clore, 2005; Fredrickson & Branigan, 2005), the current study did not find any relation between depression as measured through the Beck Depression Inventory and either AB errors ($r(49) = .05$, $p = .73$) or IC errors ($r(49) = -.01$, $p = .96$). However, this might have been due to very low BDI scores, with an average of 6.08 out of 63, corresponding to minimal levels of depression. Thus, the lack of results is likely to be due to floor effects.

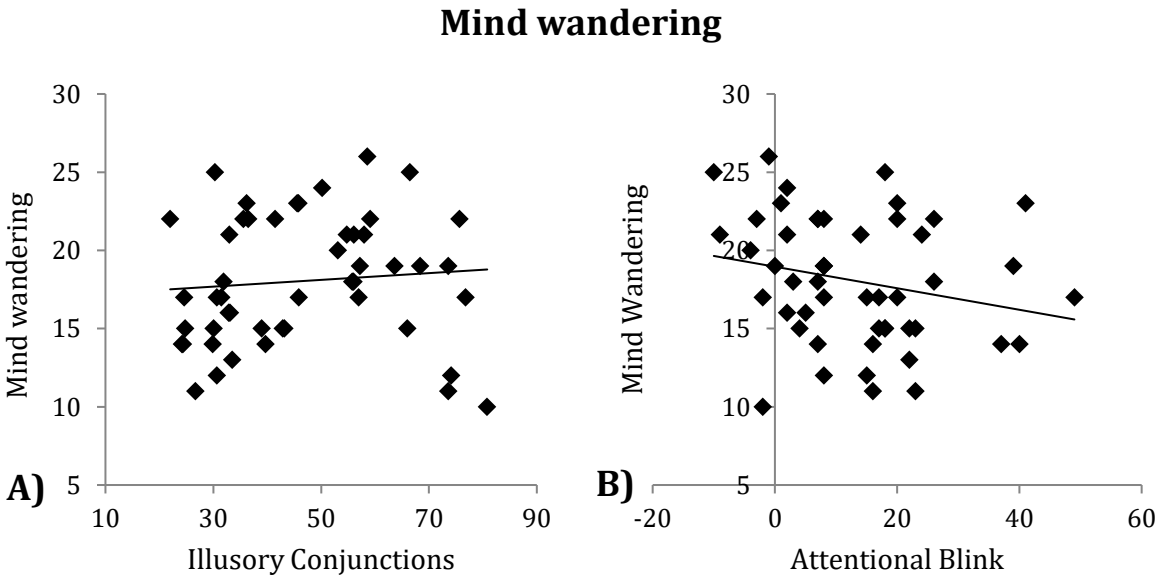

Figure 6. Differences in how **(A)** Illusory Conjunctions and **(B)** Attentional Blinks correlate to Mind Wandering during task.

Apart from affective state, we also investigated how mind wandering was associated with the temporal attention trade-off. We predicted that mind wandering would be positively related to distributed temporal attention and

negatively related to focused attention. Indeed, mind wandering during the task (retrospectively rated through a self-report, average MW = 18.04 of a total 35) showed a trend towards being differently related to AB and IC error scores (Fishers' Z = -1.51, p = .065; Figure 6), such that more mind wandering was associated with reduced AB errors but increased rates of Illusory Conjunction errors. However, although the comparison was marginally significant, the two separate correlations were not reliable (MW – IC r = .09, p = .54; MW – AB r = -.22, p = .12).

Within participant factors affecting the temporal attention trade-off

The final hypothesis of interest was that within-participant factors, which are known from previous literature to increase attentional focus or broadening, would affect performance in the two task in opposite ways. We looked at three types of between-trial variations inherent in the task design, which were predicted to have an impact on attention trade-offs: foreperiod length (delay between RSVP onset and T1 onset), saliency of T1 by letter discriminability, and saliency of T1 by colour. For completeness, we analysed the impact of each factor on detection rates for the T1 letter in addition to our main interest in the impact on AB and IC error rates.

Effects of foreperiod length

The foreperiod length varied between trials as a function of the position of T1 within the RSVP stream (4^{th} to 9^{th} with equal likelihood). It was predicted that T1 position would have opposite effects on AB and IC scores, with short foreperiods benefitting the IC and longer foreperiods benefitting the AB, according to previous studies (Woodrow, 1914; Zahn & Rosenthal, 1966; Badcock et al., 2013).

We began by looking at effects of foreperiod length on T1 detection rates, using a repeated measures ANOVA with within participants factors of position in the RSVP stream (4-9) and task (AB vs. IC). We found that T1 was detected less accurately at longer foreperiods ($F(5,240) = 12.4$, $p < .001$; Figure 7A) as shown by a main effect of position and a linear trend ($F(1,48) = 22.5$, $p < .001$). This confirmed previous findings that short foreperiods benefit target detection most (Woodrow, 1914; Zahn & Rosenthal, 1966). There was no main effect of task ($F < 1$), but there was a significant interaction between task and position ($F(5,240) = 3.9$, $p = .002$). However, when comparing the first three and the last three positions, we did not confirm any effect of task or interaction ($F < 1$). We only found an effect of position ($F(1,48) = 14.8$, $p < .001$), with better T1 accuracy at earlier positions.

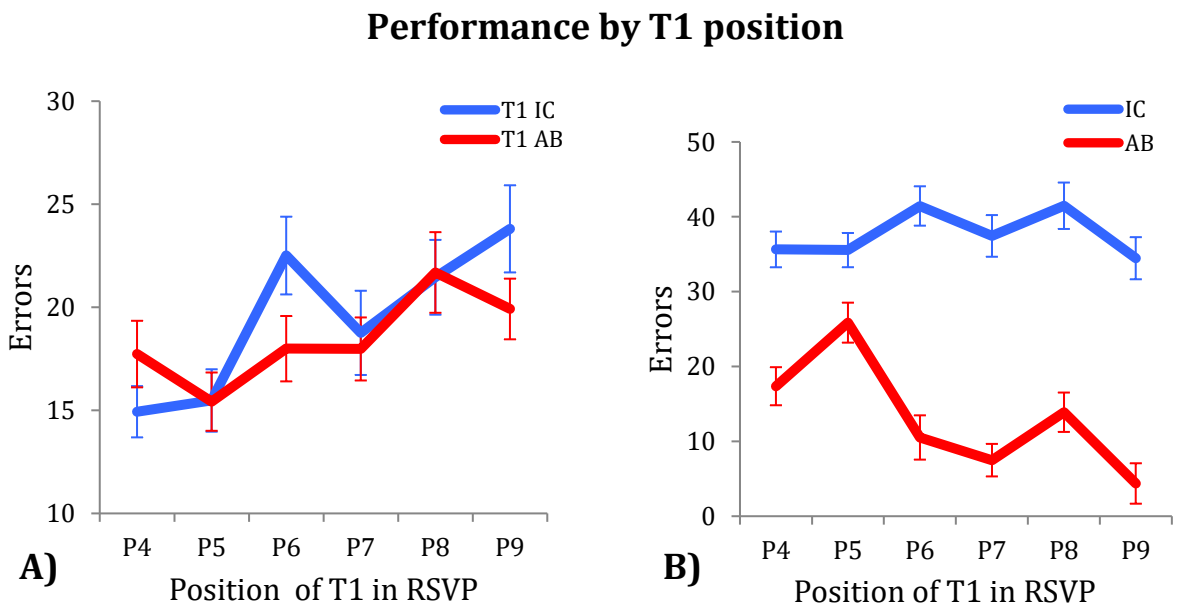

Figure 7. (A) Errors in detecting T1 as a function of its position in the RSVP. **(B)** AB and IC scores as a function of T1 position within the RSVP.

A similar repeated measures ANOVA on AB and IC error scores showed a main effect of task, with more frequent errors in the IC than AB task ($F(1,48) = 57.2$, $p < .001$), as reported above. Furthermore, we observed a main effect of position ($F(5,240) = 11.5$, $p < .001$) coupled with an interaction with task ($F(5,240) = 11.7$, $p <. 001$; Figure 7B). This confirmed a dissociable impact of foreperiod length on AB and IC performance. Separate ANOVAs showed that foreperiod length reliably impacted on AB score ($F(5,240) = 15.1$, $p < .001$). A linear trend ($F(1,48) = 31.2$, $p < .001$) revealed a larger attentional blink at short foreperiods, in line with previous research (Badcock et al., 2013). With regard to IC error scores, there was also a main effect of foreperiod ($F(5,240) = 4.8$, $p < .001$). However, there was no reliable linear trend ($F < 1$) and Figure 7B does not confirm any simple monotonic relationship between T1 position and IC performance. Thus, the prediction that shorter foreperiods would benefit illusory conjunctions was not clearly supported (Woodrow, 1914; Zahn & Rosenthal, 1966).

Salience of T1

Salience is known to draw attention to a stimulus in studies of spatial attention (Treisman & Gelade, 1980). Similarly, Weichselgartner and Sperling (1987) found that in an RSVP task, the processing of salient targets benefitted at the expense of subsequent stimuli. In an AB task, Chua (2005) found that salient T1 was better detected, but this was detrimental to T2 detection. We expected to find the same effect in our AB task, while also predicting that salient T1s would reduce illusory conjunctions. To analyse this, we exploited the natural variability in salience of the letter and colour stimuli we used. Indeed, this variability was reflected in differences in T1 detection rates. As has been reported above, letter identity had a main effect on T1 accuracy ($F(8,384) = 41.6$, $p < .001$), such that some letters were consistently better detected than others. Similarly, the accuracy of reporting the T1 letter was affected by its colour ($F(1,48) = 17.2$, $p < .001$), with detection rates ranging from 75.7% (orange) to 86.2% (dark green).

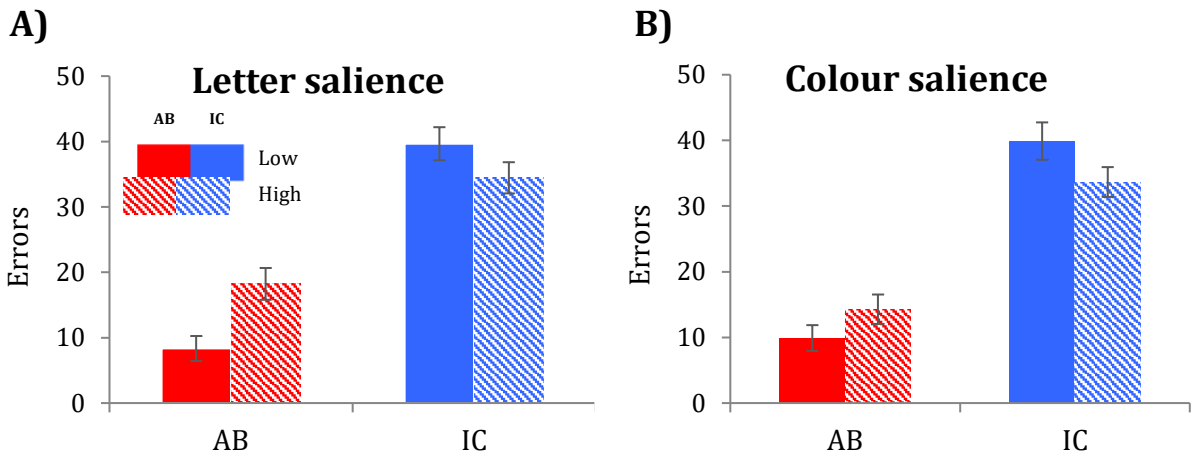

Figure 8. (A) Effects of T1 letter salience on AB and IC errors and **(B)** effects of T1 colour salience on AB and IC scores.

To test the prediction that letter salience would affect AB and IC task performance, we split trials into a low salience group (letters C, D, R and T) and a high salience group (A, K, Q and U). The median salience letter (H) was excluded to balance trial numbers. A potential confound was identified: because there were no letter repeats in any RSVP stream, in the low salience group the T2 letters were chosen from a pool which included more high salience than low salience letters. This could have affected the analysis by inflating T2 detectability in the low salience T1 group. Moreover, the reverse would have been the case in the high salience group. To counteract this confound, trials in each of the two groups were further split into low and high T2 salience subgroups. Thus, AB and IC error scores were computed separately for each subgroup, and then averaged together by group. An ANOVA by salience and task on the final scores confirmed the main effect of T1 salience on AB and IC error rates ($F(1,48) = 5.1$, $p = .023$), as well as an interaction ($F(1,48) = 41.5$, $p < .001$) suggesting that letter salience affected AB and IC scores differently (Figure 8A). Attentional blink errors were increased in trials with high salience T1 letters (18%) compared to low salience trials (8%, $t(48) = 5.4$, $p < .001$). On the other hand, people were less likely to make illusory conjunctions when the T1 letter was high salience (34%) as opposed to less salient trials (40%, $t(48) = -4.5$,

$p < .001$). These results confirmed previous findings that salience of T1 increases attentional blink errors (Weichselgartner & Sperling, 1987; Chua, 2005), and added the contrasting decreased illusory conjunctions rates.

To proceed further, we analysed the effects of colour salience on the AB-IC task errors. Again, trials were split into a low salience group (colours: brown, dark blue, red, orange) and a high salience group (light blue, yellow, green and dark green) based on each colour's impact on T1 detection rates. The median saliency stimulus (purple) was excluded to balance trial numbers. Furthermore, subgroups were formed depending on the colour salience of T2, and scores were averaged together for the two subgroups in each group. Finally, an ANOVA on salience and task showed no main effect of T1 colour salience, $F < 1$. However, there was a significant interaction between salience and task, $F(1,48) = 14.5$, $p < .001$, Figure 8B. There were more attentional blink errors in high salience T1 trials than in low salience trials, $t(48) = 2.7$, $p < .05$, while the opposite was the case for illusory conjunction errors, $t(48) = -2.9$, $p < .01$, as shown in Figure 8B. Again, results supported the idea that increasing T1 salience led to increased rates of attentional blinks, while adding the evidence of an opposing effect on illusory conjunctions, although the latter effect is necessarily observed given the way trials were split into high and low salience as a function of T1 colour.

Discussion

The first experiment in this thesis provided a large dataset on which the AB and IC task scores were tested for reliability, helping to arrive at two robust measures to be used throughout future experiments. Stable individual differences in temporal attention style along a focused to distributed continuum were not supported, as the predicted negative correlation between IC and AB performance was not observed. Mind wandering was marginally dissociably related to AB and IC error rates, suggesting a beneficial effect on the AB and detrimental effect on the IC. Furthermore, the dissociation of the AB and IC tasks, and their validity in measuring distributed and focused temporal attention respectively, was supported by results relating to intrinsic task variations between trials, such that both the length of foreperiod to T1 and the salience of T1 differentially affected IC and AB task errors. Therefore, in our first study we provide not only two robust measures of attentional blinks and illusory conjunctions in the novel AB-IC paradigm, but also observed some evidence of the dissociation of temporally distributed and focused attention, especially in relation to mind wandering and task variations previously known to affect attention.

The AB-IC paradigm

The AB-IC paradigm was designed to provide a context for investigating focused and distributed attention. As classically found (e.g. Raymond et al., 1992), in the AB task participants were worse at detecting the second letter when it came at a lag of two items after the first target, compared to a lag of six items. The Illusory Conjunctions task was designed as visually equivalent, but now participants were asked to report only the first letter and its colour. The accuracy of detecting the first target did not differ between the AB and IC tasks, confirming similar level of baseline difficulty. We sought to maximise the reliability of AB and IC scores. For the Attentional Blink, this meant slightly deviating from the standard measure (e.g. Raymond et al., 1992) and computing the difference in accuracy between a

compound of T1 and T2 at lag 6, and T2 at 'blink' lags (short lags). In the case of IC, we fitted a model function onto data in order to achieve reliability. Essentially, this new IC measure took into account all the elements that the AB computation did: both T1 detection and the spread of attention over RSVP items from focused on T1 to distributed around and to unengaged. Even though other functions might have fit the data equally well, our chosen one was simple and intuitive. It was thus considered to be an appropriate measure to use in the current and in future experiments, both theoretically and in terms of satisfying statistical criteria.

The current experiment achieved the aim of designing visually equivalent tasks in which one's ability to report two targets or a target and its colour are reliably measured. We conducted several tests of the validity of the AB and IC tasks as measures of distributed and focused attention. However, before that, a primary reason to believe the IC task is valid as a measure of focused temporal attention is that existing literature suggests a conceptual validity. Illusory conjunctions in the visuospatial literature are classically considered to be due to unfocused attention (Treisman & Gelade, 1980; Treisman, 1996) and various manipulations that focus attention have been found to prevent conjunctions (Cohen & Ivry, 1989; Prinzmetal et al., 1986), while not letting attention focus led to more conjunctions (Treisman & Schmidt, 1982; Treisman & Paterson, 1984). Illusory Conjunctions have also been reported to occur in RSVP streams and within the AB task (Raymond et al., 1992; Vul et al., 2008a; 2008b; Popple & Levi, 2007). The appearance of illusory conjunctions in reporting the T1 item was initially interpreted as poor filtering and as evidence that the 'attentional gate' needs to close after T1 to prevent distractors from entering (Raymond et al., 1992). Even this initial interpretation pointed to an important role of selective attention in the prevention of illusory conjunctions within the AB paradigm. The conceptual validity was thus quite strong and supported by the findings that the spread and frequency of illusory conjunctions in the current experiment matched those previously found.

Individual differences in temporal attention

Using the newly devised AB-IC paradigm, the current experiment set out to investigate individual differences in temporal attention on the focused–distributed spectrum. Based on previous findings of reliable individual differences in attentional blink size (Martens et al., 2006; Willems & Martens, 2016; Klein et al., 2011; Dale & Arnell, 2013b; Dale et al., 2013) such that some people can be categorised as 'blinkers' and others as 'non-blinkers', we expected a negative correlation between performance in the AB and the IC task. Our prediction was further strengthened by evidence of individual differences in local and global spatial attention (Zmigrod et al., 2015; Dale & Arnell, 2010; Dale & Arnell, 2015). However, our results did not support the hypothesis. We partialled out intelligence scores and mental speed, which could have made for a common variance due to cognitive abilities reflected in the two attention scores (AB and IQ: Colzato et al., 2007, but Martens & Johnson, 2009; AB and mental speed: Wagner et al., 2014, but Arnell et al., 2006; selective attention and cognitive abilities: Cowan et al., 2006; Krumm, Schmidt-Atzert, Bracht & Ochs, 2011). Despite this, the negative correlation remained unreliable.

There is a potential factor in our task design that might have contributed to the lack of a negative correlation. This is the blocked design of the AB-IC paradigm, in which participants could calibrate their attention mode for each of the tasks differently. Thus, an ability to control one's attention mode flexibly could have confounded individual differences in preferred attentional style. To control for this, in a further experiment in this thesis we will examine a non-blocked AB-IC design in which participants will be asked to report both letter targets as well as the colour of the first target in each trial. The question of individual differences will be tested again in this set-up in Experiment 9.

Despite the lack of reliably measured individual differences in attentional style, we found that individual differences in mind wandering affected the temporal

attention trade-off. Generally, mind wandering during a task relates to poor performance (Smallwood & Schooler, 2006; 2015; McVay & Kane, 2012; Smallwood et al., 2008) as well as distractibility (Forster & Lavie, 2014) and periods of inattention (Smallwood et al. 2004; Macdonald, et al. 2011). On the other hand, people who mind wandered more during a task have been found to show reduced rates of attentional blinks (Thomson et al., 2015). In the current study, we found that mind wandering was marginally differently related to attentional blinks, for which it appeared beneficial, and illusory conjunctions, which it seemed to increase. One potential reason behind the lack of significance of the result is that we used a self-report post-task questionnaire. This measurement has been used elsewhere in the literature (e.g. Smallwood et al., 2012), but is known to be subject to individual differences in the ability to report on inner states (Schooler et al., 2005). Because mind wandering is by definition a subjective experience, this drawback cannot be entirely avoided. However, this confound can be attenuated by sampling mind wandering more frequently during the task using probes (Kahneman et al., 2004; Smallwood & Schooler, 2006; Smallwood et al., 2004) for example every few trials as has been done by Christoff et al. (2009) or Macdonald et al. (2011), and by conducting a within-participants comparison of the effects of mind wandering on the attention trade-off. We aim to follow-up by implementing these two changes in Experiment 5.

Dissociable effects of intrinsic variation in task design on temporal attention trade-offs

In a final set of analyses, we investigated the effects of intrinsic variations in task design on the temporal attention trade-off. To begin with, the varying position of the T1 in the RSVP stream enabled an analysis of effects of short and long foreperiods. While short delays between a cue and a target were previously shown to benefit target detection, suggesting that they help focus attention (Woodrow,

1914; Zahn & Rosenthal, 1966), on the other hand long foreperiods reduce the attentional blink (Badcock et al., 2013). While our results supported a dissociable effect of foreperiod length on the AB and IC tasks, and confirmed a reduced attentional blink rate at long foreperiods, on the other hand no linear reduction in illusory conjunctions errors was found. The lack of a reliable effect on illusory conjunctions might be because here foreperiod length was variable and implicit. On the other hand, Coull and Nobre (1998) used explicit cues instructing participants to attend to a target appearing at a short or long delay. There, the benefit was again observed at short delays. In Experiment 3 we investigate the effects of explicit cueing and of predictable foreperiod length on the temporal attention trade-off.

Apart from foreperiod length, we also looked at how the salience of T1 impacted the temporal attention trade-off. In spatial attention, target detection is improved for salient targets (Posner & Cohen, 1984; Muller & Rabbitt, 1989). In temporal attention, salience of T1 also benefitted its processing at the expense of further targets or at the expense of the attentional blink (Weichselgartner & Sperling, 1987; Chua, 2005). In the current experiment, salience of the letter and colour stimuli varied between trials. In trials with high salience T1 stimuli, illusory conjunctions were less likely to appear, while attentional blinks were more frequent. These findings replicated previous studies with the AB task, while extending these to show opposing effects on the novel illusory conjunctions task. However, a potential drawback of the current results is that they rely on intrinsic task variability. Thus, we follow-up these results in Experiment 2 where we test the effects of an experimental manipulation of salience on the temporal attention trade-off.

The dissociation of how foreperiod length and saliency, both known to focus attention, affect the two tasks differently, goes further to support the theory that an overfocused attention is detrimental to the AB (Olivers & Nieuwenhuis, 2005;

2006) and thus that the AB task measures distributed temporal attention, since distraction improves AB. The dissociation also presents a challenge to capacity limitation theories (Raymond et al., 1992; Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998), since a factor that increases focused attention could not negatively affect attentional capacity. But most importantly, the dissociable associations between performance in the AB and IC tasks and foreperiod length, salience and mind wandering all suggest that there is a trade-off between two attention modes. In the next chapters we will investigate further the hypothesis that sometimes a focused attention is optimal, while in other circumstances a distributed attention is more beneficial to performance.

Chapter 3

Effects of temporal orienting on the temporal attention trade-off

Introduction

In Chapter 2 we reported that the most compelling evidence for trade-offs in temporal attention was in relation to within-participants variations in task design, such that salience of T1 was associated with fewer illusory conjunctions but more attentional blinks. Using the AB-IC paradigm, Chapter 3 aims to follow up these results to investigate how within-participants experimental manipulations of exogenous and endogenous orienting to T1 affect the temporal attention trade-off. Moreover, in Experiments 3a and 3b we look at endogenous cueing using a fast and a slow presentation rate and report unexpected effects of speed of presentation on the attention trade-off. To replicate these findings in a within-participants set-up, Experiment 4 compares the effects of speed of presentation on temporally focused and distributed attention.

Orienting attention using exogenous and endogenous cues

Much effort has been put into investigating what circumstances and manipulations favour an optimally focused attention. In spatial attention, such manipulations were needed to help the attentional 'spotlight' select stimuli at a specific location (Eriksen & Hoffman, 1973), to aid in binding visual features of a stimulus together in a coherent visual object (Treisman & Gelade, 1980; Treisman & Schmidt, 1982), or to bias the competition of visual stimuli for representation at the neural level (Desimone & Duncan, 1995; Kastner & Ungerleider, 2000). A classic study of how attention can be experimentally oriented was conducted by Posner (1980) using the 'Posner cueing paradigm', in which participants have to detect or categorize stimuli presented to the left or right of fixation. Prior to stimulus onset, an arrow cue appears in the center of the screen or a peripheral cue appears on a side of the screen indicating the future target location validly or invalidly. Posner (1980) showed that valid orienting cues facilitated target detection whether presented centrally or peripherally as compared to invalid cues or to no cues.

Following Posner's initial work, the dissociation between two types of orienting became important. In Posner tasks, peripheral cues acted more rapidly than central cues, already affecting performance at 50 ms post-presentation (Muller & Rabbitt, 1989). Evidence suggested that peripheral cues were automatic and exogenous or externally-driven: their effects were less disrupted by secondary working memory tasks, by whether the cue actually contained additional target location information and by voluntary suppression (Jonides, 1981). As a contrast, arrow cues were symbolic and thus oriented attention endogenously, in a voluntary manner. The distinction between exogenous and endogenous orienting mechanisms was supported by neuroscientific findings. In the hierarchical architecture of the visual system, information flow is bidirectional rather than purely feedforward (Corbetta & Shulman, 2002). First, neural signals can

originate in the early visual cortices encoding location and basic features such as orientation of a stimulus. These signals are sent upstream to higher-order cortices where the object representation is formed. Such bottom-up signals might mediate exogenous orienting. On the other hand, endogenous orienting might originate in top-down signals that are goal-related and are sent downstream to modulate activation in lower areas (Ungerleider & Mishkin, 1982; Desimone & Ungerleider, 1989; Kanwisher et al., 1997).

A broad range of exogenous and endogenous cues have been used in spatial attention studies. Exogenous orienting involves attention being drawn involuntarily. According to James (1890), this can be triggered by intense, large or sudden onset stimuli. The pop-out property of a stimulus is key: a red poppy captures attention more rapidly in a field of orange tulips compared to a field of orange, red and purple ones (Duncan & Humphreys, 1989). Exogenous orienting can also be achieved by pairing a target stimulus with a salient marker, such as a bright box around a target stimulus (Handy, Jha & Mangun, 1999) or presented at a target location (Prinzmetal, McCool & Park, 2005). As a contrast, endogenous orienting is usually driven by symbolic cues that act as instructions: arrows pointing to target location (Posner, 1980) or indicating the direction of motion of subsequent targets (Shulman et al, 1999) or verbal instructions to guide search, such as the aim to find a person with a red hat within a visual scene (Folk, Remington & Johnston, 1992). Finally, it is worth noting that exogenous and endogenous cues can be used in additive ways, for example we are more likely to notice people wearing red clothes when looking for a friend with a red hat, a phenomenon termed ‘contingent capture’ (Folk et al., 1992). On the other hand, Theeuwes (1992; 2004) observed that salient stimuli can sometimes capture attention even if they are overriding the top-down goals and actually distracting one from their task. However, when this happens there is a quick recovery of attention back to aligning to top-down goals (Theeuwes, Atchley & Kramer, 2000). Overall, the broad range of endogenous and exogenous cues used by

researchers not only provide well-characterised options for future research, but also testify to the robustness of the cue-orienting phenomenon.

Orienting attention in time: exogenous

Whereas attentional orienting has been well documented in the spatial domain, research into temporal orienting only developed later. To begin with, warning signals have been known to improve detection of subsequent target stimuli (Wundt, 1887). Despite this, orienting to a moment in time is biologically different than orienting to a location in space. As Nobre (2010) pointed out, specific brain cells code for a location in space, but probably not for a moment in time. Instead, time might be coded across neural networks in the brain (Nobre & O'Reilly, 2004; Karmarkar & Buonomano, 2007; Buonomano & Maass, 2009) and temporal expectancy might be formed through brain oscillations, for example in the alpha band (Oprisan & Buhusi, 2014). Because of this population coding, temporal cueing can yield task-unspecific readiness in the brain, as has been seen experimentally (Fischer et al., 2013).

If temporal orienting is differently implemented in the brain than spatial attention orienting, there are also substantial differences behaviourally. Indeed, the mapping of orienting mechanisms onto exogenous and endogenous is somewhat different in the temporal compared to the spatial domain. Exogenous temporal orienting is typically studied using rhythmicity of presentation of stimuli to guide attention. This has been shown to reduce reaction times and improve accuracy of detecting targets (Praamstra et al., 2006; Doherty et al., 2005; Martin et al., 2005; Coull & Nobre, 2008; Mathewson et al., 2010; Sanabria et al., 2011). A dichotomy between exogenous and endogenous temporal orienting was highlighted by Rohenkohl et al. (2011) who showed that the rhythm of a ball trajectory on the screen guided detection of a cross on the ball automatically, while a symbolic cue (colour of the ball) only had an effect if participants were instructed to attend to it voluntarily.

If in spatial exogenous cueing, salience is most commonly used, in temporal orienting Lawrence and Klein (2013) also observed that salient warning cues had an effect on target detection. More relevant to the present study, in an RSVP study, Weichselgartner and Sperling (1987) increased the salience of a target by presenting a box around it, a method that was also used in spatial attention (Handy et al., 1999; Prinzmetal et al., 2005). The manipulation led to poorer detection of subsequent RSVP items up to 300 ms later. In the AB task, Raymond et al. (1992) argued that the white colour of their T1 in contrast to the black distractors opened an 'attentional gate' which improved T1 processing. An experimental test of the effect of T1 salience was done by Chua (2005) who reported that saliently coloured T1 targets were better detected at the expense of T2 detection. In adding to the literature, Experiment 1 in this thesis found that high salience T1 letters or colours led to fewer illusory conjunctions but more attentional blinks. In Experiment 2 we aim to test the effect of exogenous cueing on attention trade-offs experimentally, using a boxed T1 stimulus.

Orienting attention in time: endogenous

For symmetry, in Experiment 3 we aim to investigate effects of endogenous cueing. Top-down orienting to a specific moment in time has been implemented by instructing participants that targets would appear early or late after a cue (Kingstone, 1992; Coull & Nobre, 1998). Studies have used symbolic cues (letters 'S' or 'L', Kingstone, 1992), circles (small/large circle, Coull & Nobre, 1998) or lines (short/long lines, Correa et al., 2004, Trivino, Correa, Arnedo & Lupianez, 2010). Top-down cueing reduced reaction time to targets. Initially, it was thought that benefits were mostly at the motor control level, since cueing effects were largely observed for late brain potentials (Coull & Nobre, 1998; Miniussi et al., 1999; Coull et al., 2000; Hackley, 2009). However, later experiments actually revealed benefits to perceptual discrimination in the form of feature detection (Griffin et al., 2002), perception of luminance threshold, orientation and

stereoscopic discrimination (Lasley & Cohn, 1981; Westheimer & Ley, 1996; Correa et al., 2005; Rolke & Hofmann, 2007). Furthermore, cueing the time onset decreased the minimum delay required between two consecutive targets in order to correctly perceive their order (Correa et al., 2006b; Bausenhart et al., 2008). In the interpretation of Correa et al. (2006b), if perceptual tasks are difficult enough then temporal orienting benefits can be observed at the perceptual level. Furthermore, Correa et al. (2010) found that endogenous temporal cueing benefitted a perceptual discrimination while decreasing participants' ability to report the direction of a target arrow flanked by distractor arrows. As the authors concluded, temporal orienting might be particularly beneficial for perceptual conflict but less so for response conflict.

In Experiment 3, we hypothesise that temporal orienting to T1 increases attentional focus at the timepoint of T1 and reduces distribution of attention. As seen above, a broad range of evidence appears to support a prediction that endogenously cueing the time of onset of T1 would focus attention on T1, improve perceptual acuity and reduce illusory conjunctions. As a trade-off, we expect attentional blink rates to be increased by endogenous cueing of T1 onset. There has been little research into temporal cueing in AB tasks. Cueing the T1 to T2 delay improved T2 without disrupting T1 detection (Martens & Johnson, 2005), and Badcock et al. (2013) found that when T1 position was unpredictable, there was a larger blink than when the foreperiod was predictable. However, their study did not explicitly cue the onset time of T1 and thus might not have tapped into top-down mechanisms for focusing attention. We believe the temporal attention literature supports the prediction that temporal orienting focuses attention and thus would trade off in less optimal distribution of attention across timepoints to process T2.

One particularity of temporal orienting has been the effect of delay length. Initially, it was reported that warning signals were most beneficial at short delays

(Woodrow, 1914; Zahn & Rosenthal, 1966). Comparatively, reaction times were slower when the delay between cue and target was longer, even if expected to be longer (Mattes & Ulrich, 1997). Later, this result was replicated in experiments cueing the time of onset of targets. Most studies found temporal orienting benefits were larger at short delays (Coull & Nobre, 1998; Naccache et al., 2002; Nobre, 2001), although long delays were sometimes beneficial as well (Correa et al., 2004) and Ariga and Yokosawa (2008) actually found better single target RSVP detection at long foreperiods. While it remains most common to find short delay benefits of temporal orienting, the attentional blink appears to benefit most from long pre-T1 foreperiods (Badcock et al. 2013). In Experiment 1, we found that long foreperiods were better for the AB task, but we did not confirm the opposite for illusory conjunctions. However, we only looked at intrinsic variations in task design, and foreperiod length was not predictable. In Experiment 3 we compare how cued, experimentally-manipulated short or long delays affect the temporal attention trade-off.

Speed of presentation and the temporal attention trade-off

To look ahead, a comparison of results in Experiments 3a and 3b revealed fewer illusory conjunctions and more attentional blinks at a slower speed of presentation. This was counterintuitive, because faster presentation means increased difficulty and a general decrease in performance, at least at face value. Indeed, various experiments have shown that difficulty leads to more blinks. When T1 was a less frequent word from the vocabulary, it was more difficult to report and also led to more blinking when reported (Botella, Privado, Gil-Gómez De Liaño & Suero, 2011). Similarly, a white T1 was more difficult to detect than a red T1 but when detected led to poorer AB (Botella et al., 2011). Even in participants who do not usually 'blink', an AB could be induced by presenting an inverted, more difficult to perceive T1 (Martens et al., 2010). Despite these previous findings, in Experiment 3 an increased speed of presentation led to a

reduced blink. The striking result nevertheless supported the idea of trade-offs in temporal attention, such that some situations increase focused attention while others lead to a more distributed attention in time. In Experiment 4 we aim to test the effect of speed of presentation in a within-participants design.

Experiments 2-4

Chapter 3 aimed to investigate the effects on attentional trade-offs of experimental manipulations known to focus attention in time exogenously (Experiment 2) and endogenously (Experiments 3a and 3b). Following a striking observation of effects of speed of presentation on the attentional trade-off (Experiments 3a versus 3b), in Experiment 4 we tested the latter effect in a within-participants design.

Experiment 2: Exogenous cueing of attention in time

Following up findings from Experiment 1 where we reported that salience of T1 had opposite effects on AB and IC, in Experiment 2 we aimed to further investigate how an experimental manipulation of exogenously cueing focused attention impacts the temporal attention trade-off. Since colour is already a design factor in the AB-IC paradigm, we chose to manipulate salience of T1 differently. In a previous RSVP experiment, Weichselgartner and Sperling (1987) had observed that a framed target draws attention and it is better processed, but at the expense of further targets. Experiment 2 predicted that exogenously cueing attention to T1 by framing it with a box would reduce illusory conjunctions while increasing attentional blink error rates.

Method

Participants

Experiment 2 involved 21 participants from Oxford, both students and non-students, of whom 7 were male and 14 were female. The mean age was 24 years (range 18 – 30). Selection criteria were the same as in Experiment 1: none of the participants were self-reported as colour blind and all had normal or corrected-to-normal vision. All participants were fluent in English and none of them was on any psychoactive medication at the time of the study. The experiment received ethical clearance from the University of Oxford Central University Research Ethics Committee. All participants received course credits or payment of £10 for their participation.

Procedure

Experiment 2 used the AB-IC paradigm and the same methods as Experiment 1. There were two conditions. In the experimental condition, participants were exogenously cued to T1 through boxing T1 with a black rectangle frame of

approximately 2° by 2° of visual angle around the letter (Figure 9). The control condition used the standard AB-IC paradigm as used in Experiment 1 (i.e., with no box around the target). In each block, half of the trials were cued, and these were randomly distributed across the block such that there were equal numbers of cued lag 2 and lag 6 trials in each block. The experiment lasted approximately one hour. Before the experiment, participants were given information and consent forms to complete. They were instructed with regard to the task requirements. No specific instruction with regard to the cues was given.

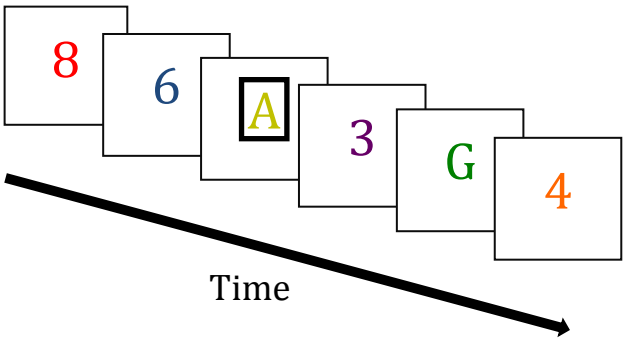

Figure 9. RSVP in exogenously cued condition in Experiment 2.

Results

Replicating what was observed in Experiment 1, T1 detection accuracy was similar in the AB and IC tasks (19.6% vs. 18.3% error rates, respectively, $t < 1$). On the other hand, attentional blink errors were considerably less frequent (10%) than illusory conjunction errors (40%), $t(20) = -4.1$, $p = .001$. In order to test the effectiveness of exogenous cueing of T1, we began by conducting an ANOVA on T1 error rates, looking at task (AB vs. IC) and condition (cued vs. not cued). There was a main effect of cueing ($F(1,20) = 6.5$, $p = .019$) such that T1 error rates were reduced in exogenously cued trials. Additionally, there was a trend interaction with task ($F(1,20) = 3.306$, $p = .084$). Follow-up analyses of cue

effects for each task separately showed that cueing improved T1 accuracy in the IC task ($t(20) = 2.9$, $p = .009$), but not significantly in the AB task ($t < 1$, Figure 10A).

The key analysis in Experiment 2 looked at the impact of exogenous cueing on AB and IC errors. A repeated measures ANOVA was conducted with within-participants factors of task (AB vs. IC) and cueing (cue present vs. absent). Exogenous cues had no main effect ($F < 1$), but the expected interaction between task and cueing was found to be significant ($F(1,20) = 5.6$, $p = .029$). As Figure 10B shows, illusory conjunction errors were reduced when exogenously cued, although this difference was only marginally significant ($t(20) = -1.9$, $p = .068$). On the other hand, attentional blink errors were numerically more frequent in cued trials, but the difference was not significant ($t(20) = 1.3$, $p > .1$).

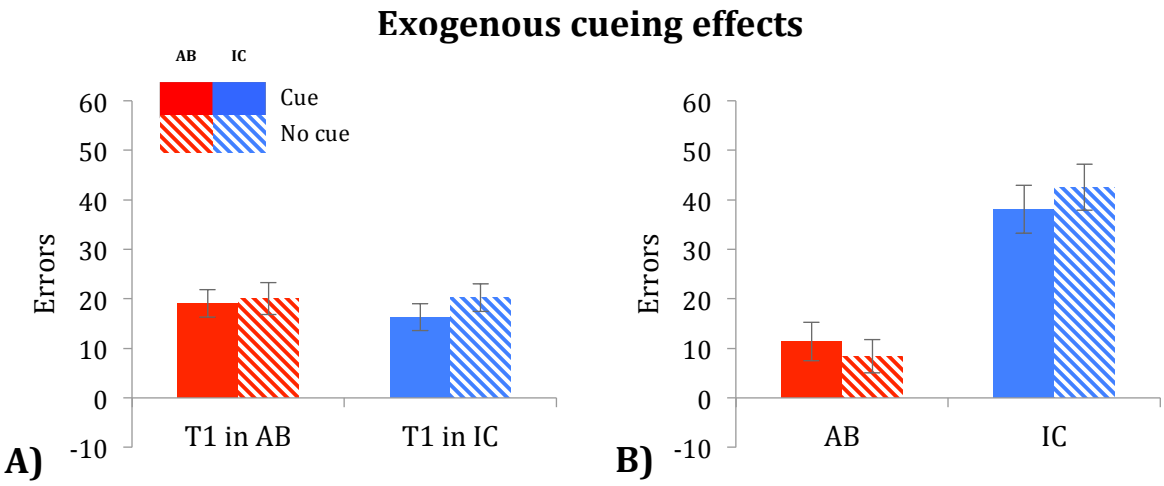

Figure 10. Effects of exogenous cueing to T1 on **(A)** T1 detection rates in AB and IC tasks and **(B)** AB and IC error rates.

Discussion

Experiment 2 looked at the effects of exogenous cueing on attentional blinks and illusory conjunctions. We observed an interaction between cueing and task, which confirmed the key prediction that exogenous cueing, which manipulated attention towards a focused state, impacted the temporal attention trade-off. However, changes were not significant for each of the tasks separately. This might have reflected an overall low rate of attentional blink errors, possibly showing floor effects. In previous RSVP and AB studies, framing the T1 target (Weichselgartner & Sperling, 1987) or increasing its salience (Chua, 2005) improved T1 detection at the expense of T2 detection. On the other hand, in the spatial attention literature salience is known to improve perception and reduce illusory conjunctions (Posner, 1980; Duncan & Humphreys, 1989; Treisman & Paterson, 1984). Experiment 2 extends these findings by showing a dissociation of attentional blink and illusory conjunction effects in temporal attention in a single study, using the integrated AB-IC paradigm.

Apart from the key dissociation, it is also worth noting that the exogenous cue only had an effect of improving T1 detection reliably in the IC task. This raises the possibility that participants had different strategies in the AB and IC blocks and thus a strategic broadening of attention in the AB blocks might have prevented exogenous cues from having a benefit. Indeed, studies on orienting effects in spatial attention show that top-down goals drive attention and counteract effects of potentially distracting exogenous cues (Theeuwes et al. 2000).

Experiment 3: Endogenous cueing

It is common for researchers to look at both exogenous and endogenous orienting of attention (e.g. Posner, 1980). Having looked at effects of exogenous cueing on the temporal attention trade-off, we continued by investigating effects of endogenous cueing. In temporal attention, endogenous cueing involves instructing participants with regard to the onset time of the target: early or late (Kingstone, 1992; Coull & Nobre, 1998). This improves target detection. In the current experiment, we chose to orient attention to T1 using lines (short for early, long for late, Correa et al., 2004; Trivino et al., 2010). We predicted that endogenous cues would reduce illusory conjunction rates while increasing the frequency of attentional blinks. Additionally, previous research found that short delays were most beneficial for target detection during cueing (Coull & Nobre, 1998; Naccache et al., 2002; Nobre, 2001), while long foreperiods were better for attentional blinks (Badcock et al., 2013), which we also reported in Experiment 1. As a secondary prediction, we expected that short delays would be beneficial for the IC task while the AB task would be better performed at long delays.

We tested these predictions in Experiment 3a. To look ahead briefly, we did not find the expected cueing effects. However, we believed this might be due to very good AB performance and very low IC scores. To counteract potential IC floor effects, we ran Experiment 3b with a slower presentation rate, which we assumed would aid focused attention and the benefit of cueing. Again, cueing had no effect. Nevertheless, we observed striking effects of presentation rate, which in itself provided insights relevant to our hypothesis.

Method

Participants

Experiment 3a tested 20 Oxford-based participants, recruited from both the student population and the general population. The mean age was 26 years with an age range of 18 to 40. There were 7 males and 13 females.

Similarly, Experiment 3b tested 20 Oxford-based participants, both students and non-students. The mean age was 26 years, and their ages ranged from 20 to 38. There were 12 males and 8 females.

Procedure

Experiment 3a extended the same AB-IC paradigm and methods as Experiments 1-2 to contrast conditions with and without endogenous cues to T1 latency. In the cue condition, participants were cued with regard to the time of onset of the T1 target, by being presented with a short or a long line (Correa et al., 2004) at fixation before each trial to represent a short or long delay to the occurrence of T1 within the RSVP stream (Figure 11). The control condition was the standard, uncued AB-IC method used in the previous experiments. At short delays, T1 appeared at positions 4 or 5 within the RSVP stream, while long delays corresponded to positions 8 or 9. There was no explicit instruction to participants regarding these specific positions. In contrast to Experiment 1, we only used these four positions, excluding positions 6 and 7, in order to make a clearer distinction between short and long delay while not allowing participants to be able to predict the exact position. Cued and uncued blocks were alternated, because previous studies found stronger effects of cuing in blocked compared to intermixed conditions (Correa et al., 2006b). As in previous experiments, each block contained 36 trials. Here, these were split in six chunks: three chunks of six trials with short delay, and three chunks with long delay. Within each block, the order of these chunks was random. Numbers of trials with lag 2 and lag 6 were

equal in the short and long delay condition, and the cued and not cued condition in each block. Experiment 3a lasted one hour.

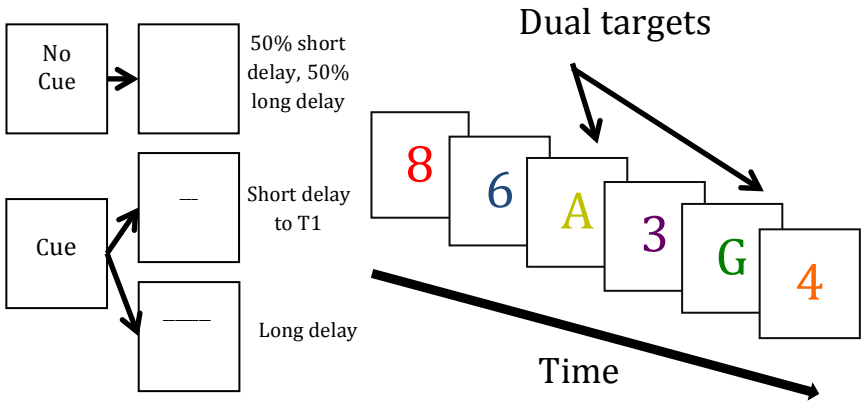

Figure 11. Endogenous temporal attention orienting to the first letter target in the AB-IC task: an AB trial presented as example.

In Experiment 3b the presentation rate was slower, at a rate of 106.6 ms/stimulus, as compared to the previously used 80 ms/stimulus. The value of 106.6 ms was chosen to fit the screen refresh rate of 75Hz. To further boost potential effects of exogenous cues by making the delay length easier to discriminate, T1 was only presented at position 4 at short delay and position 9 at long delay. Due to the increase in presentation time per stimulus, the experiment was shortened to ten blocks in order to keep total experimental time to one hour. Otherwise, in all other respects, the design of Experiment 3b was the same as in Experiment 3a.

Results

Alike to previous experiments, in Experiment 3a accuracy of T1 detection did not differ reliably between the AB and IC tasks (26.6% and 26.1% errors, $t < 1$). The same was the case in Experiment 3b where T1 detection did not differ reliably between the AB task (14.2% errors) and the IC task (15.8% errors), $t(19) = 1.8$, $p = .08$.

Experiment 3a showed low error rates in attentional blinks (5.7%), paired with a high frequency of illusory conjunctions (47.4%). This raised the concern of ceiling and floor effects, which prompted Experiment 3b. In Experiment 3b, attentional blink error rates were 18.4%, while illusory conjunction error rates were at 26.4%.

The key hypothesis in Experiments 3a and 3b was that top-down orienting would focus attention at the expense of distributed attention, predicting that endogenous cues would show dissociable effects on IC and AB performance. To begin with, an initial verification of the effectiveness of endogenous cues was conducted by looking at how these cues affected T1 detection. In Experiment 3a, the effectiveness of endogenous cues was confirmed in a repeated measures ANOVA looking at effects of task (AB vs. IC) and condition (cue vs. no cue) on T1 error rates. The effect of task has been discussed above. There was a main effect of cue, with fewer errors in the cue condition (24.6%) than the no cue condition (28.1%), $F(1,19) = 10.3$, $p = .005$, Figure 12A. There was no interaction with task ($F < 1$) such that, as expected, cues affected T1 detection across both tasks. On the other hand, in Experiment 3b, endogenous cues did not significantly reduce T1 error rates ($F < 1$) in any task, as shown by no reliable interaction between condition and task ($F < 1$), Figure 12C. This was perhaps due to the high overall performance.

The central prediction was that endogenous cueing would decrease illusory conjunction rates while increasing attentional blink error rates. For Experiment 3a, a repeated measures ANOVA was conducted with within participant factors of task (AB vs. IC) and condition (cue vs. no cue). There was no reliable effect of cue ($F < 1$, Figure 12B) and crucially, no interaction with task ($F < 1$), although the differences in the AB task were in the expected direction, with greater rates of AB task errors when endogenous cues were presented, as Figure 12B shows. The lack of consistent effects of endogenous cueing, especially on illusory conjunction scores, might have been due to ceiling effects (the error rate in the IC task was 47%). However, in Experiment 3b the same ANOVA analysis also revealed no reliable main effect of cue ($F(1,19) = 2.8$, $p = .111$), and no interaction between cue and task ($F(1,19) = 1.5$, $p = .242$, Figure 12D). Thus, current results did not corroborate the hypothesis of endogenous cueing effects on the temporal attention trade-off.

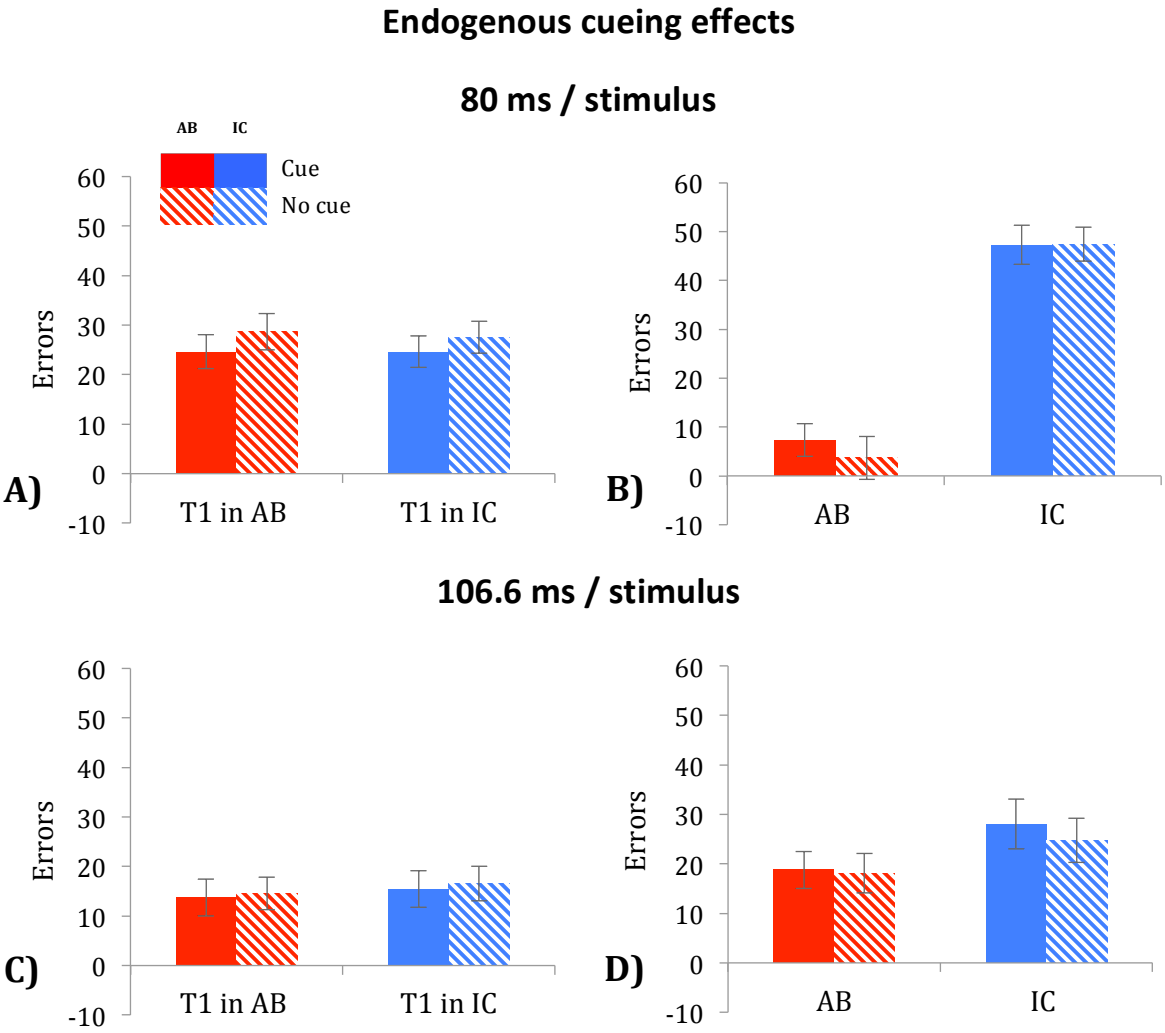

Figure 12. Effects of endogenous cueing to T1 on **(A)** T1 detection rates at 80 ms/stimulus; **(B)** AB and IC error rates at 80 ms/stimulus; **(C)** T1 detection rates at 106.6 ms/stimulus and **(D)** AB and IC error rates at 106.6 ms/stimulus.

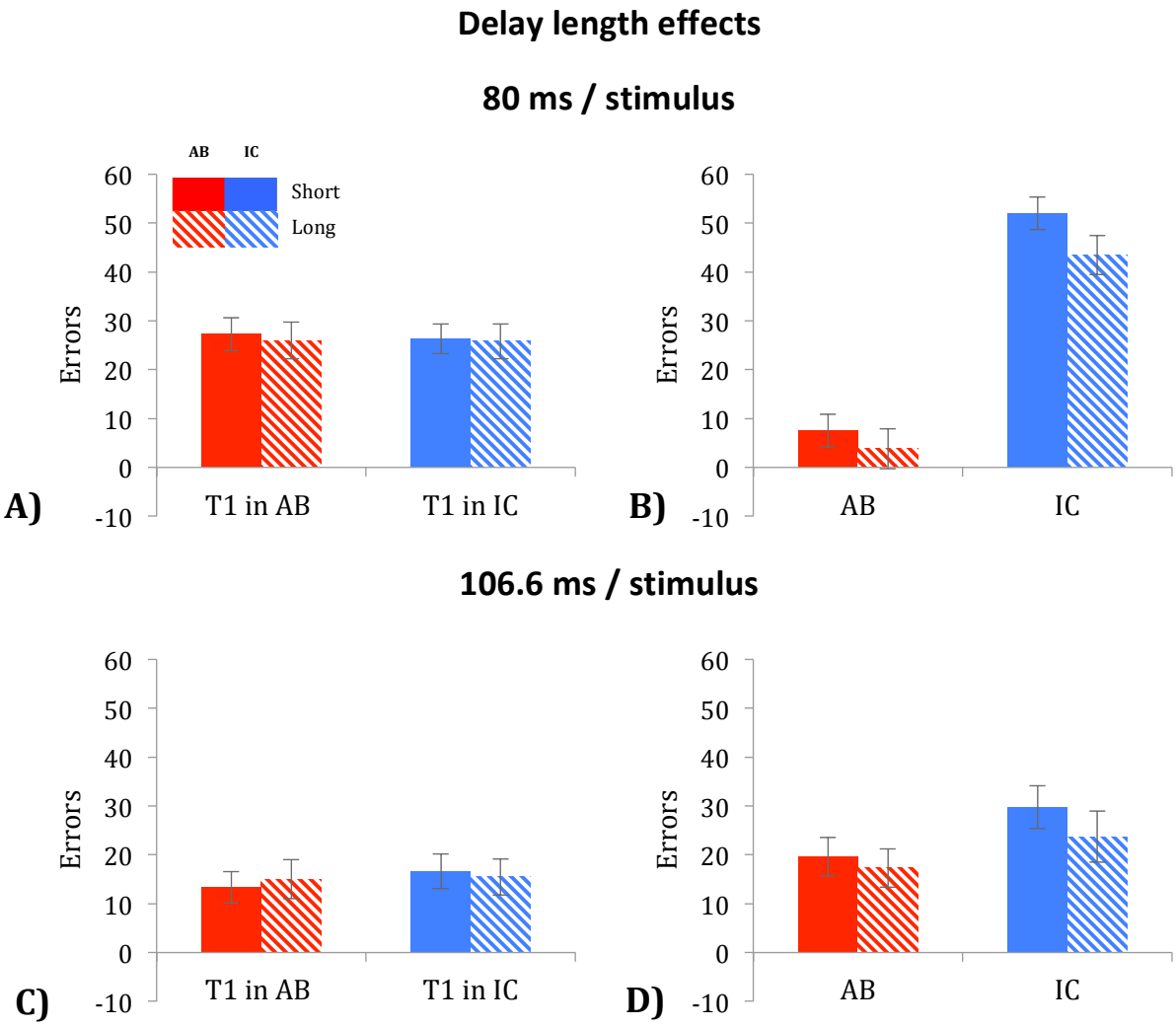

Figure 13. Effects of the length of delay to T1 on **(A)** T1 detection rates at 80 ms/stimulus; **(B)** AB and IC error rates at 80 ms/stimulus; **(C)** T1 detection rates at 106.6 ms/stimulus and **(D)** AB and IC error rates at 106.6 ms/stimulus.

A secondary prediction of Experiments 3a and 3b was that delay length (that is, whether T1 appeared early or late in the RSVP stream) would have dissociable effects on attentional blinks and illusory conjunctions. For consistency, we began by looking at the effects of delay length on T1 error rates, in Experiment 3a. A repeated measures ANOVA was conduced with within participant factors of task (AB vs. IC) and delay length (short vs. long) on T1 errors. There was no reliable effect of delay length (Figure 13A) and no interaction with task ($F < 1$). In Experiment 3b, an equivalent ANOVA also showed no reliable impact of delay length (short vs. long) on T1 detection rates ($F < 1$, Figure 13C), as well as no significant interaction between delay length and task ($F(1,19) = 2.4$, $p = .14$). These results were in contrast to findings from Experiment 1, which found that T1 was less accurately detected with long foreperiods.

To look at effects of delay length on attentional blinks and illusory conjunctions, a repeated measures ANOVA in Experiment 3a was conducted on effects of task (AB vs. IC) and delay (short vs. long) on task performance. There was a main effect of delay on error rates ($F(1,19) = 10.6$, $p = .004$) such that performance was better overall at long delays (23.7%) than short delays (29.8%), Figure 13B. The effect did not differ between the AB and the IC tasks, as revealed by the lack of a reliable interaction between delay length and task ($F(1,19) = 1.86$, $p > .1$). In Experiment 3b, a similar ANOVA showed that there was a significant effect of delay on task scores ($F(1,19) = 5.2$, $p = .034$) and again performance was better at long delays (20.5% error rates) than short delays (24.8% error rates) in terms of both attentional blinks and illusory conjunctions (Figure 13D), as revealed by the absence of a reliable interaction between delay length and task ($F(1,19) = 1.3$, $p = .27$). Collectively these results indicate that delay length had little effect on T1 detection rates, and correspondingly little impact on AB and IC errors, in contrast to Experiment 1, where T1 performance was reliably worse at longer delays and there were dissociable effects of delay on AB and IC errors.

Between-experiments comparison

As mentioned, we observed a striking difference in performance between Experiments 3a and 3b such that in the latter there were fewer illusory conjunctions but more attentional blinks. We conducted a further between-experiments comparison to look into these differences. The total sample of 40 participants was divided into two groups: the fast presentation group (80 ms/stimulus, Experiment 3a) and the slow presentation group (106.6 ms/stimulus, Experiment 3b). It should be noted that Experiment 3b also had two additional differences in design: fewer T1 positions (4 and 9, compared to 4, 5 and 8, 9 in Experiment 3a) as well as only ten experiment blocks instead of twelve.

To begin with, a mixed model ANOVA was conducted on mean T1 error rate, with a between participants factor of group (fast vs. slow) and the within participants factor of task (AB vs. IC). Overall, group had a significant effect on T1 accuracy ($F(1,38) = 5.9$, $p = .020$), while there was no reliable interaction between group and task ($F(1,38) = 1.2$, $p = .287$). There was better T1 detection at slower presentation rates in Experiment 3b (15.0% errors) compared to fast presentation rates in Experiment 3a (26.4% errors).

The effects of speed of presentation on AB and IC error rates were tested using a mixed model ANOVA with the between-participant factor of group (fast vs. slow) and the within participants factor of task (AB vs. IC). There was no significant effect of group ($F(1,19) = 1.1$, $p >. 1$), but there was a reliable interaction between task and group ($F(1,38) = 20.0$, $p < .001$). The interaction was further investigated using independent samples t-tests for each task separately. This confirmed significantly higher attentional blink rates at slower presentation rates in Experiment 3b (18.4%) compared to fast presentation rates in Experiment 3a (5.7%), $t(38) = -2.5$, $p = .016$. By contrast, illusory conjunction error rates were

lower with slow presentation (26.4%) than with fast presentation rates (47.4%, $t(38) = 3.6$, $p = .001$), thus confirming the reliability of the observed dissociation.

Discussion

In Experiment 3, we aimed to look into the effects of endogenous cueing on temporal attention trade-offs. To begin with, we expected to find a benefit to T1 accuracy, because previous research shows that top-down temporal orienting boosts target detection (Kingstone, 1992; Coull & Nobre, 1998; Correa et al., 2004; 2006b). Surprisingly, the prediction of a benefit was only supported in Experiment 3a and not 3b. Compared to previous studies in temporal orienting (e.g. Coull & Nobre, 1998), the current study used the AB-IC paradigm, which requires two target responses rather than detection of one single target. Furthermore, two different attentional states are necessary for the AB vs. IC tasks. Nevertheless, a difference in strategy between the two tasks cannot explain the lack of effects, because this would imply differences in T1 benefit by task, which was not seen in Experiment 3a. A more likely cause for the lack of an impact in Experiment 3b is the overall low rate of T1 detection errors, possibly reflecting floor effects.

Following the dissociable effects of exogenous cueing on the temporal attention trade-off reported in Experiment 2, it was expected that in Experiment 3 cues would also reduce illusory conjunction rates while increasing attentional blink frequency. Neither Experiment 3a nor Experiment 3b confirmed this prediction. For the attentional blink task, the idea of trade-offs predicted increased error rates when attention was cued to focus on T1 by making the onset time of T1 predictable. On the other hand a previous study found that when using a set, highly predictable foreperiod length to T1, attentional blink rates were reduced compared with a condition when foreperiod lengths were randomised (Badcock et al., 2013). A potential explanation for this contrast is that predictable foreperiods might in fact help participants strategically match their attentional

state to task requirements, whether these are to increase focus at the T1 timepoint or withhold focus at that timepoint.

An interpretation of these results is difficult because surprisingly we also did not observe any cueing benefit on illusory conjunctions. In spatial attention, focusing attention has been repeatedly shown to prevent illusory conjunctions (Treisman & Schmidt, 1982; Treisman & Paterson, 1984; Prinzmetal et al., 1986; Cohen & Ivry, 1989). In the temporal domain, Correa et al. (2006b) noted that orienting might only aid perceptual discrimination when a task is difficult enough. In Experiment 3a the IC task appeared to be rather difficult, but the very high error scores raised concerns about ceiling effects. Experiment 3b was therefore conducted with a slower presentation rate, to calibrate the difficulty in the IC task. Although IC performance was better at slower presentation rates, endogenous cues still did not yield any benefit to illusory conjunctions.

The second prediction of Experiment 3 was that delay would have dissociable effects on focused and distributed temporal attention. Findings from past research indicate that short delays benefit target detection (Woodrow, 1914; Zahn & Rosenthal, 1966; Coull & Nobre, 1998; Naccache et al., 2002), and Experiment 1 also found benefits to T1 detection at short foreperiods. However, Experiment 3 did not replicate this benefit. With regard to effects of delay length on the attentional trade-off, short delays were expected to reduce illusory conjunctions but increase attentional blinks, in line with a previous study showing more attentional blinks at short delays (Badcock et al., 2013). In Experiment 1 we had reported that short delays were detrimental in the AB task, but no consistent effect was observed in the IC task. In Experiment 3, we find that performance was better at long delays in both tasks, which is in line with expectations for the AB task but in contrast to predictions in the IC task. The discrepancy in results between Experiment 1 and the current study might be

caused by the fact that T1 onset was predictable here but random in Experiment 1.

Finally, even though not within the original aims of Experiment 3, we observed a striking dissociable effect on speed of presentation on AB and IC performance across Experiments 3a and 3b. At slower presentation rates, T1 detection and IC performance benefitted, at the expense of increased rates of AB errors. At face value, slower presentation should make a task less difficult, which better T1 detection appears to confirm. But in the case of the AB task, slower presentation appeared to increase the difficulty of distributing attention across RSVP timepoints. The dissociable effect supports the idea of trade-offs between focused and distributed attention as two distinct states with different characteristics. Experiment 4 was conducted in order to confirm the explorative findings in a controlled experimental setting.

Experiment 4: Effects of speed of presentation on the temporal attention trade-offs

Following the striking dissociable effects of presentation speed on attentional blinks and illusory conjunctions across Experiments 3a and 3b, we aimed to confirm the findings in Experiment 4 in a within-participants design. This was needed because the reported findings were exploratory, and Experiments 3a and 3b differed in other ways besides in the speed of presentation.

Method

Participants

Experiment 4 involved 20 participants from Oxford, both students and participants from the general population. The mean age was 26 years and the age range was 20 to 38. There were 6 males and 14 females. Participants were paid £12 for their time, because the experiment took longer than previous ones in this thesis.

Procedure

Experiment 4 used the AB-IC paradigm and followed the same general methods. Furthermore, it involved two conditions: A fast condition (80 ms/stimulus rate) and a slow condition (106.6 ms/stimulus rate). There were six blocks in each condition, randomly intermixed. The experiment lasted around one hour and a quarter.

Results

To begin with, effects of speed of presentation on T1 error rates were investigated. An ANOVA on mean T1 error rate, with within participant factors task (AB vs. IC) and presentation speed (fast vs. slow), revealed for the first time in the series of experiments in this thesis a main effect of task ($F(1,19) = 5.5$, $p = .031$), such that T1 detection was better in the IC task (12.4% errors) than the AB

task (15.5% errors). Speed of presentation did affect T1 detection, with better detection at slow presentation (9.3% errors, $F(1,19) = 58.2$, $p < .001$) compared to fast presentation rates (18.6% errors, Figure 14A), irrespective of task ($F(1,19) = 1.1$, $p > .1$) as the lack of an interaction showed.

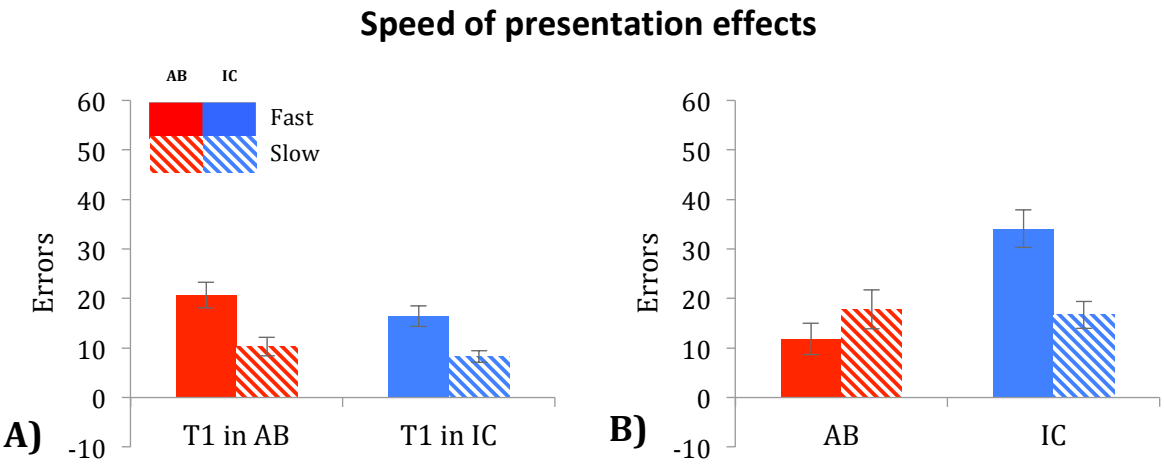

Figure 14. Effects of speed of presentation on **(A)** T1 detection rates across tasks and **(B)** AB and IC error scores.

The key prediction was that, in line with Experiments 3a and 3b, a slower speed of presentation would benefit IC performance while being detrimental to AB performance. An ANOVA revealed a marginal effect of task with lower AB error rates (14.8%, $F(1,19) = 4.2$, $p = .056$) compared to IC error rates (25.4%). Crucially, as predicted, presentation rate had a significant impact on task performance ($F(1,19) = 16.2$, $p = .001$) which reliably differed by task ($F(1,19) = 28.1$, $p < .001$). At follow-up, paired-samples t-tests revealed that slower presentation rates reduced illusory conjunctions errors significantly from 34.1% to 16.7% ($t(19) = 7.9$, $p < .001$), while on the other hand attentional blink errors were increased, albeit only marginally reliably, by slower presentation rates (17.8% errors compared to 11.8% errors at fast presentation ($t(19) = -2.0$, $p =$. 061, Figure 14B).

Discussion

In Experiment 4, we replicated the striking findings from Experiments 3a and 3b: A slower presentation rate improved T1 detection and IC task performance. On the other hand, despite the longer temporal interval between T1 and T2, attentional blink error rates were marginally increased by slower presentation.

At face value, slower presentation rates might be interpreted as a decrease in difficulty. Benefits to T1 detection appear to confirm this. However, the detrimental effects in the AB task are in opposition to previous results from experiments looking at difficulty. When T1 was more difficult to process, for example being a less frequent vocabulary word, or an inverted stimulus, attentional blink rates were increased (Botella et al., 2011; Martens et al., 2010; Burt et al., 2011). This was probably because more difficult T1 items required more focused attention to T1. Burt et al. argued that increased T1 detection difficulty led to depleted resources, leading to the missing of the T2 target by a limited-capacity processor. By contrast, the current findings provide an argument against the limited-capacity theory of the Attentional Blink (Raymond et al., 1992; Chun & Potter, 1995; Arnell & Jolicoeur, 1999), which would have predicted that a decrease in T1 processing difficulty would leave more free capacity and improve T2 processing. Alternatively, current results can be interpreted within the overinvestment theory of the Attentional Blink (Olivers & Nieuwenhuis, 2006), which proposes that too focused attention to T1 leads to missing T2. Throughout the series of experiments in this thesis, a fast presentation rate of 80 ms/stimulus consistently led to low performance in the IC task. Thus, a slower presentation rate might have allowed participants to adequately focus on T1. As a result, in attentional blink task blocks, attention might have focused on T1 more than was optimal for block specific requirements.

Finally, it is worth mentioning that there is a potential confound in the interpretation of these results. The slower presentation rate of 106.6

ms/stimulus fell within the alpha band of 8-12 Hz. There is accumulating evidence that cortical oscillations synchronise to the rhythm of presented stimuli (Muller et al., 1997) especially when stimuli are attended to (Muller & Hillyard, 2000). More relevant to the current study, Martens et al. (2006) found that blink rates were increased when alpha-band oscillations were entrained to presentation rhythm. What is more, when entrainment was high at the time of T1 (benefitting T1 processing through increasing T1 event-related visual potentials, Gruber et al., 2014), blinks were more likely to occur (Keil et al., 2006; Keil & Heim, 2009; Petro & Keil, 2015). This dissociation between an increased visual processing at the time of T1 and higher attentional blink rates is reflected in our findings. However, the potential involvement of entrainment in presentation rate results does not exclude the trade-off interpretation of our data. This is because in a previous study, when given a secondary task during an AB experiment, participants showed less entrainment and an improved blink performance (Wierda et al., 2010) in line with the overinvestment theory (Olivers & Nieuwenhuis, 2006). Thus, entrainment might in fact act to drive an attentional state that focuses on T1 in the detriment of T2 processing. Irrespective of how the brain implements the temporal attention trade-off, or indeed what circumstances shift the trade-off in one or the other direction, it is still the case that our findings of dissociable effects of speed of presentation on AB and IC scores lend support to the existence of trade-offs such as one attentional state is optimal in some circumstances, while another is optimal in different circumstances.

General Discussion

The experiments reported in this chapter investigated how manipulations known to help focus attention in time affect the trade-off in temporal attention within the AB-IC paradigm. The key hypothesis driving the research in Chapter 3 was that exogenously and endogenously orienting attention to T1 would increase attentional focus and thereby reduce illusory conjunctions while increasing rates of attentional blinks. Results showed that exogenous cueing had the expected effects on temporal attention, although individual task effects were not significant. On the other hand, endogenous cueing effects on the temporal attention trade-off were not confirmed. A secondary prediction was that short delays to T1 onset would benefit focused attention, while long delays would be better for distributed attention. Instead, it was found that long delays were best for both the AB and IC tasks. Finally, we observed a striking dissociation of effects of speed of presentation on attentional blinks and illusory conjunctions, which was replicated in a further experiment, lending additional support to the idea that attention trades off in time between focused and distributed modes.

Overall, Chapter 3 shows some evidence that the temporal attention trade-off can be manipulated through temporal orienting of attention towards a focused state, and the first line of support comes from exogenous cueing. In Experiment 2 we found a reliable dissociation of effects on attentional blink and illusory conjunction errors when exogenously cueing attention to T1 through framing T1 to increase its salience (after Handy et al., 1999; Prinzmetal et al., 2005; Weichselgartner & Sperling, 1987). The finding is consistent with previous findings of illusory conjunction reductions due to enhanced salience in spatial attention (Posner, 1980; Duncan & Humphreys, 1989; Treisman & Paterson, 1984) and target processing benefits in temporal attention (Weichselgartner & Sperling, 1987; Chua, 2005). While in Experiment 1 we found that colour and letter salience variations intrinsic to task design had the expected results on

temporal attention trade-offs, Experiment 2 extended this to show effects of experimentally manipulated salience. Together, Experiments 1 and 2 add to previous literature by showing that salience and exogenous orienting in time focus attention and reduce illusory conjunctions.

We sought additional evidence that orienting can affect the temporal attention trade-off through endogenous cueing. Surprisingly, no effect of cueing was found, even after slowing down the rate of stimulus presentation in order to avoid ceiling effects in IC task error rates. Top-down orienting using symbolic instructions has been known to focus attention and improve target processing in space (Posner, 1980). In temporal attention, when cues indicated the time of onset of a target (Kingstone, 1992; Coull & Nobre, 1998; Nobre, 2001; Naccache et al., 2002), benefits to target detection as well as difficult perceptual processing were observed (Correa et al., 2006b). However, no reductions in illusory conjunctions in time were observed in Experiment 3. Furthermore, we did not confirm any decrements in the AB task. Although the trade-off hypothesis predicted a negative impact on cues in the AB task, a previous study reported fewer attentional blinks at predictable foreperiods to T1 onset (Badcock et al., 2013), suggesting that in fact knowing the onset time of T1 might help participants deploy attention more strategically within the AB task. To further investigate the effects of endogenous orienting to T1 on the temporal attention trade-off while controlling for the potential confound of strategic deployment of attention, future studies can use a non-blocked design of the AB-IC paradigm, which will be introduced in Chapter 6.

An alternative potential explanation for the lack of any effect of endogenous cues is that orienting in time is very different to orienting in space in terms of its neural substrate (Nobre, 2010) because no single brain cell can code for a specific moment in time. Since temporal expectations might be instead coded through neural networks and brain oscillations (Nobre & O'Reilly, 2004; Karmarkar &

Buonomano, 2007; Buonomano & Maass, 2009; Oprisan & Buhusi, 2014), orienting might lead to task-unspecific brain readiness (e.g. Fischer et al., 2013) confounding any benefits in specific tasks such as the IC and AB tasks. In contrast to typical temporal orienting tasks where participants need to report one target (e.g. Coull & Nobre, 1998), the current tasks required a dual response and a strategic deployment of attention in time, making the requirements more specific and subject to confounds.

Unexpected support for the idea of trade-offs in temporal attention came from the dissociation of effects of speed of presentation on attentional blinks and illusory conjunctions. An exploratory analysis, further confirmed in a controlled experiment, revealed that slow presentation rates were favourable for reducing illusory conjunctions, while fast presentation rates were better for preventing attentional blinks. The striking finding supported the idea of trade-offs between focused and distributed attention in time suggesting that contexts that are optimal for a focused attention (slower presentation rates, at face value decreasing task difficulty) may not be optimal for a distributed attention. In order to test this dissociation further, in Chapter 4 we aim to look at effects of manipulations known to distract attention from T1 processing, and we predict a benefit to T2 detection along with an increase in illusory conjunction rates.

There is an alternative explanation for results presented in this Chapter, albeit not necessarily an explanation that is incompatible with trade-offs in attention states. Particularly, slower presentation rates might reduce illusory conjunctions by favouring an individuation of items in the RSVP, while at fast presentation rates the stream might be instead perceived as a single object, leading to conjunctions but also to distribution of attention across timepoints and processing of both targets. Indeed, exogenous cueing of attention to T1 by framing it might have resulted in the same individuation of the target, leading to fewer illusory conjunctions at the expense of T2 processing. The individuation vs.

single object explanation is not out of line with trade-offs. Instead, it might represent one of multiple mechanisms that dissociate a focused from a distributed attention in time.

One aspect to note with regard to results in the current chapter is the importance of strategies of deploying attention. Because the AB-IC paradigm presents the AB and IC tasks in separate blocks, participants can adapt their attentional state to each block's task demands. This might explain why exogenous cues only significantly improved T1 detection and only marginally improved conjunction rates in the IC task, where the effects of cues were in line with the strategy employed by participants. As has been previously shown in cuing experiments in spatial attention, exogenous orienting effects are strongest when in line with top-down goals (Theeuwes et al., 2000). In addition to cueing, delay effects might also relate to strategic attention: long delays might benefit both tasks because they give participants the opportunity to calibrate their attentional state to task demands. A further investigation of attentional trade-offs that controls for the confound of strategic deployment of attention will be conducted in Experiment 9, where, as mentioned, we employ a non-blocked version of the AB-IC paradigm.

A more immediate theme emerging from this current chapter is the need to continue investigating the effects of manipulations that help distribute attention in time. The combined results of Experiments 2-4 support the idea that trade-offs occur in temporal attention, such that any improvement in focused attention comes at the expense of decrements in distributed attention. For completeness, there is a need to investigate the reverse, with the prediction that manipulations that increase distraction and distribution of attention will reduce attentional blink rates while increasing illusory conjunction rates. Therefore, the aim of Chapter 4 will be to investigate effects of manipulations known to distribute or distract attention on the AB-IC paradigm.

Chapter 4

Distributed attention in time

Introduction

While it has long been believed that human performance is optimal when attention is focused (James, 1890), in the past years it has become increasingly acknowledged that people continuously balance the need to stay focused on a specific task with the need to keep monitoring their environment (e.g. Kurzban et al., 2013). In fact, it has been documented that when using visual information to make decisions, people alternate between periods when they only exploit a small number of visual samples and periods when they statistically sample more broadly (Summerfield et al., 2011). In spatial attention, focused attention is optimal in circumstances such as identifying the location of a specific target, but distributed attention is optimal in other circumstances such as perceiving the mean size of an array (Chong & Treisman, 2005a; 2005b). All these perspectives share a view of attention as being subject to a continuous trade-off. While much research has looked into how attention can focus in space and time and how people can perform well in one task, less is known about how the mind explores. Several lines of research have approached the subject from different perspectives, notably studying the phenomena of mind wandering, of dividing one's attention and of spatially distributing attention. Experiments in the current chapter will investigate distributed attention in time in relation to previously researched types of distributed attention.

Mind wandering

When not focused on a task, people are busy mind wandering (Antrobus, Singer, Goldstein & Fortgang, 1970; Smallwood & Schooler, 2006). Mind wandering is associated with activity in the default mode network of the brain (Mason et al., 2007; Buckner et al., 2008; Andrews-Hanna, Reidler, Huang & Buckner, 2010). Neuroimaging experiments have consistently observed that this brain network activates when a person is not engaged with an experimental task (Mazoyer et al., 2001). From this point of view, the default mode network is in contrast with networks that mediate a focused attention, such as the dorsal attention network (e.g. Corbetta et al., 2008). However, as Corbetta et al. (2008) explain, while both the ventral network and the default mode network deactivate during goal-directed behaviour, they do so in different ways. While the ventral network is active when reorienting and visually exploring one's environment, the default mode network does not activate during these periods and is distinct in terms of functional connectivity (Fox et al., 2006; Corbetta et al., 2008). When in the 'default mode' the mind does not freely explore its environment, but is mostly occupied with inner cognition (Kam & Handy, 2013; Schooler et al., 2011), wandering to past events and future plans (Baird et al., 2011; Smallwood et al., 2009; Smallwood & Andrews-Hanna, 2013). If the default mode network is involved in internally-driven cognition while the ventral network mediates reorientation and visual exploration, there may be a similarity between their roles, in that they both relate to foraging for information. If exploration of one's environment aims to gather information to guide future decisions, then perhaps people also gather information by foraging within their own memory stores.

Another indirect association between mind wandering and exploration may be related to LC tonic activity. On the one hand, tonic activity of LC noradrenergic neurons is believed to mediate exploration behaviours and distributed or distracted attention (Aston-Jones & Cohen, 2005), while a marker of this tonic LC-

Na activity is thought to be found in pupil dilation (Murphy et al., 2014). On the other hand, similar patterns of pupil dilation are also associated with periods of mind wandering (Smallwood et al., 2012).

Scientific interest in mind wandering and its relation to human performance has increased recently (Smallwood & Schooler, 2006) because psychologists have long been wary of studying phenomena that can only be subjectively reported. In fact, people report mind wandering in almost 50% of occasions when they are probed, and this occurs during the performance of daily activities as well as rest (Killingsworth & Gilbert, 2010). Generally, mind wandering or task-unrelated thinking is detrimental to performance in most tasks (Smallwood & Schooler, 2015). Mind wandering increases error rates and reaction time variability in the sustained attention to response task (Smallwood et al., 2004), as well as decreasing performance in working memory tests (Mrazek et al., 2012). If people mind wandered during an IQ test, their scores were lower (Mrazek et al., 2012) and this decrease correlated with earlier SAT exam scores. Moreover, a trait-like measure of mind wandering tendencies predicted distractibility in experimental tasks (Forster & Lavie, 2014). In our lab, it has been found that performance in a continuous attention task fluctuates in the order of minutes, and lapses are reflected in both neural correlates of alpha oscillatory activity and self-reports of mind wandering (Macdonald et al., 2011). Again, this highlights the detrimental effects of mind wandering, but it also suggests that mind wandering is intrinsically part of the way that cognitive performance fluctuates.

Although it is generally seen as detrimental to performance, mind wandering may also yield benefits (Smallwood & Andrews-Hanna, 2013; Mooneyham & Schooler, 2013). Task-unrelated thoughts may play a key role in future planning, since their content is generally targeted towards future events (Baird et al., 2011). Moreover, Baird et al. (2012) found that performance in tasks believed to measure creativity is improved after an undemanding task during which mind wandering occurred

most. Some other potential roles for mind wandering suggested by Mooneyham and Schooler (2013) but that are yet to be further investigated are dishabituation (e.g. because distributed practice is more effective than focused practice and the former may be served by mind wandering, Underwood & Ekstrand, 1967), relief from boredom and attentional cycling between multiple concurrent goals. Particularly, the idea of attentional cycling may relate to the findings with regard to attentional fluctuations (Macdonald et al., 2011). In terms of attention, a highly relevant recent finding is that self-reported mind wandering during a sustained attention task predicted smaller attentional blinks in an AB task (Thomson et al., 2015). Moreover, the same study reported that an increased tendency to mind wander in daily life, as reported through a questionnaire, was also negatively related to the size of the attentional blink. This was probably the first study to suggest that mind wandering could be beneficial for at least one attention task, the Attentional Blink, although the study did not actually measure levels of task unrelated thoughts during the Attentional Blink task. A similar finding has been reported by Olivers and Nieuwenhuis (2005; 2006) who found that asking participants to think about their holidays improved attentional blink task performance. Their theoretical interpretation was that the Attentional Blink is a task in which distributed temporal attention is optimal, rather than overfocused attention.

In Experiment 1 of the current thesis, we found preliminary evidence that mind wandering during the Attentional Blink – Illusory Conjunctions (AB-IC) paradigm relates in opposite ways to scores on the two tasks. Our findings suggested that mind wandering might improve AB but impair IC performance. In Experiments 1-4 we have shown that the Illusory Conjunctions task benefits from a temporally focused attention, and that a trade-off in temporally focused and distributed attention can be observed such that one mode is optimal in one of the tasks and vice versa. In Experiment 1, we measured mind wandering through a post-task questionnaire self-report. Although this type of measure is often used in the

literature (e.g. Smallwood et al., 2012), it comes with the drawback that people are limited in reflecting on their inner states and may forget how much they actually mind wandered (Schooler et al., 2005). Furthermore, the measure does not capture potential fluctuations in attentional state throughout the experiment, such as those observed by Macdonald et al. (2011). Thus, in Experiment 5 of the current chapter we used mind wandering probes (Kahneman et al., 2004; Smallwood & Schooler, 2006) throughout the experiment, in a similar line to Christoff et al. (2009), Macdonald et al. (2011) or Thomson et al. (2015).

Divided attention

One well-researched circumstance in which people distribute their attention is when doing several tasks at once. The performance of two concurrent tasks is a complex cognitive endeavor, involving both attention as well as working memory and task switching (Pashler & Johnston, 1998). Dual-tasking or divided attention refers to a wide range of tasks, for example searching for two object features in a visual display containing a number of visual objects (e.g. Corbetta et al., 1991), reporting when one's name is spoken in an auditory stream while listening to another stream in dichotic listening experiments (Colflesh & Conway, 2007) or performing two or more complex tasks simultaneously. Dual task paradigms are widely used both in order to assess patient abilities in neuropsychological research (e.g. Moscovitch, 1994) and to help understand more about the architecture of the human mind (Pashler & Johnston, 1998). It is worth noting that the relationship between divided attention in dual tasking and definitions of distributed attention is not clearly mapped. This is because dual tasking is cognitively complex and might involve both parallel processing and serial processing with switching between tasks (Pashler & Johnston, 1998). The degree to which two tasks can be processed in parallel was at first believed to depend on resource limitations (Kahneman, 1973), but is now held to depend on how much they rely on shared rather than separate cognitive mechanisms (Wickens, 1991).

Irrespective of the reasons why, it remains widely established that dual tasking typically causes performance decrements. This effect is often investigated in studies of the three components of working memory: the phonological loop, visuospatial sketchpad and central executive (Baddeley & Hitch, 1974; Baddeley, 1996). What is commonly found in working memory experiments is that if two tasks are both verbal and therefore draw on the phonological loop, interference is high. The same is the case if both tasks are visual. However, there is less interference between one visual and one verbal task, although some decrements in performance can be observed relative to individual task performance if both tasks rely on the coordination of the central executive. For these reasons, it is common for researchers to use dual task paradigms in which one task is verbal and one is visual. One example is a study by Miyake et al. (2000), which used a word generation task concurrently with a Maze Tracing Speed Test (Ekstrom, French, Harman & Dermen, 1976). The authors found that concurrent performance was worse than individual task performance. Further research by Lavie, Hirst, de Fockert and Viding (2004) showed that under conditions of dual tasking not only performance in the two tasks is decreased, but there is also an increased susceptibility to interference from distractors. These results put dual tasking in a negative light: performance is decreased, and distractibility increases.

But the findings of Olivers and Nieuwenhuis (2006) show that dual tasking is not always detrimental. The authors found that performing a secondary task concurrently with the Attentional Blink task reduced blink rates. In this case, the secondary task was a visual working memory task requiring the comparison of two visual patterns presented before and after each RSVP trial. The same reduction in blink rates was obtained when a secondary task requiring detection of a colour change in a moving dot was performed during an Attentional Blink experiment (Wierda et al., 2010; Taatgen et al., 2009). According to Olivers and Nieuwenhuis (2006), secondary tasks are distracting and prevent an overinvestment of attention to the processing of the first target, thus enabling

second target processing. Indeed, the same improvement was found in the Attentional Blink as a result of the presence of irrelevant visual stimuli alone, even if participants were not required to respond to these (Arend et al., 2006). Similarly, a benefit was found in an inattentional blindness paradigm in which blindness to change in a visual display was prevented by distraction (Pammer, Korrel & Bell, 2014). As such, the beneficial effect of dual tasking on the Attentional Blink might be either merely due to distraction, or due to a divided attention mode. Regardless, for the present purposes the key point is that a secondary task is repeatedly found to improve Attentional Blink performance.

The reduction in blink rates suggests that a secondary task induces a distributed attention mode, either through divided attention or through distraction. To ascertain that this is the case and that results are not simply due to perceptual artifacts, one needs to compare the effects of a secondary task upon two visually identical tasks that only differ in their instruction to focus or distribute attention in time. The AB-IC paradigm put forward in the current thesis provides a context to test this, which will be the aim of Experiment 6.

Distributed attention in space

While mind wandering and dual tasking offer examples of circumstances when a mind is not entirely focused on a task at hand, a distributed attention has been most commonly investigated in the domain of visuospatial attention. Although in this field the distinction between focused and distributed attention has been more clearly established, the ways in which distributed spatial attention is defined varies. One of the early dichotomies was between spatially local and spatially global attention. Navon (1977) devised a display in which a large letter was made of small letters, and participants were instructed to attend to either the local or the global letter. When the small and large letters were not congruent, there was a delay in response for both instructions. Subsequent experiments used both Navon letters and other types of similar stimuli such as Navon arrow

displays in which participants were asked to report the arrow directions (e.g. Han & Humphreys, 1999). In support of the dichotomy between attentional modes, it was found that pre-cueing participants with regard to the stimulus level to which they needed to attend accelerated their response to target (Robertson et al., 1993). Similarly, the global or local breath of attention in a previous trial benefitted or interfered with the current trial response if it remained the same or changed respectively (Ward, 1982). A global precedence bias was observed, such that global level stimuli created more interference with responding to local stimuli than the reverse (Hoffman, 1980; Miller, 1981; Pomerantz, 1983). Thus, Navon stimuli experiments not only supported the dichotomy of spatially local and global attention, but additionally there is a resemblance between the bias towards a global spatial attention and the default quality of the mind wandering state (Andrews-Hanna et al., 2010).

Local vs. global is not the only proposed dichotomy contrasting focused and distributed spatial attention. Treisman (2006) proposed a distinction between spatially focused attention which serves to bind object features into a single visual object and prevent illusory conjunctions (Treisman & Gelade, 1980; Treisman & Schmidt, 1982); and spatially distributed attention which can either refer to statistical processing of a visual display or to processing a visual whole rather than its parts. The dichotomy was investigated in a series of experiments (Chong & Treisman, 2005a; 2005b) contrasting a focused, local spatial attention that favoured perception of individual items and a broad, distributed spatial attention that favoured perception of statistical properties of the display. The idea that there are two attentional modes that people can be in was more recently supported by the work of Summerfield et al. (2011), who found that people sometimes make perceptual judgments based on statistical sampling while at other times based on the features of only several individual items.

In light of the dichotomy between spatially focused and distributed attention, it is interesting to consider how attention in space and time relate to each other. In terms of neural architecture, the spatial and temporal attention systems appear quite different, since there are neurons that code for spatial locations and enable spatially focused attention, but there are no time-interval specific neurons (Nobre, 2010). Moreover, Nieuwenhuis et al. (2007) argued that the locus coeruleus noradrenergic system might mediate temporally selective but not spatially selective attention. The LC-Na system shows a phasic, transient response to behaviourally relevant stimuli, suggesting a potential role in temporally selective attention (Usher et al., 1999; Berridge & Waterhouse, 2003; Aston-Jones & Cohen, 2005). However, Nieuwenhuis et al. (2007) found that pharmacological manipulation of noradrenaline levels did not have any effect on temporally distributed attention as measured through the Attentional Blink task, but slowed reaction time in a spatial visual search task. Despite the differences in neural correlates, behavioural associations between spatial and temporal selective attention may exist, for example as illustrated by findings that both types of selective attention are affected in children with dyslexia (Ruffino et al., 2014), although this might merely reflect the ability to stay on task.

While a shared mechanism behind focused attention in space and time remains uncertain, there is evidence of an association between distributed attention in space and time. The attentional blink, which has been proposed to reflect poor distributed attention in time (Olivers & Nieuwenhuis, 2006), is reduced when a broader spatial attention is induced. Studies found that attentional blinks were less frequent when participants concurrently had to detect a peripheral red dot (Taatgen et al., 2009; Wierda et al., 2010). Furthermore, there was a more rapid recovery from the attentional blink, in terms of the post-T1 lags at which it occurred, when attention was directed to the global rather than the local level of a Navon-like attentional blink stimulus (Crewther, Lawson & Crewther, 2007). On the other hand, the same experiment found that T1 identification also benefitted

from a global level of attention, so the benefit might have reflected a general improvement in performance. Also, Arend et al. (2006) observed that moving dots reduced the attentional blink whether their movement was inwards towards the RSVP or outwards, although an association between broad spatial and distributed attention might have predicted a specific benefit for outward movement. In terms of individual differences, a Navon global bias was negatively associated with attentional blink sizes, while a local bias was positively associated with occurrence of attentional blinks (Dale & Arnell, 2010).

To clarify these mixed findings, Experiment 7 investigates the effects of induced spatially local or spatially global attention on the temporal attention trade-off. The prediction is that asking participants to detect the direction of a Navon global arrow before a trial would reduce blink size and increase illusory conjunction rates, while the reverse would happen if response to a local Navon arrow is required.

Experiments 5-7

The experiments in Chapter 4 aimed to investigate how trade-offs between focused and distributed temporal attention were affected by broadening of attention. To achieve this, three types of attentional broadening were examined: distraction in the form of mind wandering, divided attention through the addition of a concurrent task, and spatially distributed attention. In Experiment 5 we hypothesized that intrinsic fluctuations in distraction, as measured through self-reported levels of mind wandering, would improve distributed temporal attention performance but disrupt focused attention. Experiment 6 hypothesized that dual tasking would broaden participants' cognitive state and improve distributed temporal attention but negatively impact focused attention. Finally, Experiment 7 hypothesized that inducing a spatially broad attention would be associated with a better distributed temporal attention but worse focused attention, and the reverse would happen if a spatially focused attention is induced.

Experiment 5: Mind wandering and temporal attention trade-offs

In the first experiment in this chapter, the hypothesis was that intrinsic distraction in the form of mind wandering would improve distributed attention in time but disrupt focused attention in time.

Method

Participants

Experiment 5 tested 18 participants from the University of Oxford student population. There were 3 males in the sample. The average age was 19 years (range 18 – 23 years). Participants were not colour blind by self report and had normal or corrected-to-normal vision. Participants were fluent in English and were not on any psychoactive medication at the time of the experiment. The study received ethical clearance from the University of Oxford Central University Research Ethics Committee. All participants received course credits for their participation.

Procedure

Experiment 5 used the Attentional Blink – Illusory Conjunctions (AB-IC) paradigm employed throughout the thesis. The same blocked design was used, with blocks of AB and IC instructions alternating in repeating XYYX order, counterbalanced between participants. Throughout the experiment, participants were asked to self-report their levels of mind wandering at the end of every fourth trial. The probe asked participants to rate what the content of their thoughts was during the past few trials on a continuous scale of 0 to 100, separately on two dimensions: on task vs. off task and aware vs. not aware of what they were thinking (cf. Christoff et al., 2009). The scales were presented orthogonally in a rectangular space with on/off task as the horizontal dimension and aware/unaware as the vertical dimension. Participants could rate their mind

wandering anywhere in the rectangular space with a mouse click (cf. Macdonald et al., 2011).

The experiment followed the same general procedure as previous experiments. Participants were instructed with regard to the task requirements. They were instructed that every few trials they will be asked to report whether their thoughts had been on task or not and whether they had been aware of their thought content or not. After 12 practice trials, the participants completed 12 blocks for a total of 432 trials, with the experimental session lasting approximately one hour.

Results

Descriptive statistics looked at how participants generally performed in Experiment 5. First, there was a high frequency of mind wandering. Across participants, the average rating of awareness of thought content was 53% and the average on-task rating was 55%. In terms of task performance, it was found that accuracy of T1 detection (i.e. reporting the identity of the first letter in the RSVP stream) did not differ reliably across the AB and IC tasks (14.8% error rate for both task, $t < 1$, $p > .1$). This result confirmed again the fact that the two tasks had similar basic demands.

The key prediction in Experiment 5 was that mind wandering would affect AB and IC performance differently, increasing illusory conjunction errors while reducing attentional blink errors. To test this prediction, we investigated the effect of self-rated mind wandering on attention. We looked at effects of both awareness and on-task ratings, because the two types of ratings were only weakly correlated. The mean of within-participants correlation coefficients was .20 (sd = .37), which was significant as shown by a t-test against zero ($t(17) = 2.32$, p = .033). However, because the correlation was only weak at .2, we continued the analyses separately for the two scores. To test the within-participants effects of

mind wandering on task performance, mind wandering scores were split into Low, Medium and High values using a tertiary split. The tertiary split was performed on both aware/unaware and on task/off task scores. We investigated how the level of mind wandering rated using these scores was related to performance on the four trials prior to the mind wandering probe.

First, the relationship between mind wandering and T1 detection rates was analysed in order to check whether the self-ratings captured variance in mental states. The expectation was that T1 error rates would increase with mind wandering, in line with previous research showing decrements in performance in various tasks (Smallwood & Schooler, 2015). Analyses were conducted for awareness and on/off-task ratings separately. To begin with, a repeated measures ANOVA was conducted on T1 error rate with within-participant factors of awareness level (Low, Medium, High) and type of task (AB vs. IC). As mentioned above, T1 detection did not differ by task. As predicted, there was a significant effect of awareness level ($F(2,34) = 9.9$, $p < .001$), with a reliable linear trend ($F(1,17) = 9.78$, $p = .006$) showing that T1 errors decreased with increasing awareness (Figure 15A). The effect did not differ significantly by task ($F(2,34) = 2.57$, $p = .091$). A similar ANOVA was conducted on on-task ratings, showing a main effect of on-task level ($F(2,34) = 14.69$, $p < .001$), with a reliable linear trend ($F(1,17) = 19.21$, $p < .001$), that did not differ significantly by task ($F(2,34) = 2.22$, $p = .124$, Figure 15C). T1 error rates decreased the more on-task participants were. The significant results are still reliable after correcting for multiple comparisons by using a p-value level of .025.

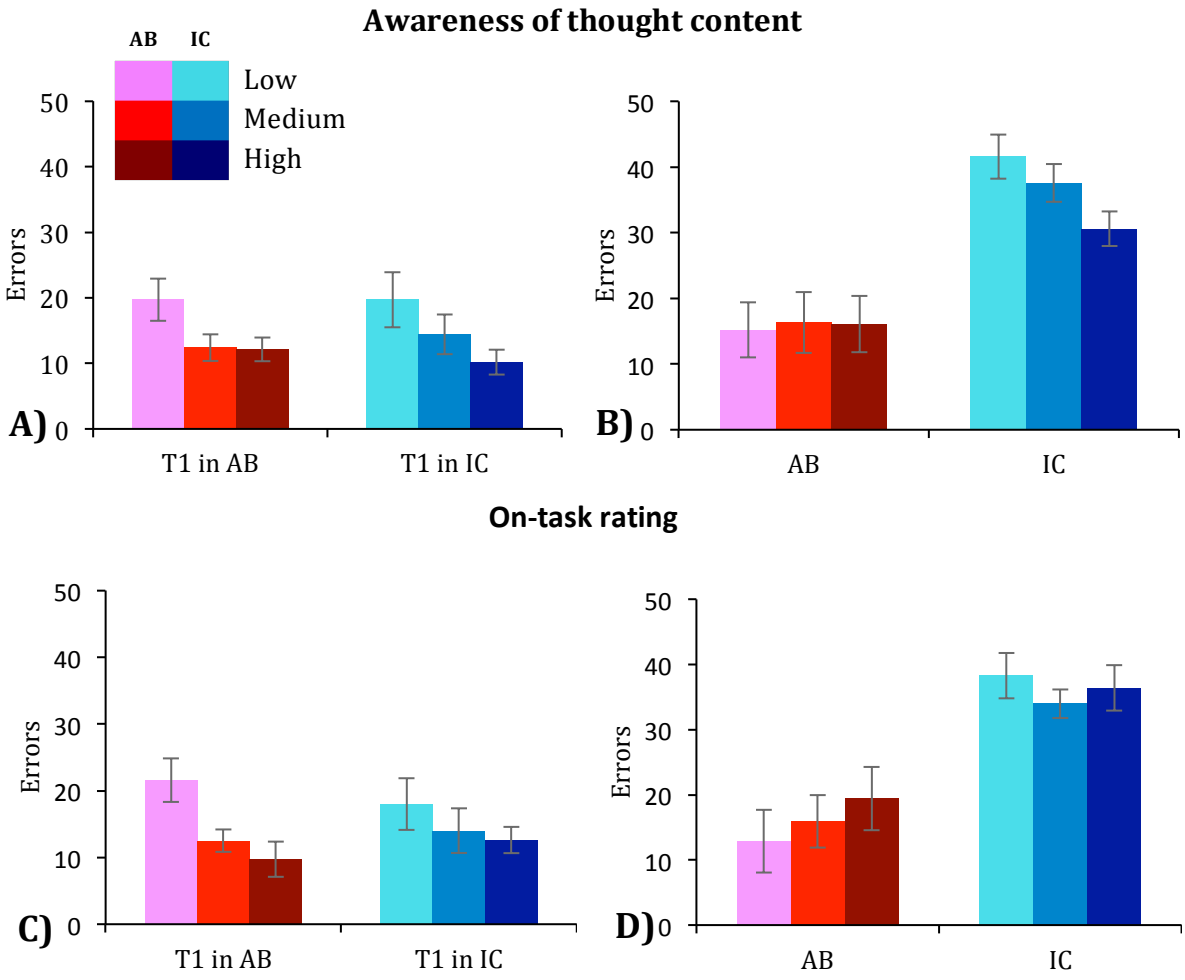

Figure 15. Differences in **(A)** T1 detection and **(B)** task performance according to self-rated awareness as well as on-taks/off-task ratings **(C-D).**

Having confirmed that mind wandering affects T1 detection rates, we considered the mind wandering self-ratings as a valid measurement of mental state and we proceeded with analysing their association with focused and distributed attention. As above, two separate analyses were conducted for each type of rating. First, a repeated measures ANOVA looked at the effect of awareness (Low, Medium, High) and task (AB vs. IC) on task error rates. We observed a main effect of task ($F(1,17) = 22.63$, $p < .001$), such that attentional blink error rates were at 15.9% while illusory conjunctions were more frequent at 36.6% errors.

Unexpectedly, there was a main effect of awareness level ($F(2,34) = 4.26$, $p = .022$) along with a significant effect and linear trend showing that task error rates significantly decreased overall with awareness (28.4% to 27.0% to 23.4%, $F(1,17) = 7.62$, $p = .013$). Additionally, in line with the prediction, there was a significant interaction of task and awareness level ($F(2,34) = 4.58$, $p = .017$, Figure 15B). In the case of the AB task, awareness did not have any reliable impact on error rates ($F < 1$, $p > .1$). On the other hand, awareness affected IC task scores ($F(2,34) = 12.41$, $p < .001$), with a reliable linear trend ($F(1,17) = 20.15$, $p < .001$). As shown in Figure 15B, IC error rates decreased with increasing awareness. Further, a repeated measures ANOVA was conducted on on-task rated level (Low, Medium, High) and task (AB vs. IC) looking at task error rates. The analysis revealed no main effect of being on-task ($F < 1$, $p > .1$) and no reliable interaction between mind wandering and task ($F(2,34) = 2.27$, $p = .119$, Figure 15D). Following the two comparisons, it is worth noting that the key results regarding the effects of awareness on task errors were reliable after controlling for multiple comparisons by using a threshold p-value level of .025.

The type of data collected allowed us to investigate between-participants associations between mind wandering and temporal attention, besides the within-participants contrasts described above. The between-participants analyses followed-up on results from Experiment 1, where we reported a trend for mind wandering to be associated in opposite ways to attentional blink rates and illusory conjunction rates. Because awareness and on-task ratings were only moderately correlated across participants ($r(18) = .57$, $p = .013$), analyses looked into how both these ratings correlated to temporal attention between participants. First, there was a marginal association of T1 errors and awareness of one's thoughts ($r(18) = -.44$, $p = .067$). There was no significant association between T1 errors and on-task ratings ($r(18) = -.37$, $p = .128$). Furthermore, there were no reliable correlations between either awareness or on-task ratings and AB

or IC errors (*ps* > .1). Thus, between-participants associations of task performance and mind wandering were not supported.

Finally, an additional set of analyses investigated whether the inclusion of mind wandering probes itself might have had an impact on task performance. To investigate this issue, we compared the results of the present experiment with those of Experiment 1, because all other studies in the thesis so far included experimental manipulations of attentional states that may confound results. To this end, we ran separate between-experiment comparisons (unpaired t-tests) on T1 detection rate, AB errors, and IC errors. There was a numerical trend for T1 accuracy to be increased for probed participants (15% vs. 19% T1 errors in Experiment 1, $t(65) = 1.64$, $p = .11$). Moreover, analyses revealed that illusory conjunctions were significantly reduced when participants were probed (36% vs. 47% in Experiment 1, $t(65) = -2.56$, $p = .01$) while attentional blinks were larger when probed, but not reliably so (16% vs. 13% in Experiment 1, $t < 1$, $p > .1$).

Discussion

Experiment 5 investigated the effects of spontaneous mind wandering on attentional blinks and illusory conjunctions. Mind wandering was self-rated in probes (cf. Kahneman et al., 2004; Smallwood et al., 2004; Smallwood & Schooler, 2006; Macdonald et al., 2011) once every four trials, on the dimensions of on task / off task and aware / unaware of thought contents (cf. Christoff et al., 2009). Mind wandering of both types occurred often in this experiment, as is the case in a wide range of daily activities and tasks (Killingsworth & Gillian, 2010). Ratings of mind wandering level of around 50% were in line with previous findings that mind wandering occurs around 50% of probed times (Smallwood al., 2004), although in the current case the rating did not directly refer to frequency.

The key finding of Experiment 5 was that mind wandering levels were differently associated with attentional blinks and illusory conjunctions respectively. Mind

wandering in the form of awareness of one's thought content was negatively associated with performance in the IC task but not the AB task. While mind wandering has been found to be detrimental to performance in a range of tasks including target detection tasks such as the Sustained Attention to Response Task (Smallwood et al., 2004; Macdonald et al., 2011), it may appear counterintuitive that this was not the case for the AB task. However, it has been previously reported that a task-irrelevant mental activity such as free associations on a theme was beneficial to the Attentional Blink task (Olivers & Nieuwenhuis, 2005). Similarly, attentional blink rates were reduced when participants were instructed to focus less on the task (Olivers & Nieuwenhuis, 2006). Moreover, self-reported mind wandering during a sustained attention task predicted smaller attentional blinks (Thomson et al., 2015). This experiment was the first to probe mind wandering during both the AB task and the visually-equivalent IC task. The dissociation of effects is important to highlight that temporal attention trades off between focused and distributed modes and that this trade-off is associated with spontaneously-occurring mind wandering.

Experiment 5 asked participants to self-rate their mind wandering both in terms of on-task or off-task thinking as well as with regard to how aware they were of the contents of their thoughts. Only self-ratings of awareness of though content were found to be significantly associated with performance in the AB and IC tasks. This importance of awareness of task content has been previously highlighted (Smallwood & Schooler, 2006). For example, it was found that periods of mind wandering without awareness were worst for response inhibition (Smallwood, McSpadden & Schooler, 2007). On the other hand, Christoff et al. (2009) did not find any difference between off-task aware and unaware periods. Future experiments can use the AB-IC paradigm to further investigate the difference between being on task and being aware, for example by looking at the neural correlates of being on task and being aware during the AB and IC tasks comparatively.

Finally, an additional analysis revealed that T1 detection was better in the current experiment compared to Experiment 1. Although the between-experiments comparison is not conclusive, it raises interesting questions regarding the role of probes in affecting attentional states. On the one hand, the probes gave the participants a short break from the task, which is known to benefit sustained attention (Ariga & Lleras, 2011; Ross, Russell & Helton, 2014; Helton & Russell, 2015). On the other hand, probing mind wandering also leads to less task unrelated thinking and thus more focusing (Seli, Carriere, Levene & Smilek, 2013; Schooler, 2002), thus the performance improvements could plausibly reflect a combined consequence of these factors. Further investigations could look into this effect by comparing blocks during which participants are probed and blocks during which they are not.

Experiment 6: Dual tasking and temporal attention trade-offs

Following the differing associations between mind wandering and focused vs. distributed attention state, the relationship between other types of attentional broadening and the temporal attention trade-off were examined. To this end, Experiment 6 tested the prediction that dual tasking would improve performance in the Attentional Blink task but increase illusory conjunctions. To test this prediction, the AB-IC paradigm was combined with a visual working memory task. The same task was previously used by Olivers and Nieuwenhuis (2006) in combination with the AB task, and was found to reduce attentional blink rates compared to when the AB task was performed by itself. In Experiment 6 we expected to replicate this result. Additionally, Experiment 6 also looked at the effects of a secondary task on IC task performance, predicting that illusory conjunctions would increase in the dual task condition.

Method

Participants

For Experiment 6, a sample of 20 participants from both student and non-student populations in Oxford were recruited, of whom 6 were male. Their mean age was 25 years with an age range of 19 to 40 years. None of the participants were colour blind and they all had normal or corrected-to-normal vision, and none were taking any psychoactive medication at the time of the study. All participants were fluent in English. Ethical clearance was obtained from the University of Oxford Central University Research Ethics Committee. Participants received course credits or £8 for their participation.

Procedure

Experiment 6 used the same blocked design of AB and IC instructions in repeating XYYX order, counterbalanced between participants. There were two conditions, which were intermixed within blocks in short sequences of trials. In the experimental condition, participants were asked to perform a secondary task in which they were presented with visual patterns at the end of each trial and they responded to indicate whenever the presented pattern matched the one shown on the previous trial (Figure 16; cf. Olivers & Nieuwenhuis, 2006). In the control condition, they were presented with the same visual stimuli but with no associated memory task, being instructed to ignore the visual patterns. Conditions were presented in sequences of six trials, which were randomly ordered with the constraint that 3 sequences of each condition appeared in each block. Participants were instructed before each sequence whether they were required to respond to visual stimuli or ignore them. One pattern was shown in each inter-trial interval, such that the probe pattern appearing at the end of trial *N* became the comparison pattern for the probe presented at the end of trial *N+1*. Patterns were made of three lines intersecting on the screen, and a minimum

length of lines was set in order to avoid the pattern being too discriminable. Half of the patterns matched the one presented in the previous inter-trial interval, requiring a mouse-click response; half of the patterns differed in one of the two lines, requiring withholding any response. Correct or incorrect responding or withholding response to visual stimuli in the secondary task was recorded, along with reaction time in trials when participants responded.

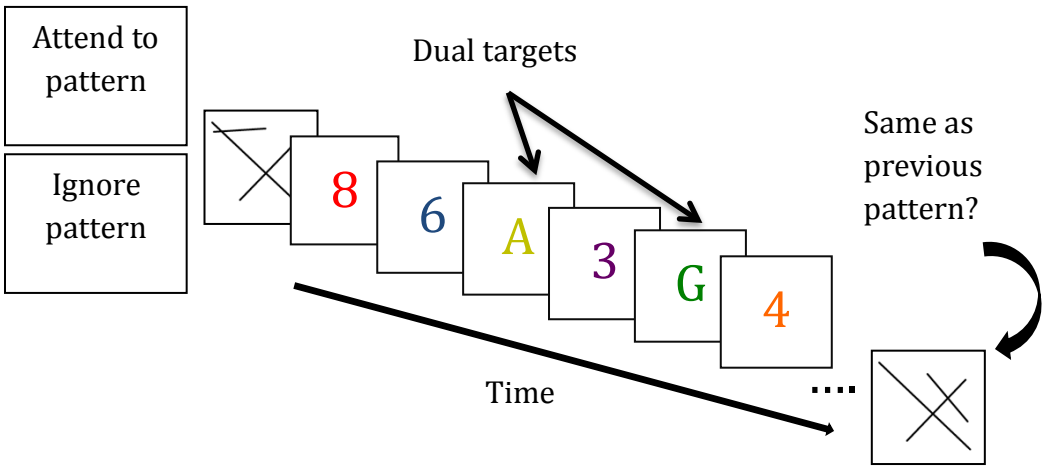

Figure 16. An example AB trial in the dual tasking condition of Experiment 6.

Experiment 6 followed the same procedure as previous experiments. Participants were instructed with regard to the requirements of the AB and IC tasks and the requirements of the working memory task. Participants were not instructed to speed their responses to patterns. Before the experimental blocks, participants performed 12 practice trials: one sequence of 6 trials for each condition, in a randomised order. The total experiment time was one hour.

Results

Experiment 6 showed again that T1 detection rates did not differ reliably between the AB (25.8% errors) and IC trials (25.7% errors, $t < 1$, $p > .1$; see Figure 17A). Because T1 accuracy was well-matched across the two tasks, we were able to investigate effects of the secondary task on T1 accuracy as a baseline validation of the distracting role of the secondary task. To achieve this, we only took the trials where participants respected the condition instruction, i.e. they accurately responded to patterns in the experimental condition (81.6% of experimental trials), and successfully withheld responses to patterns in the control condition (96.6% of control trials). Thus, comparing accurate experimental and accurate control conditions, we found a strong decline in T1 accuracy when participants performed a secondary task, from 27% error rate when successfully ignoring the secondary task to 39% errors when successfully responding ($F(1, 19) = 67.5$, $p < .001$, Figure 17A) and, as expected, this effect did not differ between the AB and IC task ($F < 1$, $p > .1$). On the other hand, when looking at all experimental trials in comparison to all control trials, irrespectively of accuracy, no effect of condition was present ($F(1,19) = 2.62$, $p > .1$).

The central hypothesis of Experiment 6 was that dual tasking would improve distributed attention but disrupt focused attention. Since the T1 results had established that the manipulation only worked for trials in which performance in the secondary task was accurate or the visual pattern was successfully ignored, we compared only those trials. A repeated measures ANOVA was conducted, looking at the effects of a secondary task on AB and IC performance. Surprisingly, there was an unexpected main effect of condition ($F(1,19) = 10.23$, $p = .005$), revealing fewer errors in the experimental (dual-task) condition compared to the control condition. As Figure 17B below indicates, however, there was a trend interaction ($F(1,19) = 3.87$, $p = .064$) of task and condition, in line with our expectations. Separate analyses by task revealed that the size of the attentional

blink was reduced when attending to the secondary task ($t(19) = -2.85$, $p = .010$). In fact, there was actually a negative attentional blink size (Figure 17B) in the experimental condition compared to the control condition. Participants were better at detecting the lag 2 T2 than the lag 6 T2 item in the experimental condition, although this was not significant in a t-test against zero ($t(19) = -1.26$, $p > .1$). On the other hand, illusory conjunctions were not reliably affected by a secondary task ($t(19) = -1.12$, $p > .1$). As we expected, none of these results were present when looking at all trials in which participants were asked to attend to or ignore a visual pattern, irrespective of their accuracy in respecting instruction (*ps* > .1).

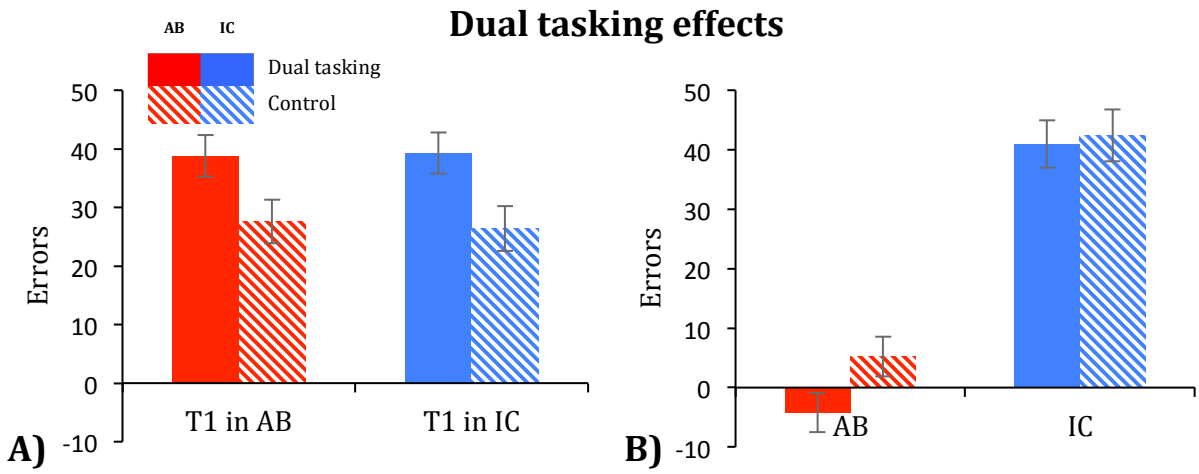

Figure 17. Effects of successful dual tasking vs. control on **(A)** T1 detection in AB and IC tasks and **(B)** AB and IC scores.

Finally, an interesting observation was that participants in this experiment seemed to be rather unfocused throughout, as reflected in their high T1 error rates of 27% across both tasks when the visual patterns were successfully ignored in the control condition. A mixed model ANOVA comparing T1 error rates

between experiments and across tasks revealed that the error rates in this experiment were significantly higher than in Experiment 1 ($F(1,67) = 7.19$, $p = .009$). The effect did not differ by task ($F < 1$, $p > .1$). Although this is a comparison between experiments and therefore not conclusive, it highlights that both here and in Experiment 5 the task context may have affected participants' attentional states in addition to the experimental manipulations.

Discussion

In Experiment 6 we investigated the effects of dual tasking on AB and IC performance. Because T1 detection rates were lower in the experimental condition, we concluded that the secondary task manipulation was valid and fulfilled its role of interfering with attention (Miyake et al., 2000), but only when participants followed the instructions to attend to or to ignore the visual patterns. Interestingly, this negative effect of additional task load on T1 accuracy was not previously observed by Olivers and Nieuwenhuis (2006) who used the same working memory task. It is worth noting that in the current study participants appeared less focused on T1 than in Experiment 1, perhaps because the presence of visual patterns itself distracted participants. Similarly, Experiment 5 probed mind wandering and revealed higher T1 detection rates than Experiment 1, perhaps because participants were more self-conscious about their level of mind wandering. Of relevance to current results, it has been previously reported that even irrelevant secondary tasks cause decrements in performance, which also reflects in different neural activity compared to instances when only a primary task is performed (Rees et al., 1997). In light of this, future experiments can investigate the effects of a concurrent working memory task in comparison with a control condition that does not involve the display of any visual stimuli.

Nevertheless, there was some evidence that dual tasking affected focused and distributed attention in different ways. This was revealed through a marginal interaction between task and condition. To begin with, the marked decrease in

attentional blink size in the dual tasking condition was in line with previous findings (Olivers & Nieuwenhuis, 2006; Wierda et al., 2010; Taatgen et al., 2009) and supported the overinvestment hypothesis of the Attentional Blink (Olivers & Nieuwenhuis, 2006). By contrast, the lack of a detrimental effect on IC performance was surprising. Previous research suggests that dual tasking decreases performance (Miyake et al., 2000; Baddeley, 1996; Wickens, 1991; Lavie et al., 2004), and distraction has also been shown to increase illusory conjunctions in the spatial domain (Treisman & Schmidt, 1982; Treisman & Paterson, 1984), thus we would have expected illusory conjunctions to be more frequent in the experimental condition, which they were not. Despite this, current results highlighted again the fact that a focused mental state is not always optimal, but sometimes distributing one's attention between several tasks is an advantage, for example in tasks such as the Attentional Blink.

Experiment 7: Spatial attention scope and temporal attention trade-offs

Having looked at how mind wandering and dual tasking relate to the temporal attention trade-off, the next experiment in the series investigated the relationship between spatial and temporal attention trade-offs. This relationship is unclear, according to previous research. On the one hand, a bias towards global Navon shapes was associated with better Attentional Blink performance, and a local bias with the reverse (Dale & Arnell, 2010). Moreover, directing attention to the global Navon stimuli improved attentional blink performance (Crewther et al., 2007), and the same was the case when participants had to detect a concurrent peripheral red dot (Taatgen et al., 2009; Wierda et al., 2010). However, the same improvement was found when concurrent dots moved outwards (encouraging spatially distributed attention) as well as inwards (Arend et al., 2006), potentially suggesting that the association was merely due to effects of distraction. These findings can be further clarified by comparing the effects of directing spatial attention locally or globally on both focused and distributed temporal attention tasks, comparatively. To achieve this, the current experiment looked at how directing attention to local and global Navon stimuli (Navon, 1977) affected focused vs. distributed temporal attention within the AB-IC paradigm. We presented Navon stimuli before each trial, asking participants to direct attention to either the local or global level. The method involved dual tasking in the sense that during each AB-IC block participants had to concurrently perform the Navon task, although no information had to be retained during AB-IC task performance. The rationale behind the design was that participants would carry the attentional scope induced during the Navon task over to the AB-IC trial, due to task-set inertia, a phenomenon by which a current task set including attention state is preserved throughout the subsequent task, even if the task set is detrimental to it (Yeung & Monsell, 2003; Allport, Styles & Hsieh, 1994).

Method

Participants

Experiment 7 tested 17 participants from the student and general populations in Oxford, of whom 7 were male. Their mean age was 24 years, and the age range was 19 to 35. Participants were not colour blind and their vision was either normal or corrected-to-normal. None were taking psychoactive medication at the time, and all were fluent in English. The experiment obtained ethical clearance from the University of Oxford Central University Research Ethics Committee. Participants received course credits or £8 for their participation.

Procedure

In Experiment 7, we presented participants with the blocked AB-IC paradigm, with the same counterbalanced order as in previous experiments. This experiment had two conditions, asking participants to attend to the direction of either the local or the global Navon arrows presented before each AB-IC trial. A global Navon arrow consisted of six small arrows all pointing in the same direction (right or left), which formed a larger arrow pointing in either the same direction or the opposite direction to the small ones. The arrows were arranged on the screen such that one of them was in the center of the screen. Trials randomly alternated between the two conditions (local vs. global) in sequences of six, with the possibility of repeat sequences and the constraint that each block contained equal numbers of trials of each condition. In each sequence of six, there were three congruent trials (directions of local and global arrows were the same) and three incongruent trials (directions of local and global arrows were different), randomly distributed. Navon task responses were always required on each trial, and participants responded with a mouse click on the right button if the arrow pointed right, or a left button in the arrow pointed left. Both accuracy and reaction time of responding to the arrow direction were recorded.

Experiment 7 followed the same general procedure as previous experiments. Participants were instructed with regard to the requirements of the AB and IC tasks and the Navon task. During the Navon task, an instruction at the top of the screen told participants 'Small arrow: click corresponding button' or 'Large arrow: click corresponding button'. Participants were not instructed to speed their responses to these stimuli. Before the experiment began, there were 12 practice trials with equal numbers of trials in each condition. The total experiment time was approximately one hour.

Results

Experiment 7 confirmed once again that the AB and IC tasks were similar in their basic demands, since T1 accuracy was comparable across the tasks (18.9% and 18.7% errors, $t < 1$ $p > .1$).

To investigate the effects of condition on general accuracy levels, a repeated measures ANOVA was conducted on T1 detection error rates, with task (AB vs. IC), condition (whether participants had been asked to report global vs. local Navon arrow directions before trial began) and congruency (whether the direction of the global and local arrows in the display was the same) as within participant factors. The analysis only included AB-IC trials that followed an accurately reported Navon arrow direction (99.9% of trials). There were no main effects of task, condition or congruency (*ps* > .1). There was a marginal interaction of condition and congruency ($F(1,16) = 3.54$, $p = .078$), but none of the other interactions were reliable (*ps* > .1). Following up on the marginal interaction, further analyses were conducted separately for congruent trials and incongruent trials. First, a repeated measures ANOVA looked at effects of task (AB vs. IC) and condition (global vs. local) on T1 detection rates, for congruent trials only. There was a main effect of condition ($F(1,16) = 4.78$, $p = .044$), while there was no effect of task and no interaction (*ps* > .1). Across both tasks, T1 detection rates were better in congruent global trials (17.1% errors) compared to congruent local

trials (19.3% errors), Figure 18A. On the other hand, a similar ANOVA conducted on incongruent trials showed no effects of condition or task and no interaction (*ps* > .1), Figure 18C.

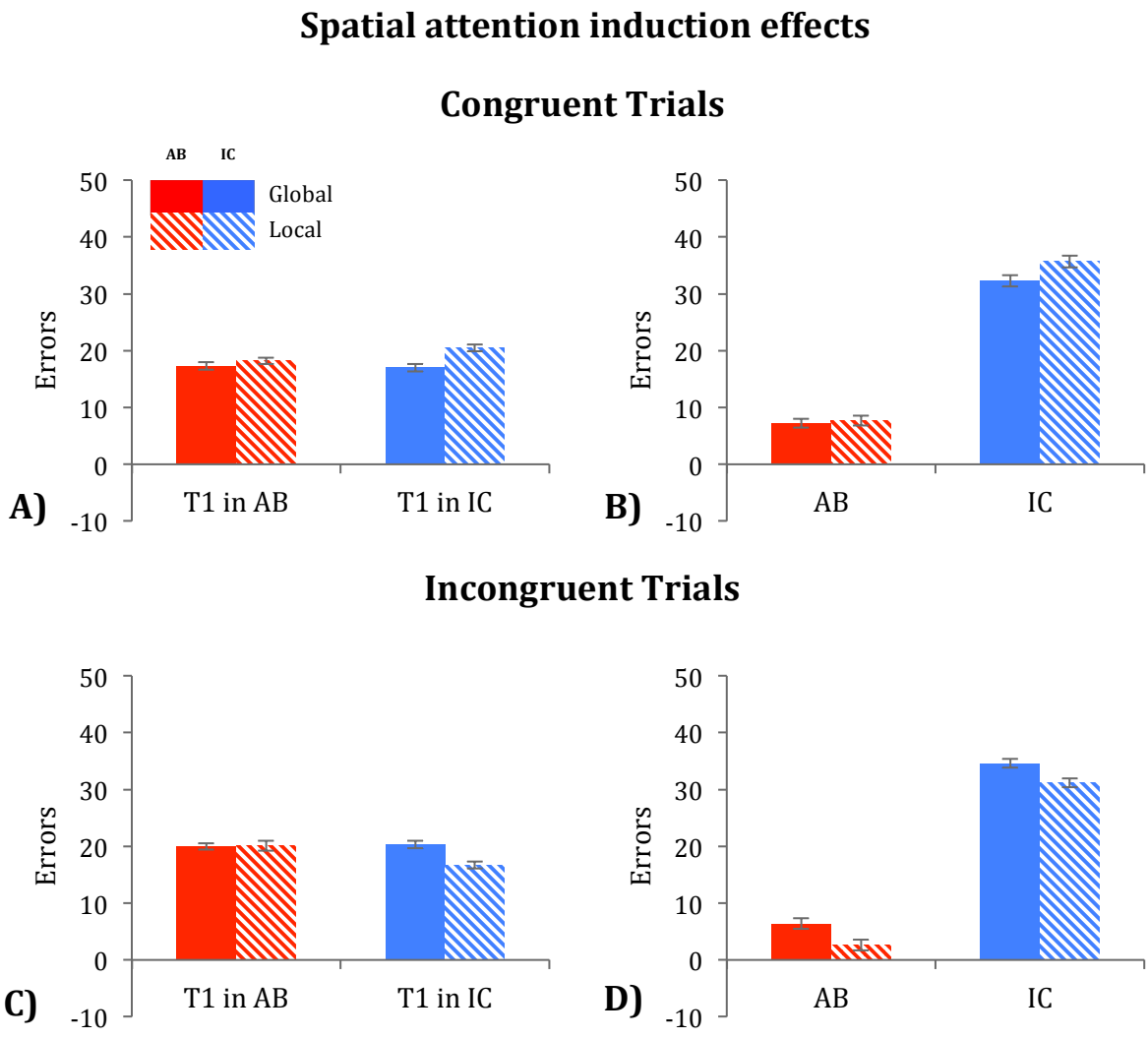

Figure 18. Effects of spatial attention scope induction in congruent trials on **(A)** T1 detection and **(B)** AB and IC scores, as well as in incongruent trials on **(C)** T1 detection and **(D)** AB and IC scores.

The key analysis in Experiment 7 looked at whether inducing a spatially local vs. global attention affected attentional blinks and illusory conjunctions differently. A repeated measures ANOVA was performed on mean error rates with within-participants factors of task (AB vs. IC), spatial focus (local vs. global) and congruency (congruent vs. incongruent trials) on error rates in AB and IC tasks. Again, only trials that followed accurate reports of arrow direction were analysed. There was a main effect of task, with attentional blink error rates of 6% and illusory conjunction rates of 33.4% ($F(1,16) = 36.89$, $p < .001$). Neither condition nor congruency had any significant effect ($ps > .1$). The relevant interaction between task and condition was not reliable ($F < 1$, $p > .1$), suggesting that the induced local or global spatial attention modes had no dissociable effects on attentional blinks and illusory conjunctions. There was an interaction trend between condition and congruency ($F(1,16) = 3.42$, $p = .083$), but again this did not differ by task ($F < 1$, $p > .1$). None of the other interactions were significant ($ps > .1$).

The reported trend interaction between condition and congruency was further analysed by conducting repeated measures ANOVAs on error rates separately for congruent and incongruent trials, with within participant factors of task (AB vs. IC) and spatial focus (local vs. global). When looking at congruent trials only, Figure XB shows that the sign of the difference was for fewer errors to follow after global Navon stimuli (19.7% errors) compared to local Navon stimuli (21.7%) but the effect of condition was not significant, and there was no reliable interaction with task ($t < 1$, $ps > .1$), Figure 18B. Following incongruent Navon stimuli, there was a numerical trend for error rates to be lower after local Navon stimuli (16.9%) compared to global Navon stimuli (20.5%), as reflected in Figure 18D. But the effect was not reliable ($F(1,16) = 2.34$, $p = .146$), and the interaction with task was not significant either ($F < 1$, $p > .1$). Thus, analyses that followed up on the trend interaction of condition and congruency did not reveal any

significant effects on task performance, in contrast with similar analyses reported above regarding T1 accuracy.

For Experiments 5 and 6, we conducted analyses of T1 detection rates in comparison to those in Experiment 1 and found better performance in Experiment 5 but decreased performance in Experiment 6. However, in Experiment 7 T1 detection accuracy did not differ reliably from Experiment 1 (18.8% vs. 18.9% errors, respectively, $t < 1$, $p > .1$).

Discussion

Experiment 7 explored associations between spatial and temporal attention trade-offs by assessing how a manipulation inducing local vs. global spatial attention affected AB and IC performance. The key dissociation of effects of the two conditions on temporal attention modes was not observed in this experiment. In comparison, researchers have previously reported a relation between people's tendency to attend to Navon global stimuli and smaller attentional blinks (Dale & Arnell, 2010). While the association reported in this earlier study related to individual differences, another study that used experimental manipulations also found a relationship between global attention and distributed attention in space. Inducing global attention reduced attentional blinks compared to inducing a locally-focused spatial attention (Crewther et al., 2007). In this study, Attentional Blink stimuli were Navon stimuli and instructions were to attend to the global or local level of targets. By contrast, the current experiment used a different design and induced attentional sets by presenting a Navon task prior to each AB-IC trial. The rationale was that this would influence performance on AB and IC tasks because of the occurrence of task-set inertia (Yeung & Monsell, 2003; Allport et al., 1994). However, Yeung and Monsell (2003) reported that endogenous preparation of task set may reduce task-set inertia. Experiment 7 used a blocked design of the AB-IC paradigm, which might have enabled participants to endogenously prepare for the AB and IC task

sets, thus eliminating effects of the induced spatial attention scope. To further investigate this, future experiments might use a non-blocked design of the AB-IC paradigm, which will be introduced in Chapter 6.

A further observation is that T1 detection was better following global congruent Navon stimuli compared to local congruent stimuli. Similarly, Crewther et al. (2007) found that T1 detection was improved when a global level of attention was induced. This finding is contrary to the hypothesis that inductions of global attention would benefit distributed attention in time, because benefits to T1 detection are expected to occur when attention becomes more focused. This calls into question whether the global Navon stimuli had the intended effect of inducing a spatially broad attention. It is relevant to note that the reliability of Navon tasks and its relation to other global–local tasks is unclear (Dale & Arnell, 2013a), suggesting the need for future studies that into the relationship between spatial and temporal attention modes using tasks other than the Navon task.

General Discussion

The three experiments reported in this chapter investigated how distributed attention of three types (mind wandering, divided attention and spatially distributed attention) impacted the temporal attention trade-off between focused and distributed modes.

Irrelevant mental activity affects the temporal attention trade-off

In Experiments 5 and 6 it was found that irrelevant mental activity had dissociable effects on attentional blinks and illusory conjunctions, thus affecting the temporal attention trade-off. The effect was present irrespective of whether the irrelevant mental activity was spontaneously occurring as in the case of mind wandering (Experiment 5) or experimentally induced as in the case of a secondary concurrent task, although in this latter case the interaction effect was only marginal (Experiment 6). The fact that both of these had similar effects on the temporal attention trade-off is interesting, because there are both common characteristics as differences between spontaneous task-unrelated mental activity and dual tasking. A key similarity is that both mind wandering and dual tasking have long been believed to be detrimental to performance in tasks requiring attention and working memory (mind wandering: Smallwood et al., 2004; McVay & Kane, 2011; Smallwood & Schooler, 2006; Macdonald, et al. 2011; dual tasking: Miyake et al., 2000; Baddeley, 1996; Wickens, 1991; Lavie et al., 2004). More recently, it has been suggested that both could be beneficial in the particular context of the Attentional Blink task: Several dual tasking experiments revealed benefits in reducing attentional blinks (Olivers & Nieuwenhuis, 2006; Wierda et al., 2010; Taatgen et al., 2009), and mind wandering during a SART task predicted fewer attentional blinks subsequently (Thomson et al., 2015). The key contribution of Experiments 5 and 6 was in extending such findings to show that the effects of distraction on tasks measuring focused and distributed attention are dissociable.

One reason why the similar effect of mind wandering and dual tasking is striking is the difference in neural substrate between the two. Mind wandering is known to involve neural activity of the default mode network, but this network has been traditionally believed to deactivate during task performance (e.g. Buckner et al., 2008). However, recent findings call this into question. Specifically, it has been shown that the default mode network may be involved in working memory tasks and task-set shifting. Particularly, the network was activated when working memory tasks had an increased level of difficulty, leading to a more global level of connectivity and less processing modularity (Vatansever et al., 2015). Additionally, the default mode network was activated in tasks requiring set shifting and cognitive flexibility (Vatansever et al., 2016). This finding is of particular relevance to the current results because in Experiment 6, dual tasking involved a visual working memory task performed concurrently with the AB and IC tasks. One interesting follow-up of current results might involve looking at whether the similar effects of mind wandering and dual tasking on the temporal attention trade-off share a neural substrate related to default mode network activity, and how this is associated with distributed attention.

While raising the possibility of shared neural mechanisms, the similar effects may also be related to shared ongoing brain activity that can be measured using electroencephalography (EEG). Mind wandering has been associated with a reduced P3 event-related potential to targets in the period prior to thought probes (Smallwood, Beach, Schooler & Handy, 2008). Similarly, during dual tasking, the amplitude of the P3 potential tracked the trade-off in attention between the two stimuli or tasks: the more attention was allocated to one task at the expense of another, the smaller the P3 to the latter (Mangun & Hillyard, 1990). Thus, a common neural correlate of mind wandering and dual tasking may be related to decreased P3 potential to T1, which has been previously shown to be associated to reduced attention blink effects (e.g. Martens et al., 2006). To date, the role of the P3 potential in both focused and distributed attention in time has

not been studied comparatively. Chapter 5 in this thesis aims to investigate this role, but it remains for future studies to look at how the P3 is correlated to irrelevant mental activity during both focused and distributed attention tasks.

When comparing the findings of Experiments 5 and 6 it is interesting to note that while the dissociation of effects was reliable in both studies, individual effects were more selectively reliable. Performance in the IC task was only reliably decreased when participants mind wandered, but not when they performed a concurrent task. This is despite the fact that both mind wandering and dual tasking have been shown to decrease task performance in selective attention tasks (e.g. Smallwood et al., 2004; Smallwood & Scooler, 2006; 2015; Macdonald et al. 2011; Baddeley 1996; Lavie 2005). An explanation for the discrepancy in results may be that mind wandering and the secondary task differ in their type of 'load'. According to the Perceptual Load theory (Lavie et al., 2004), distractor interference is reduced when perceptual load is increased, but participants become more distracted when working memory load is increased. Accordingly, it may be that the visual secondary task in Experiment 6 merely increased perceptual load without increasing interference of nearby colour distractors. By contrast, mind wandering is believed to occupy working memory and recruit executive control (Smallwood & Schooler, 2006) or to lead to failures of executive control (McVay & Kane, 2010), both of which imply a 'load' on working memory, along with a decoupling of attention from perception (Kam & Handy, 2013; Schooler et al., 2011; Barren, Riby, Greer & Smallwood, 2011). A potential avenue for future research is to look at how different types and levels of perceptual load affect the temporal attention trade-off.

In terms of the AB task, it was found that only a secondary concurrent task had a reliable effect of reducing attentional blink rates, while mind wandering did not. Previous studies reported that secondary tasks of various types reduced attentional blinks (Olivers & Nieuwenhuis, 2005, 2006; Wierda et al., 2010;

Taatgen et al., 2009), but being instructed to think about something other than the current task also had a benefit (Olivers & Nieuwenhuis, 2006). In the current study, probes might have increased participants' focus overall, as shown by a comparison of T1 detection rates between Experiments 5 and 1 and by previous research (Seli et al., 2013; Smallwood et al., 2012). One method to counteract this effect might be to increase the overall task demand. In Chapter 6, we investigate the effects of mind wandering on the temporal attention trade-off in a non-blocked version of the AB-IC paradigm, a version that involves an increased difficulty at least at face value, because it requires participants to report T1 and its colour as well as T2 on every trial.

Distributed attention in time, in space and beyond

Experiment 7 explored how inducing local vs. global spatial attention affected the temporal attention trade-off, but no reliable effects were found. The study was based on previous findings that attending to local vs. global Navon stimuli within the AB task affected the attentional blink effect in opposite ways (Crewther, et al., 2007). The lack of support in the current study might have been due to the methodology used, such as presenting the Navon stimuli before rather than during the task (cf. Crewther et al., 2007), because Navon stimuli might not as reliably induce or measure global–local attention (Dale & Arnell, 2013a), or due to the fact that the blocked design allowed for endogenous preparation to cancel the effects of task inertia (Yeung & Monsell, 2003).

Conceptually, there are reasons to believe that future studies may nevertheless find an association between spatial and temporal distributed attention modes, perhaps by using a different methodology. The conceptual rationale is that both temporal and spatial distributed attention modes may rely on a cognitive mechanism that favours global processing. As evidenced by Chong and Treisman (2005a), spatially broad attention is related to parallel processing of visual stimuli. The existence of a general 'broad' processing mode is supported by the

results of Experiments 5 and 6 where similar effects of mind wandering and dual tasking were reported, despite the fact that the two types of distributed processing differ in several ways. It remains for future studies to further investigate an association between distributed modes in the spatial domain, temporal domain and beyond. The non-blocked version of the AB-IC paradigm introduced in Chapter 6 may provide a context for such future studies. Crucially, experiments reported in Chapter 4 complemented those reported in Chapter 3 by showing that manipulations to divide attention and spontaneously occurring irrelevant mental activity affected the temporal attention trade-off in the opposite way to how manipulations to focus attention were reported to affect this trade-off.

Chapter 5

EEG correlates of the temporal attention trade-off

Introduction

The experiment reported in this chapter investigates the neural correlates of the temporal attention trade-off. We used EEG (electroencephalography) methodology to capture the temporal dynamics of attention within the AB-IC paradigm. We were interested in how the neural correlates of responding to targets differed between the AB and IC tasks. Furthermore, the study assessed pre-trial brain activity and how this differed between the two tasks.

Event-related potentials and the temporal attention trade-off

If attention trades off between focused and distributed states, with each of these states being optimal in different circumstances, then brain activity should reflect this trade-off. One way in which the neural substrate of attention has been researched is through looking at functional anatomy, and indeed a frontoparietal network of areas shows activation during fMRI studies of attention in general (Corbetta & Schulman, 2002; Desimone & Duncan, 1995), including the AB task (Choi et al., 2012; Kranczioch et al., 2005; Marois & Ivanoff, 2005). However, this finding sheds little light on the dynamics of temporal attention, where the neural differences between focused and distributed attention in time take place in the

order of milliseconds as revealed by the RSVP tasks in the AB-IC paradigm. This is a timescale that fMRI techniques cannot readily capture.

A method that captures neural correlates of temporal events is electroencephalography (EEG). Most commonly, studies in attention have looked at event-related potentials to uncover how the brain processes stimuli. Of these, a positive wave occurring at around 300 ms after stimulus onset, the P3, has been found to be related to stimulus processing, attention to a stimulus and orienting to a stimulus. There are two principal subcomponents to the P3: the P3a peaking at fronto-central electrode recording sites, and the P3b peaking at parietal areas (Squires, Squires & Hillyard, 1975; Polich, 2007). While the P3a is often linked to involuntary attentional orienting and novelty (Friedman, Cycowicz & Gaeta, 2001; Barcelo, Escera, Corral & Perianez, 2006), or difficult detection of targets amongst distractors (Polich & Comerchero, 2003; Polich, 2007), the P3b appears to track improbable events and processing difficulty (Polich, 2007).

The P3 potential has been repeatedly linked to focused attention. In spatial attention tasks, the integration of visual features and prevention of illusory conjunctions is reflected in enhanced negativity and delayed P3b potentials (Cortese, Bernstein & Alain, 1999). Moreover, focused attention in time, when oriented through cueing, is reflected in enhanced P3 potentials (Miniussi et al., 1999; Nobre, 2001; Doherty et al., 2005), although effects on other event-related potentials such as the earlier N1 have also been observed (Griffin et al., 2002). In relation to illusory conjunctions in time, a role for the P3 has been little investigated thus far. Within an Attentional Blink RSVP task, correctly reporting a target word and avoiding a type of illusory conjunctions (i.e. erroneous reports of words presented before or after the target word in the RSVP) was reflected in an enhanced positive potential that started around 300 ms and peaked at 450 ms after stimulus onset (Botella et al., 2008). The study did not measure illusory conjunctions as they are defined by Treisman and Schmidt (1982), in terms of incorrect binding of target features with features of nearby objects. In the current

experiment, the role of P3 potentials in avoiding conjunctions of stimulus features in time will be investigated.

In addition to indexing focused attention states, the P3 potential is also associated with target detection in the Attentional Blink task. To begin with, studies have looked at ERPs elicited by T2, aiming to understand how the AB impacts processing of the T2 stimulus. It was reported in early studies that at short lags, when T2 is not detected, the P2 and P3 elicited by T2 are suppressed (Vogel, Luck & Shapiro, 1998). However, Kranczioch, Debener and Engel (2003) noted that the P3 rather than the P2 was related to T2 detection. While early potentials evoked by T2 such as P1 and N1 remain intact even when T2 targets are not identified, on the other hand the potentials that typically occur after 170-300 ms from T2 are suppressed when T2 is not reported (Sergent, Baillet & Dehaene, 2005). These include the N2, N3, P3a and P3b components. Interestingly, the authors reported that 'seen' targets gained an advantage over 'unseen' targets around 300 ms post-stimulus over left temporal and inferior frontal regions, after which the difference in neural correlates spread to lateral prefrontal and anterior cingulate cortices at around 440 ms. A more recent study by Dell'Acqua et al. (2015) confirmed that both P3a and P3b elicited by T2 are modulated within the attentional blink: the P3b elicited by T2 was both decreased in amplitude and occurred later than usually, and the P3a was decreased in amplitude. The relationship between amplitude and latency of P3b to T2 on the one hand, and attentional blinks on the other hand, was taken to reflect working memory consolidation (Craston, Wyble, Chennu & Bowman, 2009; Akyurek, Leszczynski & Schubo, 2010) or conscious processing of the target (Sergent et al., 2005; Kranczioch, Debener, Maye & Engel, 2007). On this note, it was argued that the P3a is less important for the attentional blink, because the P3a potential occurs even in the in the absence of conscious perception (Muller-Gass et al., 2007), which is key to T2 detection in the task (Kranczioch et al., 2007).

In addition to the P3 associated with T2 processing, performance in the Attentional Blink task is also related to the amplitude of event-related potentials elicited by T1. In fact, Sergent et al. (2005) argued that blink and non-blink trials could be differentiated on the basis of ERPs to T1 alone, with larger P3 to T1 in blink trials. The authors highlighted the competition between amplitudes of two potentials: the P3 to T1 and the N2 to T2, and suggested that this competition was associated with AB performance: larger P3 to T1 was related to larger attentional blink sizes, while larger N2 to T2 was associated with detecting T2. Furthermore, Kranczioch et al. (2007) reported that T2 detection was predicted by the trade-off between P3 to T1 and P3 to T2, such as larger P3 linked to T2 but smaller P3 to T1 predicted T2 detection. The P3 to T1 also differentiated between blinkers and non-blinkers, the latter group having an earlier peak latency of the ERP (Martens et al., 2006). A reduced P3 to T1 as a predictor of better T2 detection may either reflect more available resources for T2 processing (Chun & Potter, 1995) or less overinvestment of attention in T1 processing (Olivers & Nieuwenhuis, 2005), thus being compatible with several theoretical frameworks of the attentional blink.

Irrespective of the theoretical implications, it is important to note that evidence suggests that both P3 to T1 and to T2 are modulated within the attentional blink task, and as was mentioned above, the enhanced P3 is also related to the avoidance of illusory conjunctions in other experimental contexts. In Experiment 8 we aim to focus on the P3 to T1 and investigate how the amplitude the potential is related to the focused and distributed temporal attention trade-off. Specifically, we expect to replicate the finding that a larger P3 to T1 is associated with an increased attentional blink, but in addition that it should be associated with reduced rates of illusory conjunction errors.

EEG oscillations and focused vs. distributed attention in time

If evidence regarding event-related potentials generates specific predictions in relation to trade-offs in attention, on the other hand a more exploratory approach towards neural oscillations in the context of temporal attention is also of interest. A key reason for this is that, as noted by Nobre (2010), neural oscillations might play an important role in how temporal expectations and attention in time are mediated in the brain. Neural oscillations are believed to reflect rhythmic activity of neuronal assemblies in the frequencies of delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (30-70 Hz) frequency bands. Oscillatory activity has been related to a range of cognitive phenomena, from stimulus selection to binding, learning and representation of temporal sequences (Buzsaki & Draguhn, 2004), as well as decision-making and attention (Siegel, Donner & Engel, 2012). One common dichotomy is that enhanced power at gamma frequency in response to a stimulus reflects better attention, while enhanced alpha reflects disengagement, but more recently a rather more complex picture has emerged (e.g., Clayton, Yeung & Cohen Kadosh, 2015).

In relation to neural oscillations, of particular interest are pre-stimulus oscillations that occur spontaneously or in anticipation of stimuli (Kastner et al., 1999; Shulman et al., 1999; Von Stein, Chiang & Konig, 2000). As noted by Engel, Fries and Singer (2001), pre-stimulus oscillations might act as biasing signals, priming subsequent event-related responses and thus aiding more rapid or thorough processing of stimuli. As a marker of the current brain state that determines how stimuli will be processed, oscillations are involved in temporal attention, including the Attentional Blink task (e.g. Hanslmayr, Gross, Klimesch & Shapiro, 2011). In the AB task, one of the less well understood phenomena is that attentional blinks occur on some trials but not on others. Interestingly, pre-stimulus oscillations appear to be predictive with regard to whether an attentional blink will occur on a given trial or not (Janson & Kranczioch, 2011). Therefore, investigating the relationship between pre-trial neural oscillations and

subsequent task performance in the AB and IC tasks may help shed more light on the temporal attention trade-off.

In Experiment 8, we make specific predictions with regard to the association between pre-trial alpha oscillation power and attention states, on the basis of previous research that is reviewed below. Moreover, we take an exploratory approach towards analyzing the relationship between brain oscillations at theta, beta and low gamma frequencies and temporal attention trade-offs. We exclude delta and high gamma frequencies because of data processing and filtering confounds.

Alpha

The relationship between alpha oscillations and attention has been highly debated. Traditionally, alpha (8-12 Hz) has been regarded as reflecting cortical idling (Pfurtscheller, Stancak & Neuper, 1996). In support of this idea, alpha has been found to be suppressed during visual stimulation or during cognitive tasks (Pfurtscheller et al., 1996). While this effect is typically observed over the parietal cortex (Ray & Cole, 1985; O'Connell et al., 2009), effects in the frontal cortex are also observed particularly in top-down tasks for example involving semantic processing (Klimesch, 1999).

Further to the idling hypothesis, a number of other theories of the role of alpha have been put forward. One of these is that alpha is a mechanisms for inhibition (Pfurtscheller, 2003; Klimesch, Sauseng & Hanslmayr, 2007), due to alpha increases observed in brain areas that are irrelevant for the current task (Worden, Foxe, Wang & Simpson, 2000; Banerjee, Snyder, Molholm & Foxe, 2011) as well as in the default mode network of the brain (Ramot et al., 2012). Another view is that alpha is a mediator of internal processes at the expense of external stimulus processing, since higher alpha power is observed during memory retention intervals (Klimesch, Doppelmayr, Pachinger & Ripper, 1997; Bastiaansen, Posthuma, Groot & de Geus, 2002) or periods when stimuli are

masked and need to be processed internally (Benedek et al., 2011). Other, more recent hypotheses are that alpha oscillations mediate predictions (Arnal & Giraud, 2012) or a feedforward inhibition organizing principle (Womelsdorf et al., 2014) that acts as a normalizing function facilitating the propagation of synchronized signals and determining an activation threshold (Pouille et al., 2009; Kremkow, Aertsen & Kumar, 2010; Kremkow, Perrinet, Masson & Aertsen, 2010; Patel & Joshi, 2013). Both of these hypotheses are supported by evidence that alpha propagates as a traveling wave (Fellinger et al., 2012) and predicts subsequent ERP latencies and amplitudes (Basar & Stampfer, 1985; Barry, Kirkaikul & Hodder, 2000; Gruber et al., 2005).

Of particular interest for the current study are pre-stimulus alpha oscillations which, as described above, might act as predictors of subsequent event-related potentials. Generally, there is a negative association between prestimulus alpha and subsequent performance (Hanslmayr et al., 2007; van Dijk, Schoffelen, Oostenveld & Jensen, 2008). As the inhibition hypothesis predicts, alpha power increases in anticipation of the task in the visual cortex responsible for the opposite-to-relevant visual space (Kelly, Lalor, Reilly & Foxe, 2006; Sauseng et al., 2005; Thut, Nietzel, Brandt & Pascual-Leone, 2006). In congruence with a negative association between alpha and attention, alpha desynchronisation occurs before the appearance of a temporally predictable target in a temporal attention experiment (Rohenkohl & Nobre, 2011). If this alpha desynchronisation is disrupted with TMS, attention suffers (Capotosto, Babiloni, Romani & Corbetta, 2009; Romei, Gross & Thut, 2010). Moreover, in sustained attention tasks, low prestimulus alpha is linked to reduced error rates (O'Connell et al., 2009), to better attentional performance in a detection task, and to increased self-rated 'on-task' attention during the same task (Macdonald et al., 2011). Similarly, low alpha power during a rest interval is predictive of good performance in a difficult perceptual discrimination task (Ergenoglu et al., 2004).

Similar to the role of alpha oscillations in attention in general, their role in the attentional blink effect has also been the subject of debate. First of all, a confound to the study of associations between alpha oscillations and attentional blink task performance is the fact that most researchers present the RSVP stream at an alpha presentation frequency. This is problematic because oscillations entrain to presentation rates (Muller et al., 1997; Hanslmayr et al., 2011). A high alpha entrainment at T1 has been found to increase attentional blink rates, leading to the suggestion that alpha entrainment alone can explain the attentional blink phenomenon (Keil et al., 2006; Keil & Heim, 2009; Zauner et al., 2012; Petro & Keil, 2015; Shapiro, Hanslmayr, Enns & Lleras, 2017). However, there are reasons to believe that attention and indeed attentional trade-offs affect the attentional blink over and above alpha entrainment. It has been shown that the amplitude of entrained oscillations increases when a stream is attended to (Muller & Hillyard, 2000; Muller, Malinowski, Gruber & Hillyard, 2003). In the AB task, brain oscillations entrained to the alpha frequency of presentation, but increased in power when AB targets were emotional, a case that is known to attract attention more strongly (Keil et al., 2006). Furthermore, the level of entrainment was also modulated by attentional styles and states, such that entrainment was enhanced in participants strongly susceptible to attentional blinks (Martens et al., 2006) but reduced when performing another concurrent task known to distract attention and to reduce attentional blink rates (Wierda et al., 2010).

Since attentional blinks are subject to attentional states over and above alpha entrainment, it becomes relevant to look at pre-stimulus alpha oscillations. In a study looking at pre-RSVP anticipatory alpha event-related desynchronisation, MacLean and Arnell (2011) found stronger alpha desynchronisation before trials when T1 was correctly identified and when T2 at long lags was correctly identified. On the other hand, stronger desynchronisation was also predictive of incorrect T2 detection at short lags. Thus, desynchronisation leading to lower alpha power was associated with larger attentional blink rates, a finding that was

in line with the overinvestment theory of the attentional blink (Olivers & Nieuwenhuis, 2006). Interestingly, the authors noted that alpha desynchronisation was highest at frontal sites compared to parietal sites (MacLean & Arnell, 2011), even though alpha is typically measured at parieto-occipital electrodes (e.g. Bastiaansen & Brunia, 2001). While pre-RSVP alpha desynchronisation predicted larger attentional blinks (MacLean & Arnell, 2011), on the other hand an increase in pre-RSVP alpha amplitude, induced by rhythmic auditory stimulation, was found to benefit T2 detection at short lags (Ronconi, Pincham, Szűcs & Facoetti, 2016). Additionally, T2 detection performance was positively related to high alpha power at pre-T1 timepoints, even if this was entrained alpha, on condition that entrainment was low at T1 (Petro & Keil, 2015).

Together, findings related to alpha during and before trial support the idea of trade-offs in attention. On the one hand, high alpha entrainment, which reflects enhanced attentional focus (Muller & Hillyard, 2000), relates to increased attentional blink rates (Keil et al., 2006; Keil & Heim, 2009). In contrast, high alpha before trial or before T1 relates to better performance in the AB task (Petro & Keil, 2015; Ronconi et al., 2016). Experiment 8 aims to extend previous findings by looking at the relationship between pre-trial alpha and trade-offs between attentional blinks and illusory conjunctions. We predict a higher alpha power before correct AB trials compared to correct IC trials.

Theta

While the current experiment makes specific predictions with regard to alpha oscillations, an exploratory approach is taken with regard to the relationship between the temporal attention trade-off and theta, beta and low gamma oscillations. To begin with, theta oscillations have been related to working memory (Raghavachari et al., 2001), navigation (Kahana et al., 1999) but also to attention both in monkeys (Tsujimoto, Shimazu, Isomura & Sasaki, 2010) and in

humans (Wascher et al., 2014). Increases in frontal and midline theta power relate to accurate processing of oddball stimuli (Mazaheri & Picton, 2005) but also to errors in long sustained attention tasks (Lal & Craig, 2001). This led Clayton, Yeung and Cohen Kadosh (2015) to suggest that theta may reflect a cognitive control mechanism signaling a discrepancy between the current attentional state and the optimal state to be achieved.

Studies regarding theta oscillations that are directly relevant to the current experiment are fewer in comparison to other frequency bands. With regard to pre-stimulus theta, high power was associated with better subsequent memory encoding (Sweeney-Reed et al., 2016), but a phase reset of the pre-stimulus theta was associated with improved attentional search performance (Dugue, Marque & VanRuller, 2015). In the Attentional Blink task, good performance has been related to increased theta synchronisation after T2 (Slagter et al., 2009) but with decreased synchronisation after T1 (Glennon et al., 2016). Considering the scarcity of directly relevant studies, we will take an exploratory approach with regard to the relationship between pre-stimulus theta and focused and distributed attention in time.

Beta

As opposed to alpha oscillations, beta and gamma frequencies have long been believed to be beneficial in attention tasks. Indeed, both monkey single-cell recordings (Steinmetz et al., 2000; Fries, Reynolds, Rorie & Desimone, 2001) and human EEG recordings (Ray & Cole, 1985; Wrobel, 2000) support the link between beta oscillations and top-down modulation of attention.

Within the Attentional Blink task, beta frequency modulation was reported by several studies. In no blink trials, an inter-area phase locking of beta oscillations began in fronto-temporo-parietal areas before T1. The synchronization peaked at around 260 ms after T1 and again after T2, while there was a strong beta desynchronisation in between the targets (Gross et al., 2004). By contrast, the

synchronization peak that followed T2 was significantly decreased in blink trials. According to Gross et al. (2004; 2006) the role of beta oscillations in the AB might be to mediate a rapid synchonisation and desynchonisation of the network in response to targets and distractors, respectively. Moreover, Kranczioch et al. (2007) found beta inter-area phase synchronisation in non-blink trials before T1 and after T2, over right temporo-parietal and over left frontal areas. Because the role of pre-stimulus beta for attentional blinks and illusory conjunctions has not to our knowledge been studied, Experiment 8 will take an exploratory approach to the investigation of how pre-trial beta oscillations predict attention trade-offs.

Gamma

Similar to beta oscillations, gamma oscillations over frontal and parietal areas also play an important role in focused attention. Studies have found that post-stimulus gamma oscillations were involved in visual search, top-down control of attention and object recognition (Tallon-Baudry, Bertrand, Peronnet & Pernier, 1998; Rodriguez et al., 1999; Fries et al., 2001), as well as conscious awareness of perceived stimuli (Summerfield, Jack & Burgess, 2002). Furthermore, gamma oscillations are believed to have a specific role in the integration of information or feature binding (Eckhorn et al., 1988; Singer & Gray, 1995). For example, in monkeys, gamma power was higher when sounds and movement stimuli occurred simultaneously rather than separately, or when two unisensory or multisensory stimuli were congruent (Ghazanfar, Chandrasekaran & Logothetis, 2008; Maier, Neuhoff, Logothetis & Ghazanfar, 2004; Maier, Chandrasekaran & Ghazanfar, 2008). Similarly, in humans an EEG study showed that feature-based attention such as attention to colour selectively enhanced gamma power, while reducing alpha power (Muller & Keil, 2004).

Pre-stimulus gamma oscillations are also important and beneficial for subsequent attention, as has been shown for example in an oddball task (Reinhart, Mathalon, Roach & Ford, 2011). While high frequency rhythms such as gamma are

associated with shorter subsequent reaction times (Jokeit & Makeig, 1994), the opposite is the case for low frequencies for example in the alpha band (Nenert, Viswanathan, Dubuc & Visscher, 2012). Moreover, the probability of neural spiking is higher during ongoing gamma rhythms (Azouz & Gray, 2003; Vinck et al., 2013). As an explanation, Fries (2009) argued that the role of gamma was to bias competition (Desimone & Duncan, 1995) by synchronizing the activity of neurons that represent relevant information. Studies in monkeys support this (Fries et al., 2001; Womelsdorf, Fries, Mitra & Desimone, 2006). Similarly, Womelsdorf et al. (2014) proposed that gamma oscillations increase the efficacy of input through providing brief time windows of enhanced sensitivity. Irrespective of the differences in explanation, evidence converges to suggest that pre-stimulus high gamma power predicts good performance in focused attention tasks.

Gamma oscillations were amongst the first to be researched in the Attentional Blink task. A first proposal was that gamma suppression at the time of T2 could account for the attentional blink, but this remained without experimental support (Fell, Klaver, Elger & Fernandez, 2002; Dehaene et al., 2003). On the other hand, pre-T1 gamma oscillations were observed. In non-blink compared to blink trials, gamma inter-area phase locking was enhanced (Nakatani et al., 2005) and the authors suggested that this might reflect an anticipatory synchronization. As Janson and Kranczioch (2011) observed, the role of gamma in the attentional blink phenomenon is not yet clear. However, because high gamma power is associated with good focused attention performance, and avoiding attentional blinks is linked to pre-T1 gamma phase locking, a tentative prediction for Experiment 8 is that high gamma power would precede both correct AB and IC trials.

Method

Participants

We tested 22 participants but only used data from 20 because of artefacts in the EEG data. The age range of the included participants was 18 – 32 years with the mean age of 22.5. There were 11 females and 9 males. Participants were recruited from Oxford, both students and non-students. They were reimbursed £15 pounds for their time.

Procedure

Experiment 8 used the AB-IC paradigm, during which EEG recordings were taken. Based on pilot tests, the shorter T2 lag for the second letter in the RSVP stream was changed from lag 2 to lag 3 in both tasks, to allow the EEG correlates of T1 and short-lag T2 processing to be distinguishable in time. The experiment involved 12 blocks for a total of 432 trials. Timing was the same as in previous experiments reported in the thesis: there was an interval of 1200 ms between trial onset and the start of the RSVP stream and the stimulus presentation rate was 80 ms/stimulus, which meant that lag 3 items were presented 240 ms post T1, while a lag 6 interval lasted for 480 ms. Each trial presented 18 items to participants, for a total length of 1440 ms. The experiment lasted approximately 1.5 hours, including preparation.

EEG Acquisition and Preprocessing

EEG data were recorded using a Neuroscan Synamps2 system with 10 GΩ input impedance and 29.8 nV resolution. Data were recorded from 32 Ag/AgCl electrodes mounted in a fabric cap at locations FP1, FPZ, FP2, F7, F3, FZ, F4, F8, FT7, FC3, FCZ, FC4, FT8, T7, C3, CZ, C4, T8, TP7, CP3, CPZ, CP4, TP8, P7, P3, PZ, P4, P8, POZ, O1, OZ, and O2, referenced to the right mastoid and to linked mastoids off-line. Eye movements were recorded above and below the right eye to measure

electro-oculograms (EOGs). Electrode impedances were kept below 50 kΩ. The sampling rate was 1000 Hz.

The continuous EEG was segmented offline into epochs. For the ERP analyses, epochs were extracted from 1s before to 1.5s after T1 onset, while for the pre-stimulus analyses epochs extended from 1s before to 2.2s after fixation cross onset. EEG epochs were baseline-corrected by subtracting the average signal of data across the 1s pre-onset (the baseline data not subsequently used in analyses). Eye blink correction was done in Neuroscan software using a regression-based method (e.g. Gratton, Coles & Donchin, 1983). Because of a technical error, the last 11 datasets were recorded without the bipolar eye channel, and thus eyeblink correction for these datasets was instead based on one of the frontal electrodes that was closest to the location of the missing eye channel, FP2. The two subsets of subjects did not differ in any of the key results presented below, but there was a decrease in the power of frontal and temporal theta ($F(2, 36) = 4.72$, $p = .015$), beta ($F(2,36) = 3.16$, $p = .055$) and gamma oscillation bands ($F(2,36) = 5.13$, $p = .011$), although this was not the case for alpha oscillations ($F(2,36) = 1.62$, $p = .212$). Furthermore, the key interaction of interest in the ERP analyses (between task, lag and R2 accuracy) did not differ between the two sets of subjects, as shown by the lack of a reliable interaction in a mixed effects ANOVA ($F < 1$, $p > .1$).

All further EEG processing was performed in MATLAB with custom-written scripts and EEGLab toolbox commands. An artefact rejection algorithm rejected trials in which the target electrodes had a signal change of over 150 microvolts (μV) in the target periods. If the process rejected more than around 150 trials for one electrode, an interpolation was done to replace the signal with the average signal of surrounding good electrodes for that particular participant. The rate of interpolation was 10.9% and ranged from 0% to a maximum of 28% in two particularly noisy datasets. For the pre-stimulus oscillatory activity topography this process retained 70.2% of trials on average, with a minimum of 38.6% of

trials for the noisiest subject. For ERP topography, an average of 81.7% of trials were preserved, with a minimum of 51.6%. For analyses of oscillations, rejection was performed on key electrode clusters for frontal (FZ, FCZ, FC3, FC4, CZ), parietal (CPZ, PZ, P3, P4, POZ) and temporal areas (FT7, T7, TP7, FT8, T8, TP8). This rejection retained an average 81.4% of trials across participants, with a minimum of 57.6%. Finally, for the ERP analyses, rejection was performed on electrodes within the scalp locations of interest. Generally (in AB experiments included), the P3b potential is recorded at Pz midline parietal electrode (e.g. Akyurek et al., 2010; Dell'Acqua et al., 2015), or at central and midline parietal electrodes. The potential tends to peak at parietal ones (Vogel et al., 1998; Sessa, Luria, Verleger & Dell'Acqua, 2007), although Kanske, Schonfelder and Wessa (2013) reported higher P3 at central electrodes in their emotional AB experiment. In the current experiment, rejection was performed on FCz, Cz and Pz, because central-parietal scalp locations were of interest, and CPz tended to be a particularly noisy electrode. Rejection analyses retained an average of 97.4% of trials across participants with a minimum of 89.1%.

EEG Data Analysis: ERPS

For the ERP analyses, data were filtered in MATLAB using the "eegfilt" command from the EEGLab toolbox. Data were high-pass filtered at 0.5 Hz and low-pass filtered at 4 Hz. This was done because of the focus on P3, which correlates to delta peaks to visual stimuli (e.g. Basar-Eroglu, Basar, Demiralp & Schürmann, 1992). Furthermore, it is to be noted that analyses with less stringent filtering, ran as a check on this analysis yielded materially similar results.

Event-related potential analyses on the EEG recordings from the RSVP period were conducted to examine brain activity related to the processing of T1 and T2. The ERP of interest, P3, is an event-related positive potential that typically peaks 300-500 ms after a target stimulus. To compare the amplitude of the P3 potential between conditions, data recorded between 1s before T1 onset to 1.5s after T1

onset were processed for these analyses. This interval included the onset of T2, which occurred either at 240 ms after T1 (Lag 3) or at 480 ms after T1 (Lag 6).

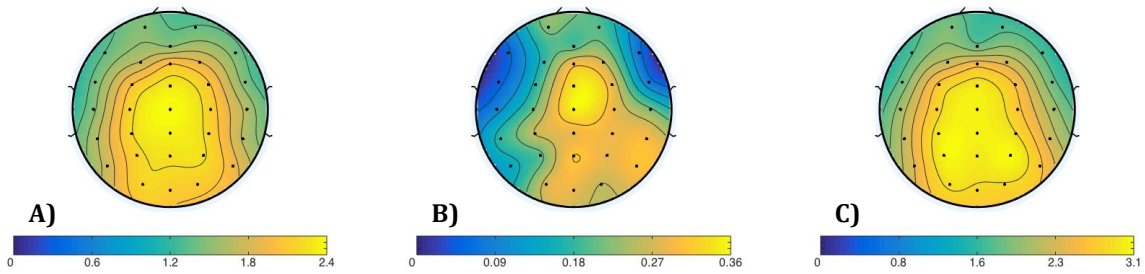

Figure 19. Scalp topographies of ERPs to **(A)** T1; **(B)** T2 at Lag 3 and **(C)** T2 at Lag 6.

In the current experiment, quantification of the P3 was based on initial analysis of the morphology and topography of ERP waveforms, which were first collapsed across conditions involved in key contrasts below to avoid 'double dipping' in identifying regions of interest in the waveforms (e.g. Kriegeskorte, Simmons, Bellgowan & Baker, 2009). These analyses revealed P3 peaks corresponding to processing of T1, T2 at lag 3, and T2 at lag 6, that were maximal at 344 ms, 667 ms, and 948 ms post-T1, respectively. Peak amplitude of all components was observed at Cz (Figure 19A-C). P3 amplitude was thus quantified at Cz as the average voltage in a 100 ms window centred around the peak latencies listed above.

EEG Data analysis: oscillations

To investigate the power of pre-RSVP oscillations in neural activity in relation to subsequent task performance, EEG recordings taken during the fixation cross period before the onset of the RSVP stream were analysed. The time period chosen for analysis was between fixation cross onset and 1024 ms after fixation cross onset. Because the fixation cross is on screen for 1200 ms, this makes the whole period of measurement contained during the display of the fixation cross. Power of oscillations was separately calculated for the first half and the second half of the recording period (512 ms each) and analysed in comparison, to better understand how the brain prepares for a focused or a distributed attention task.

To quantify pre-RSVP power in each of the oscillation bands for each condition of interest, a Fast Fourier Transform (FFT) was conducted for the time-frequency analysis. This deconstructed the data acquired during the window of interest into its frequency spectrum. The processed data was then averaged across conditions of interest, including task (AB vs. IC), accuracy of the second response (R2 was either the colour of T1 or T2), lag (Lag 3 vs. Lag 6), periods (first half vs. second half of the fixation cross period, 512 ms each) and scalp locations (frontal: FZ, FCZ, FC3, FC4, CZ, parietal: CPZ, PZ, P3, P4, POZ, temporal: FT7, T7, TP7, FT8, T8, TP8). Finally, the average power for each frequency band of interest was calculated, aiming to avoid overlap: theta (3-7 Hz), alpha (8-12 Hz), beta (13-30 Hz) and slow gamma (>30-45 Hz). The analysis only included slow gamma as opposed to the whole gamma spectrum in order to avoid confounds from 50 Hz noise, but also because a previous study of gamma oscillations within the AB task looked at a 38-45 Hz band where key contrasts were observed (Nakatani et al., 2005). Analyses were only conducted on Lag 3 data because in some groups of trials the Lag 6 data did not contain sufficient trial numbers, in particular for T1 colour or T2 errors. Hereafter, T1 colour or T2 errors will be referred to as R2 (second response) errors for simplicity, because analyses reported in this chapter

compare R2 correct vs. incorrect trials rather than calculating AB and IC error rates across conditions as previous chapters.

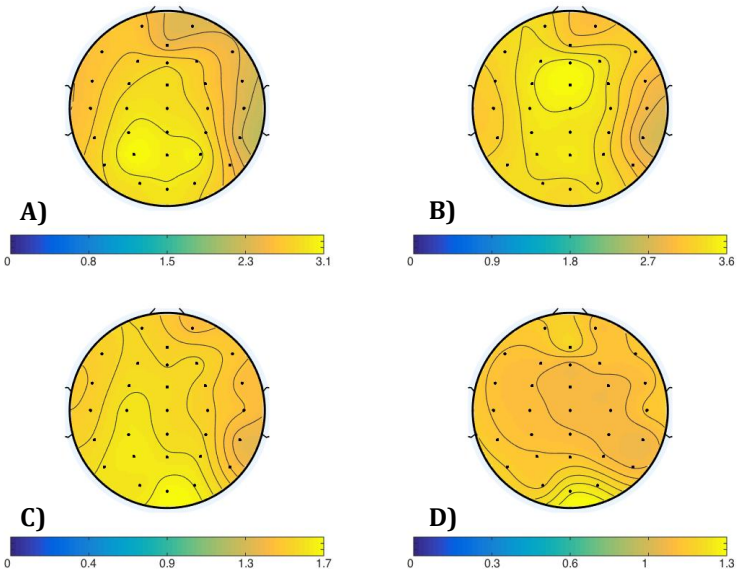

Figure 20. Scalp topographies for power of oscillations within **(A)** alpha; **(B)** theta; **(C)** beta; and **(D)** slow gamma bands.

There was an initial analysis of the power of each frequency band over scalp locations (frontal, parietal, temporal) in order to check the quality of the data. A repeated measures ANOVA was conducted on frequency band (alpha, theta, beta, slow gamma) and scalp locations (frontal, parietal, temporal). Power significantly changed with scalp location ($F(2,38) = 34.91$, $p < .001$) and with band ($F(3,57) = 65.46$, $p < .001$), being highest at theta (3.04 μV), followed by alpha (2.6 μV), beta (1.38 μV) and slow gamma (.96 μV). There was a significant interaction between scalp location and frequency band, as shown by Figure 20, ($F(6,114) = 30.83$, $p < .001$). As commonly observed, alpha power was highest over parietal electrodes ($F(2, 38) = 33.57.$, $p < .001$; Ray & Cole, 1985; O'Connell et al., 2009). Power in the theta band was highest over frontal locations ($F(2,38) = 38.3$, $p < .001$), as previously reported (Mazaheri & Picton, 2005). Beta power was higher over

parietal electrodes ($F(2, 38) = 24.69$, $p < .001$), having been observed in temporo-parietal as well as frontal areas in previous studies (e.g. Gross et al., 2004; Kranczioch et al., 2007) and finally slow gamma was marginally higher at parietal electrodes ($F(2, 38) = 2.59$, $p = .088$), whilst a previous study of gamma oscillations within the AB task had found synchronisation across the whole brain (Nakatani et al., 2005).

Results

Behavioural results

Again there was no reliable difference in T1 detection rates between tasks ($t < 1$, $p > .1$), with a T1 error rate of 15.2% in AB blocks and 15.8% in IC blocks. The size of the attentional blink was 14.5%, a value that was similar to Experiment 1 as shown by an independent samples t-test ($t < 1$, $p > .1$). This suggested that the attentional blink size did not change substantially, although a different short lag duration was used in Experiment 8 (lag 3 vs. lag 2 in Experiment 1 and all other studies in the thesis). The rate of illusory conjunctions in Experiment 8 was 35.7%, significantly reduced compared to Experiment 1 where it was 46.6% ($t(67) = 2.51$, $p = .015$), suggesting that perhaps participants were more focused in the current study, and that the lack of a reliable difference in attentional blink rates needs to be interpreted with caution.

Event-related potentials

The first key hypothesis of the current experiment was that the P3 event-related potential to T1 would differentiate between correctly focused trials (when the P3 would show a high amplitude) and correctly distributed trials (when the P3 to T1 would show a comparatively smaller amplitude). Before investigating the contrasts in P3 amplitude across tasks, lags and accuracy, trial numbers were verified. It was noted that several participants had no IC trials in which T1 was

missed but its colour was correctly identified (N=7 for lag 3 and N=6 for lag 6 of such instances). These conditions were consequently not used in the analyses. On the other hand, one participant did not have any AB lag 6 trials in which neither T1 nor T2 was correctly identified. Because this condition was important, data from this participant were excluded and all subsequent ERP analyses were conducted on data from 19 participants only.

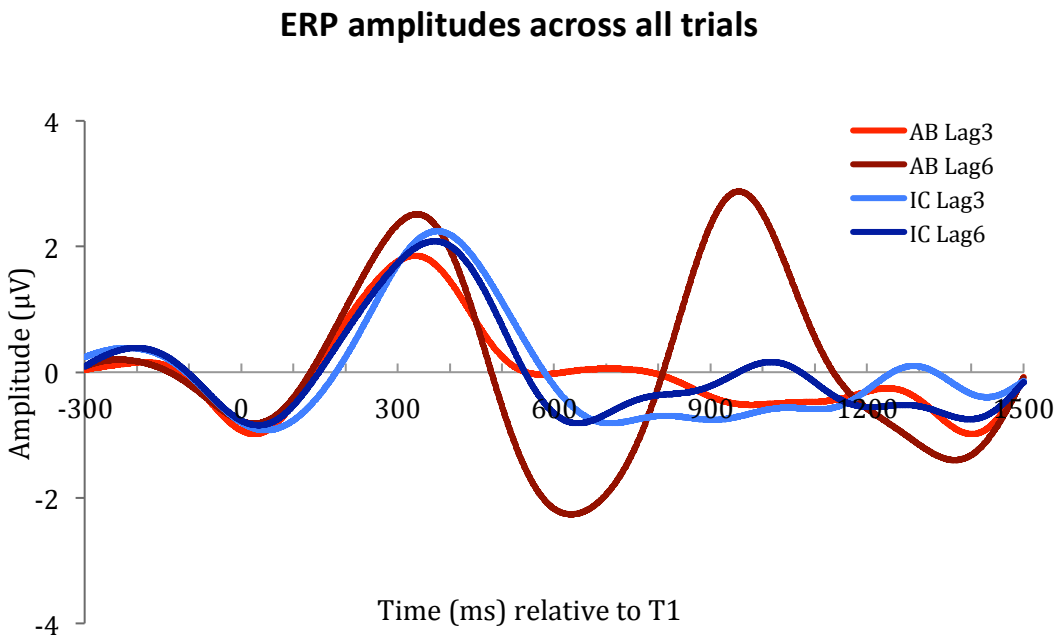

Figure 21. Waveforms show peaks for T1 across tasks and conditions, for T2 in the AB task at Lag 3 and for T2 in the AB task at Lag 6.

An overview of the waveforms recorded across conditions, irrespective of accuracy of T1, colour, or T2, is shown in Figure 21. Clear P3 peaks can be observed in relation to the presence of T1 across tasks and lags (at approx. 350 ms post-T1) as well as in relation to T2 in the AB task at lag 3 (approx. 700 ms post-T1) and at lag 6 (approx. 950 ms post-T1). However, key analyses reported hereafter focus only on P3 to T1 in relation to performance in both attention tasks. Although P3 amplitude to T2 is an important predictor of T2 detection

accuracy (e.g. Sergent et al., 2005), on the other hand it is striking that T2 detection can be predicted on the basis of the amplitude of P3 to T1 alone (Sergent et al., 2005; Kranczioch et al., 2007; Martens et al., 2006). Moreover, it is P3 to T1 that is most informative with regard to the object of interest of the current study, which is the trade-off between two attention states.

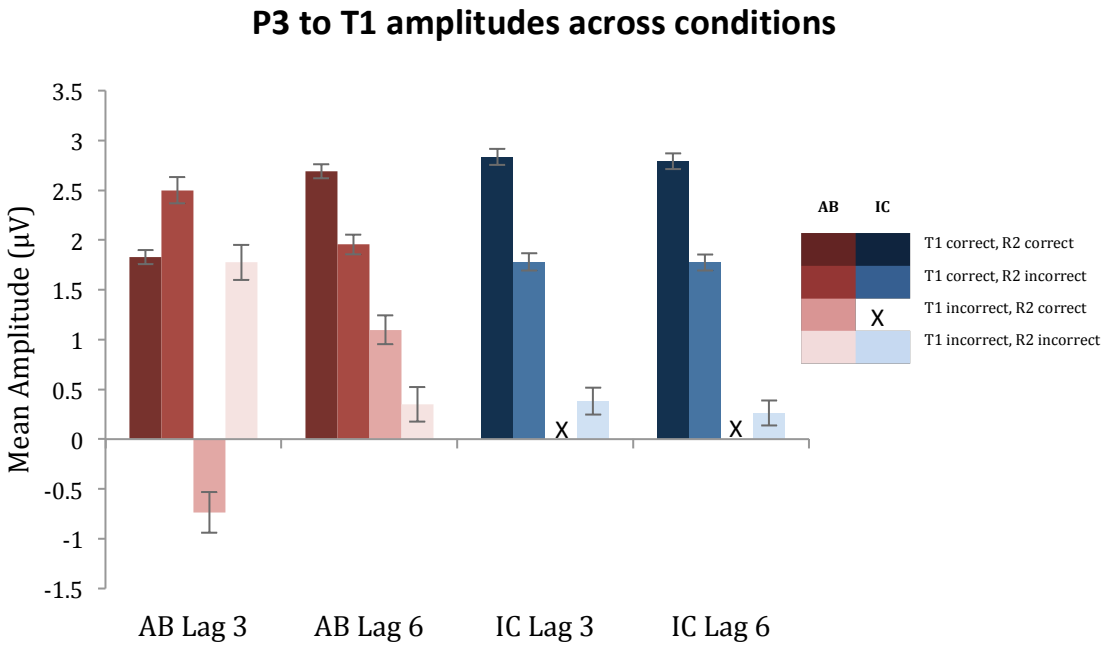

Figure 22. Mean amplitude of P3 to T1 across tasks, conditions and by accuracy of T1 and R2 (colour or T2). The graph does not show T1 incorrect, R2 correct data for the IC task due to lack of trials for many participants.

To begin with, the role of P3 as an indication of stimulus processing and attention was tested. If P3 is associated with stimulus processing, it is expected that P3 to T1 is modulated by the accuracy of T1 detection. To test this prediction, we analyzed the amplitude of the P3 elicited by T1 using a repeated-measures ANOVA with factors of task (AB vs. IC), T2 lag (lag 3 vs. lag 6) and T1 accuracy

(correctly vs. incorrectly reported). Only trials on which R2 was incorrect were analysed in this ANOVA, because many participants lacked any trials when T1 was missed but its colour was identified (Figure 22). It was found that the P3 evoked by T1 was significantly higher when T1 was correctly identified (2 μV, second bars to the left in each set in Figure 22) compared to T1 incorrect trials (0.7 μV, first bars to the right in each set in Figure 22), $F(1,18) = 13.98$, $p = .002$. There was also a marginal effect of task ($F(1,18) = 3.88$, $p = .064$), with somewhat greater P3 to T1 in the AB task than the IC task, which could be explained by the fact that the analysis only looked at trials when R2 was missed, which is interpreted as reflecting an unfocused attention in IC trials but an overly focused attention to T1 in AB trials. None of the other main effects or interactions were reliable (*ps* > .1). Thus, the analysis confirmed that P3 tracks stimulus processing, because P3 to T1 was increased on trials when T1 was detected.

In order to test the key hypothesis that P3 tracks the attention trade-off such that its amplitude is associated differently with accuracy in the AB and IC tasks, a repeated measures ANOVA was conducted on P3 amplitude to T1, with within participant factors of task (AB vs. IC), T2 lag (lag 3 vs. lag 6) and R2 accuracy (colour/T2 correctly reported vs. incorrectly reported). Only trials when T1 was correctly identified were analysed, in order to keep with the measurements that have been used so far in the thesis for AB and IC performance (i.e. measures that have computed the accuracy of the second response given that the first response is correct). First, there was no reliable main effect of task on the amplitude of P3 to T1 (2.24 μV for the AB task, vs. 2.29 μV for the IC task, $F < 1$, $p > .1$). However, there was a reliable main effect of R2 accuracy (2.54 μV in correct trials vs. 2 μV in incorrect trials, $F(1,18) = 6.55$, $p = .020$). There was no main effect of lag ($F < 1$, $p > .1$). R2 accuracy interacted with task ($F(1,18) = 11.74$, $p = .003$), and there was a reliable three-way interaction between task, lag and R2 accuracy ($F(1,18) = 5.78$, $p = .027$). None of the other interactions were reliable (*ps* > .1).

We first explored further with follow-up repeated measures ANOVAs on the effects of R2 accuracy (correct vs. incorrect) and lag (lag 3 vs. lag 6) separately for each of the tasks. We observed that P3 amplitude tracked R2 accuracy significantly in the IC task ($F(1,18) = 27.22$, $p < .001$), where amplitude was enhanced in colour correct trials (2.81 μV) compared to colour incorrect trials (1.78 μV), as can be observed in first vs. second bars to the left in each IC set in Figure 22. There was no main effect of lag and no interaction between lag and R2 accuracy ($F < 1$, $ps > .1$). On the other hand, in the AB task, there were no main effects of lag or R2 accuracy ($F < 1$, $ps > .1$), but there was a reliable interaction between lag and R2 accuracy ($F(1,18) = 4.95$, $p = .039$). Figure 22 (first vs. second bar in the AB Lag 3 set) reveals that at lag 3, P3 amplitude to T1 tended to be higher in incorrect trials although not reliably so (2.5 μV vs. 1.83 μV, $t(18) = -1.61$, $p = .124$). At lag 6, similar to IC trials, the P3 to T1 was larger in correct trials, although again not reliably so (2.69 μV vs. 1.96 μV, $t(18) = -1.61$, $p = .124$; first vs. second bar in AB Lag 6 set in Figure 22). This set of analyses suggests that P3 amplitude tracks accuracy in focused attention trials, but the relationship between P3 amplitude and T2 detection is lag-dependent in AB trials.

The key prediction of the experiment was that P3 to T1 would be differently associated with a correctly focused vs. correctly distributed attention. To investigate this further, we conducted repeated measures ANOVAs of the effects on P3 amplitude of task (AB vs. IC) and lag (lag 3 vs. lag 6) separately for R2 correct trials (Figure 23A) and R2 incorrect trials (Figure 23B).

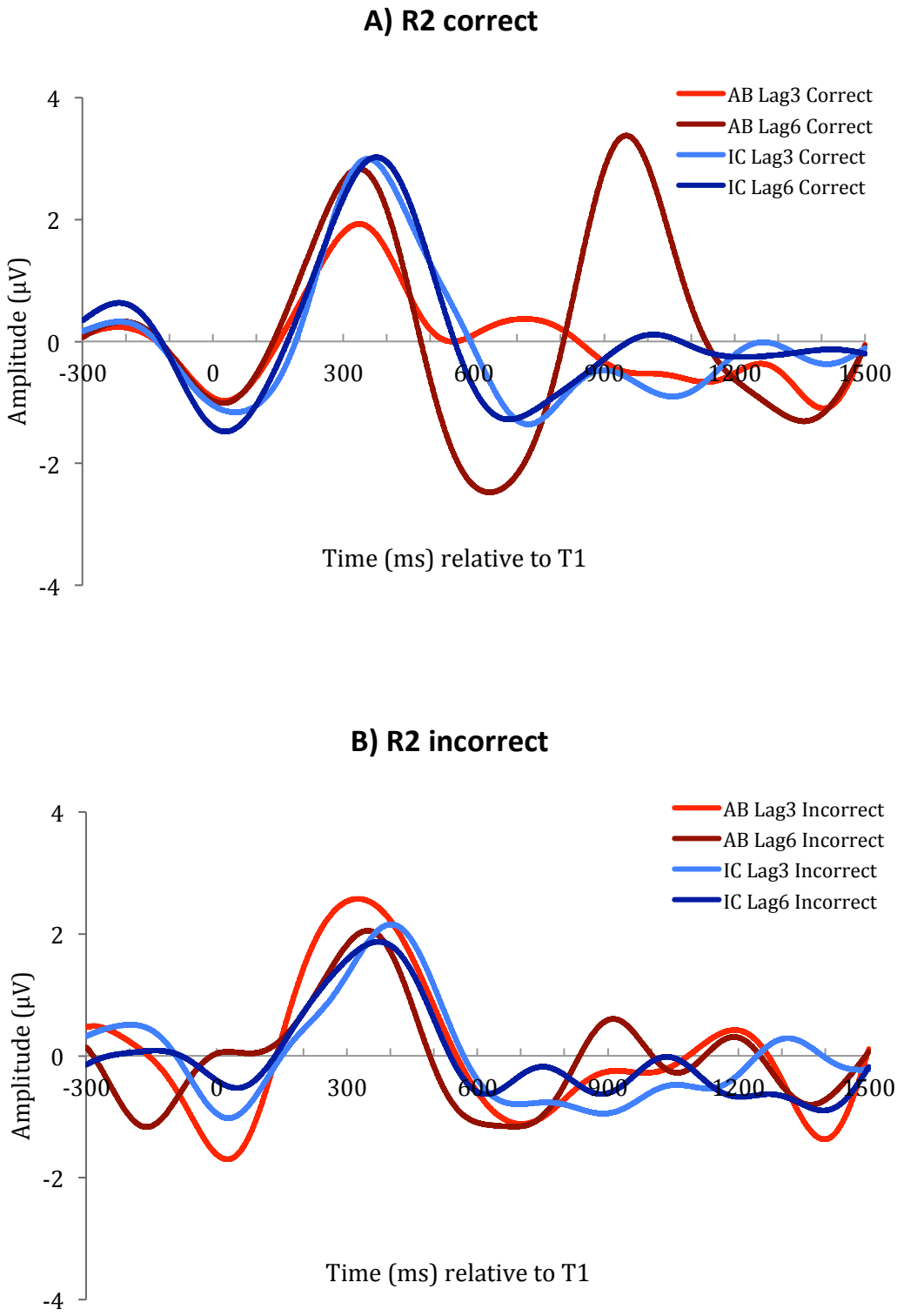

Figure 23. Waveforms showing P3 to T1 across tasks and conditions in **(A)** R2 correct trials and **(B)** R2 incorrect trials.

To begin with, analyses conducted for R2 correct trials are reported (Figure 23A). A significant main effect of task was found ($F(1,18) = 6.09$, $p = .024$), with higher P3 to T1 in the IC task (2.81 μV) than the AB task (2.26 μV). There was a marginal effect of lag ($F(1,18) = 3.45$, $p = .080$), such that P3 to T1 was overall larger in the lag 6 condition (2.74 μV) than the lag 3 condition (2.33 μV). Crucially, as predicted, there was a reliable interaction between task and lag ($F(1,18) = 10.31$, $p = .005$). Follow-up paired-samples t-tests revealed that the P3 to T1 was reliably lower in lag 3 correct trials (1.83 μV) compared to lag 6 correct trials (2.69 μV) in the AB task ($t(18) = -3.2$, $p = .005$). In colour correct IC trials, the amplitude of P3 to T1 did not differ between trials when the T2 letter was presented at lag 3 (2.83 μV) or lag 6 (2.80 μV, $t < 1$, $p > .1$). Furthermore, importantly, when comparing between visually matched trials, it was found that when T2 was presented at lag 3, then P3 to T1 was significantly higher in IC colour correct trials (2.83 μV) compared to AB correct trials (1.83 μV, $t(18) = -3.2$, $p = .005$). By contrast, there was no reliable difference in P3 amplitude to T1 between correct AB and correct IC trials in the lag 6 condition (2.69 μV and 2.8 μV respectively, $t < 1$, $p > .1$).

A similar ANOVA analysis on R2 incorrect trials revealed no reliable effect of task ($F(1,18) = 2.54$, $p = .128$) although interestingly there was numerically a higher amplitude in the AB task (2.23 μV) compared to the IC task (1.78 μV). There was no effect of lag ($F < 1$, $p > .1$) and no reliable interaction between task and lag ($F < 1$, $p > .1$), such that P3 amplitude to T1 did not vary consistently across conditions (Figure 23B).

These results are consistent with the hypothesis that more distributed attention (reflected in reduced P3 to T1) is necessary for the correct processing of T2 in the AB task, when it occurs at a short lag but not a long lag. This interpretation is supported by the fact that the effect of lag was not present across T2 correct and incorrect trials together (as reflected in a lack of main effects of lag or interaction of lag and task, in the main three-way ANOVA reported above) and thus the result

is not a mere reflection of the presence of T2 at short lags (240 ms post-T1) when it overlaps with time of occurrence of P3 to T1 (300-400 ms post-T1). Instead, the current findings are in line with the key hypothesis that P3 to T1 tracks the temporal attention trade-off: it is overall enhanced in the IC task when the colour is correctly reported, but crucially it is decreased on trials when T2 is correctly identified at a short lag.

Neural oscillations

The second aim of the current study was to explore the roles of pre-stimulus neural oscillations in the temporal attention trade-off. Taking mostly an exploratory approach, we looked at oscillations in the theta, alpha, beta and slow gamma bands across frontal, parietal and temporal scalp locations. Only analyses of alpha power were driven by a specific prediction, with the expectation that a higher alpha power would precede trials with distributed attention (AB correct trials) compared to trials marked by more focused attention (IC correct trials). This prediction is informed by previous findings of low alpha being associated with a focused and sustained attention (Rohenkohl & Nobre, 2011; Macdonald et al., 2011) while alpha synchronisation and high power preceded good performance in the AB task (MacLean & Arnell, 2011; Ronconi et al., 2016). Analyses regarding the relationship between theta, beta and gamma were mostly exploratory, along with a tentative prediction that gamma would be enhanced before correct trials across both tasks (e.g. after Muller & Keil, 2004; Nakatani et al., 2005).

Power of oscillations in each frequency band was separately calculated for the first half and the second half of the recording period (512 ms each) and analysed in comparison, in order to better understand how the brain prepares for a focused or a distributed attention task. Below, we present analyses based on four-way ANOVAs conducted on FFT power with within-participant factors of scalp location (frontal, parietal, temporal), period (first or second half of fixation cross),

task (AB vs. IC) and R2 accuracy (correctly vs. incorrectly identified colour or T2 letter), separately for each of the four frequency bands. Analyses were only conducted on lag 3 data because in some groups of trials the lag 6 data did not contain sufficient trial numbers (in particular for R2 errors). Analyses were conducted on data from all 20 participants. In what follows, due to the complexity of the four-way ANOVA analysis, only the significant or otherwise relevant findings with regard to effects of scalp location, period, task and R2 accuracy are presented.

Alpha

The key prediction with regard to alpha power was that this would be higher before AB compared to IC trials, particularly for correct trials (e.g. Petro & Keil, 2015, Ronconi et al., 2016; O'Connell et al., 2009). A marginal effect of task was observed ($F(1,19) = 3.44$, $p = .079$). In line with predictions, alpha power was higher before AB trials (2.52 μV) compared to IC trials (2.44 μV), as can be seen in Figure 24. Overall, alpha power was numerically higher before incorrect R2 trials (2.51 μV) compared to correct trials (2.45 μV), but this was not reliable, $F(1,19) = 2.39$, $p = .138$. Surprisingly, there was also no reliable interaction between task and T2 accuracy ($F < 1$, $p > .1$).

An analysis looked at whether alpha power differed between the first and the second half of the fixation cross periods, but no reliable difference was observed ($F < 1$, $p > .1$), as well as no interaction between fixation cross period and task ($F < 1$, $p > .1$) although previous literature points to a dissociation of pre-stimulus alpha synchronisation and desynchronisation between focused and distributed attention tasks (MacLean & Arnell, 2011; Rohenkohl & Nobre, 2011).

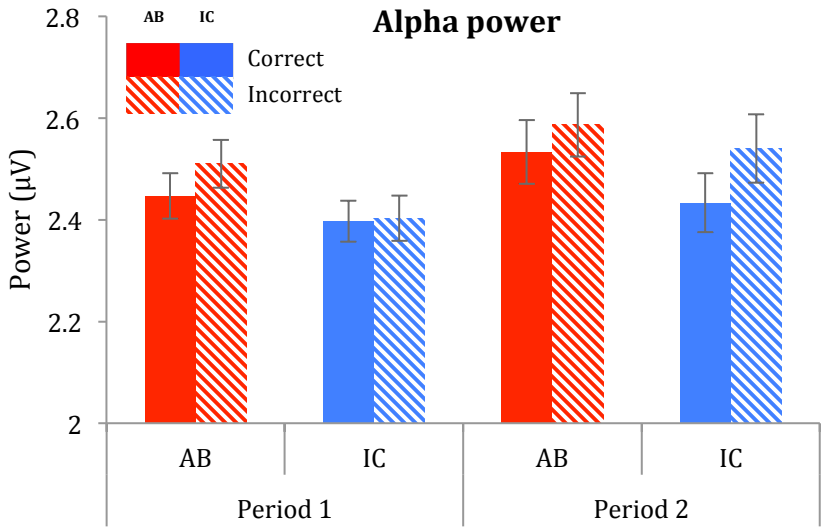

Figure 24. Alpha power by task, R2 accuracy and period, averaged across all scalp locations.

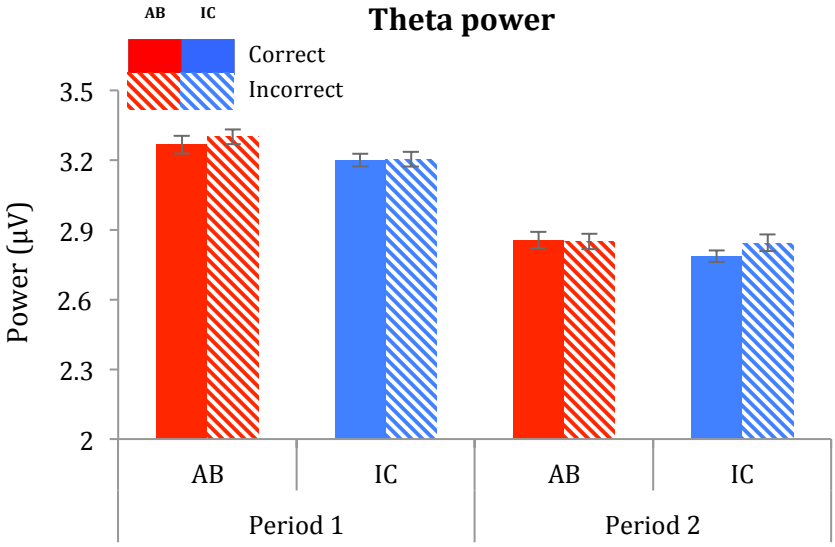

Figure 25. Theta power by task, accuracy and period, averaged across all scalp locations.

Theta

Analysis of the relationship between pre-trial theta (4-7 Hz) power and performance was exploratory. This analysis revealed no consistent differences in pre-trial theta power between the AB and IC tasks ($F(1,19) = 1.35$, $p = .260$) or between correct or incorrect R2 trials ($F < 1$, $p > .1$) and there was no interaction of task and R2 accuracy ($F < 1$, $p > .1$). Overall theta power did change significantly during the fixation cross period ($F(1,19) = 17.04$, $p = .001$), decreasing from 3.24 μV in the first half to 2.84 μV in the second half, Figure 25. This effect did not interact with scalp location, task or R2 accuracy ($F < 1$, $ps > .1$). The decrease may reflect task preparation. As Clayton, Yeung and Cohen Kadosh (2015) commented, theta may signal a discrepancy between the current and the optimal attentional state to be achieved. In this view, a decrease in theta may reflect a calibration of the current attentional state to task requirements. Overall, no relationship between theta and the focused-distributed attention distinction was observed.

Beta

Beta oscillations are typically associated with increased attentional focus, and therefore our exploratory hypothesis was that beta would vary across tasks in the opposite way to alpha, being increased prior to the IC task and reduced prior to AB task trials. Analyses conducted on beta (13-20 Hz) power revealed that neither task nor accuracy had an overall effect on beta power ($F < 1$, $ps > .1$; Figure 26), and nor was the interaction between task and R2 accuracy reliable ($F(1,19) = 1.97$, $p = .176$). Numerically there was a trend interaction between period, task and R2 accuracy, but this did not reach significance ($F(1,19) = 2.79$, $p = .111$). In the first, but not the second period, beta power tended to vary inversely as a function of accuracy for AB and IC task trials, with increased power before errors in the AB task versus increased power before correct responses in the IC task (Figure 26). In addition, we observed an interaction of period and

scalp location ($F(2, 38) = 3.39$, $p = .044$), but follow up contrasts revealed no consistent pattern to this effect ($F < 1$, $ps > .1$).

Slow Gamma

The investigation of associations between slow gamma power and performance were largely exploratory, although a tentative prediction was that high power of slow gamma would precede accurate performance across both tasks (e.g. after Muller & Keil, 2004; Nakatani et al., 2005). However, analyses revealed no consistent main effect of R2 accuracy ($F < 1$, $p > .1$). There was also no reliable effect of task ($F < 1$, $p > .1$), as well as no reliable interaction of task and accuracy ($F(1,19) = 1.71$, $p = .206$).

The only reliable effects observed in the ANOVA were a reliable decrease in gamma power during the fixation cross from 0.98 to 0.95 μV, ($F(1,19) = 8.54$, $p = .009$), as Figure 27 highlights, and a significant interaction between period and scalp location ($F(2, 38) = 9.99$, $p < .001$). Follow-up analyses indicated that this decrease during fixation cross period was reliable at frontal locations ($F(1,19) = 7.38$, $p = .014$, from .92 μV to .9 μV) and parietal locations ($F(1,19) = 12.43$, $p = .002$ from 1.02 μV to .98 μV), but not reliable at temporal locations ($F(1,19) = 2.46$, $p = .133$, from .99 μV to .98 μV). The overall decrease in gamma power prior to task engagement was contrary to the hypothesis that high gamma power is positively associated with attention.

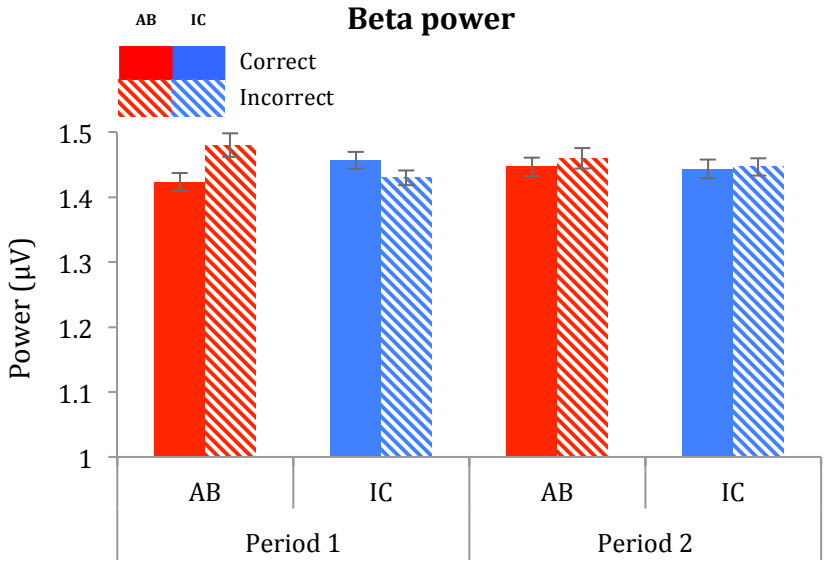

Figure 26. Beta power by task, accuracy and period, averaged across all scalp locations.

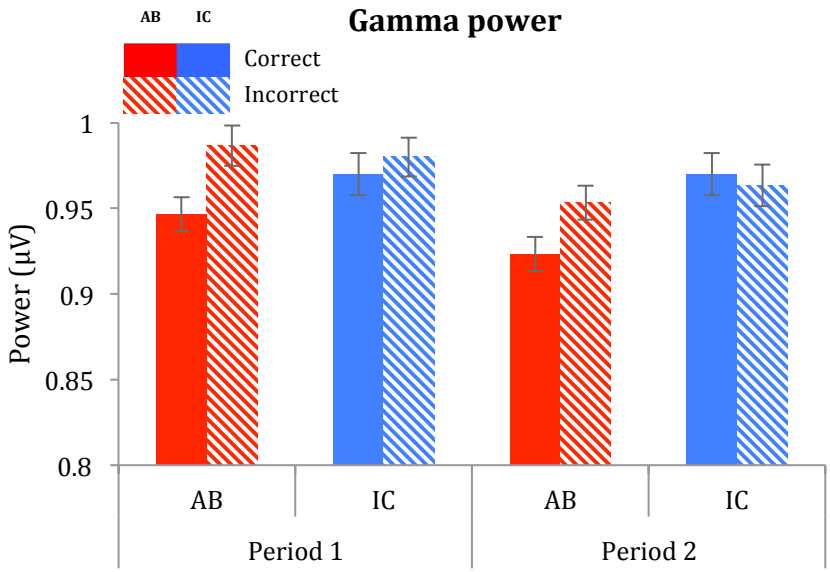

Figure 27. Slow gamma power by task, accuracy and period, averaged across all scalp locations.

Discussion

This experiment investigated the neural correlates of the temporal attention trade-off within the AB-IC paradigm. Two key sets of analyses were conducted, focusing on the P3 event-related potential component as a marker of T1 processing, and on pre-trial oscillations as an index of attentional state. It was predicted that the P3 to T1 would track the temporal attention trade-off. Results were in line with the predictions, with high P3 amplitude to T1 in accurately focused (IC task) trials and low P3 to T1 in accurately distributed (AC task) trials at a short lag. Further, it was predicted that alpha power would be higher before distributed attention compared to focused attention, but there was only weak support for this. Exploratory analyses of the relationship between theta, beta and slow gamma oscillation power and attention revealed few consistent differences between the tasks.

Event-related potential analysis

The first focus of the experiment was on event-related potentials, because these have been long investigated in relation to attention. Our analyses focused on the P3 component, specifically at central electrodes where its amplitude was highest. When occurring centrally, the potential is often categorized as P3a (Squires et al., 1975; Polich, 2007), which is known for instance for its involvement in detection of targets amongst distractors, in addition to its role in involuntary attentional orienting (Polich & Comerchero, 2003; Polich, 2007). However, the peak of our P3 potential was 344 ms post T1, which is more in line with the time window of P3b (250-500 ms) than of P3a (200-250 ms). The P3b is known for reflecting difficult target processing and improbable events (Polich, 2007). Within the Attentional Blink task, both the P3a and P3b have been observed in relation to target detection, but it was argued that only the P3b could be crucial, since the P3a occurs even in the absence of conscious perception, which is believed to be important for reporting T2 in the AB task (Muller-Gass et al., 2007). Since our

topographical maps show the P3 potential to be more posterior than frontal and in accordance with its peak time, we consider that our results reflect P3b modulation.

The P3 potential has been associated with stimulus processing in spatial attention (Squires et al., 1975; Polich, 2007) as well as target processing in temporal attention tasks (Miniussi et al., 1999; Nobre, 2001; Doherty et al., 2005). Similarly, in Attentional Blink tasks, the amplitude of P3 to T1 tracks T1 detection, and the amplitude of P3 to T2 tracks T2 detection (Sergent et al., 2005; Kranczioch et al., 2007; Dell'Acqua et al., 2015). In the current experiment, we observed P3 potentials that followed the T1 target as well as the T2 targets at both lag 3 and lag 6. However, analyses only focused on P3 to T1, because of the key prediction regarding an association between P3 to T1 and the temporal attention trade-off.

The current results provided support for this prediction. Crucially, the amplitude of P3 to T1 differentiated between correct AB trials requiring a distributed attention at short lags, and correct IC trials requiring a focused attention at the same short lags. But in comparison, P3 did not differentiate between tasks in the lag 6 condition. This latter finding is important, because it shows that the higher amplitude of P3 to T1 in colour correct trials did not merely reflect the fact that participants had to report two features of T1 (identity and colour) in the IC trials, while only one feature was reported in relation to T1 in the AB trials. If this difference were driving the P3 amplitude differences, then the same would be expected in lag 6 trials. On the other hand, the reduced P3 to T1 in the lag 3 T2-correct trials might be due the coincidence in timing between T2 (at 240 ms post-T1) and the P3 to T1 (which peaked at 344 ms) causing an attenuation of the neural correlate of T1 processing. Alternatively, less invested attention to T1 might lead to lower P3 amplitude and also allow processing of lag 3 T2. Both of these interpretations are in line with the idea of trade-offs in attention, whether a correctly distributed attention is possible following a prompt reaction to the appearance of T2 that prevents further processing of T1 in the first case; or in the

context of an attention state which started off as distributed. A differentiation between these potential explanations can be further investigated by looking at earlier ERPs to T1 that peak before the onset of short lag T2 targets.

The current findings extend previous results that separately showed associations of P3 to focused attention on the one hand and to poorly distributed attention on the other hand. In spatial attention tasks, P3 amplitude was associated with the avoidance of illusory conjunctions (Cortese et al., 1999), while a positive potential peaking at 450 ms was associated with fewer erroneous reports of nearby words instead of target words in an AB task (Botella et al., 2008). The current study provided further evidence that P3 marks the avoidance of illusory conjunctions in temporal attention, as shown by higher P3 amplitude in correct IC trials. Conversely, previous research has shown that P3 to T1 can differentiate between 'unseen' and 'seen' trials and between blinkers and non-blinkers in the AB task (Sergent et al., 2005; Martens et al., 2006). In the current experiment, P3 amplitude to T1 was differentially associated with AB performance at lag 3 and lag 6, and was considerably larger in correct lag 6 trials compared to correct lag 3 trials, but there was no difference in incorrect trials. Thus, our results show a difference in the amplitude of P3 when attention was correctly distributed, compared to when target detection at long lags was correct, the latter of which does not require distributed attention.

The key contribution of the current study was to provide evidence of a dissociation in the way that the P3 to T1 relates to performance in focused and distributed attention respectively, within the AB-IC paradigm, as an extension to previous findings that reported associations to each type of attention separately. Therefore, to our knowledge, the current study is the first to provide evidence for P3 neural correlates of a trade-off between focused and distributed attention in time.

Neural oscillations

The second aim of the current experiment was to assess how pre-trial neural oscillations relate to the temporal attention trade-off. Previous research has shown neural oscillations to be involved in temporal attention and temporal expectations (Nobre & O'Reilly, 2004; Karmarkar & Buonomano, 2007; Buonomano & Maass, 2009; Oprisan & Buhusi, 2014). Particularly, pre-stimulus neural oscillations are believed to bias subsequent even-related responses to stimuli (Engel et al., 2001). Furthermore, within the Attentional Blink task, pre-stimulus brain oscillations are related to subsequent attentional states, predicting whether a blink will occur on a given trial or not (Janson & Kranczioch, 2011).

The current experiment was driven by a specific prediction that higher alpha would precede correctly distributed trials compared to correctly focused trials. The marginal dissociation of alpha power before the two tasks, with somewhat greater alpha power in the pre-trial period on AB trials relative to IC trials, provides preliminary evidence for its differential involvement in task preparation. Pre-stimulus alpha oscillations have been previously shown to predict subsequent event-related potentials, thus correlating to subsequent attentional states (Basar & Stampfer, 1985; Barry, Kirkaikul & Hodder, 2000; Gruber et al., 2005). In one viewpoint, alpha oscillations may acts as a normalizing function that determines the activation threshold to incoming signals (Womelsdorf et al., 2014). Moreover, a high alpha power is often seen as reflecting idling (Pfurtscheller et al., 1996), internal mental activities (Bastiaansen et al., 2002; Benedek et al., 2011) or the activity of the default mode network (Ramot et al., 2012). Within this larger context, higher alpha power before AB trials might reflect a broader, distributed attentional state, while lower alpha before IC trials might reflect preparation for focused task engagement. In order to investigate the association between alpha power and focused and distributed attention while controlling for task preparation, future experiments

can look at neural correlates of a non-blocked version of the AB-IC paradigm, which will be introduced in Chapter 6.

The role of neural oscillations as a mediator of task preparation was also supported by changes in oscillation power during the fixation cross period. We observed these changes in the theta and gamma bands, where power decreased from the first to the second half of the fixation cross interval. Our theta suppression result follows on from past findings that pre-stimulus theta phase reset was related to good attentional search performance (Dugue et al., 2015) and theta desynchronization after T1 related to attentional blink avoidance (Glennon et al., 2016), although in contrast other studies found that higher theta power was beneficial to oddball stimuli processing (Mazaheri & Picton, 2005). According to Clayton, Yeung and Cohen Kadosh (2015), theta may signal a discrepancy between the current attentional state and the optimal one to be achieved. This view fits our findings: as a task approached, participants may have optimized their attention state to the task requirements, leading to decreases in theta power before both tasks, but differentially affecting the alpha power. On the other hand, there was also a decrease in gamma power during the fixation cross period, which is contrary to prior findings that high gamma power and gamma locking were linked with better attentional performance in selective attention and the Attentional Blink task, respectively (Reinhart et al., 2011; Nakatani et al., 2005). To further explore the association between theta and gamma frequency bands and the temporal attention trade-off outside of task preparation, future studies can employ the non-blocked version of the AB-IC paradigm introduced in the next chapter.

Finally, no reliable effects were found in the beta frequency band, which was surprising since previous research shows an association between beta and top-down attention (Ray & Cole, 1985; Wrobel, 2000) as well as a modulation of beta synchronisation within the AB task (Gross et al., 2004; Kranczioch et al., 2007). A recent report by Shapiro et al. (2017) notes a phenomenon of beta entrainment

within the Attentional Blink task. The authors show that attentional blinks occur when the RSVP presentation rate is within the alpha frequency as well as within the beta frequency, but not within the theta or gamma frequencies. On the other hand, in Chapter 3 of the current thesis we reported that attentional blink rates were higher at a presentation rate of 106.6 ms/stimulus (9.4 Hz, alpha range) compared to 80 ms/stimulus (12.5 Hz, low beta range). Thus, the association between beta oscillations both before and during task and the temporal attention trade-off remains to be further studied.

Neural correlates of temporal attention states

Overall, findings in this chapter lend support to the idea of trade-offs in temporal attention states, by showing that these dissociate in terms of their neural correlates. Particularly, we observed a contrast in the amplitude of the P3 event-related potential to T1 in relation to the AB vs. IC task performance, with high amplitude being optimal for focused temporal attention while a lower amplitude being associated with distributed attention at short lags. Further, we found another dissociation, although only marginal, in the power of pre-trial alpha oscillations before the AB and IC tasks, which suggested that higher alpha was associated with preparing to distribute one's attention, while an alpha suppression may have marked preparation for focused attention. Both this preliminary finding regarding alpha power, as well as reductions in theta and potentially gamma oscillations, suggested the importance of strategic preparation for performing both the AB and IC tasks in our studies so far. In all experiments presented thus far in this thesis we have used a blocked design, allowing participants to strategically calibrate their attentional state to current task demands. In contrast, the following and final experiment (Experiment 9) in this thesis will employ a non-blocked AB-IC design to further investigate the temporal attention trade-off and spontaneous fluctuations in attentional states.

Chapter 6

Individual differences and fluctuations in temporal attention trade-offs

Introduction

The experiments reported throughout the previous chapters have demonstrated that there is a trade-off in temporal attention between a focused and a distributed mode, such that each is optimal in different task circumstances. Previous chapters have demonstrated further that this trade-off is affected by experimental manipulations as well as intrinsic fluctuations in mental states. Each of the previous experiments used a different task context, and there was evidence suggesting that task context may have affected the temporal attention trade-off additionally to the experimental manipulations, by inducing a more focused or more distributed mode. Despite such findings, an open question that remains from these studies is whether individual differences may also impact the temporal attention trade-off such that some people tend to be more focused and others more distributed. One reason why studies reported in previous chapters were not conclusive with regard to this is because they used a blocked design of the AB-IC paradigm, which may have enabled participants to strategically deploy their attention according to task requirements over and above any potential individual differences. Moreover, for the same reason, we may not have been able to observe the effects of momentary mental states on temporal attention to their full extent. Therefore, the current chapter aims to further investigate individual

differences in temporal attention as well as effects of fluctuations in mental states on temporal attention, by using a non-blocked version of the AB-IC paradigm. Before this, however, an analysis will be conducted on data reported thus far in the thesis, in order to investigate how participants varied in their temporal attention across the whole data sample.

Individual differences in attention style

The key hypothesis of the current thesis is that focused and distributed attention trade off. We first looked at this trade-off in terms of individual differences in Experiment 1, predicting that participants would vary in their tendency to be more focused or more distributed in their temporal attention. As was reported in Chapter 2, this prediction regarding individual differences was based on prior studies. In the spatial domain, individual differences have been observed in the Navon task, where some participants show a greater global interference effect while others show a larger local interference effect (Zmigrod et al., 2015). Such dispositional differences were reliable (Dale & Arnell, 2010) and furthermore they predicted the size of participants' attentional blinks (Dale & Arnell, 2015). Indeed, individual differences in attentional blink size are also quite striking, to the degree that people can be labeled as 'blinkers' or 'non-blinkers' (Martens et al., 2006; Willems & Martens, 2016). These individual differences in attentional blink size were stable and reliable (Dale & Arnell, 2013a; 2013b; Dale, Dux & Arnell, 2013).

Based on the idea of trade-offs in temporal attention, in Experiment 1 we expected to find a negative correlation between the size of the attentional blink and participants' tendency to make illusory conjunctions. But results in Experiment 1 were not reliable. This was perhaps because the experiment used a blocked design, presenting participants with separate AB and IC task blocks, which may have enabled participants to strategically deploy their attention according to task demands. Key abilities that enable strategic deployment of

attention, such as task-switching or cognitive flexibility (e.g. Allport, Styles & Hsieh, 1994; Miyake et al., 2000) have been shown to vary between individuals (Friedman et al., 2008; Kane & Engle, 2002). These individual differences in cognitive flexibility may have been a confounding factor for attention styles in Experiment 1. The present chapter returns to the hypothesis of individual differences in attentional style, which is tested both on data from Experiments 1-8 and in a new AB-IC design in Experiment 9.

Fluctuations in attention states

Apart from investigating individual differences, this chapter also aims to further investigate fluctuations in attention states within participants. This is to follow up from previous chapters where it was reported that intrinsic fluctuations in mental state between sequences of trials, in the form of mind wandering, affected the temporal attention trade-off. Furthermore, it was previously shown that fluctuations in sustained attention occurred, and lapses were correlated with self-reports of mind wandering (Smallwood & Schooler, 2015; Smallwood et al., 2004; Macdonald et al., 2011). The same fluctuating nature was reported with regard to distributed attention, because participants show variability in Attentional Blink performance, only blinking in around 50% of trials (Cohen et al., 2012). Similarly, it has been suggested that variability in attentional blinks is related to the neural state at the time of the trial or prior to the trial, and particularly to spontaneously occurring fluctuations in neural oscillations (Pincham & Szucs, 2012; Nakatani et al., 2005; MacLean & Arnell, 2011; MacLean, Arnell & Cote, 2012). Consistent with this interpretation, in Experiment 8, we found that the power of alpha oscillations was higher (albeit only marginally reliably) before the AB task compared to the IC task.

In the current chapter, we examine fluctuations in temporal attention as well as their relation to mind wandering. Extending on previous findings, which revealed that both selective and distributed attention fluctuate, we investigate how these

two attention states fluctuate together, again testing the prediction that periods of high mind wandering will relate to decreases in focused attention performance but not distributed attention performance. In the experiments reported so far within this thesis, the blocked design did not allow an investigation of how focused and distributed attention fluctuate together. In Experiment 9 in the current chapter, the non-blocked design of the AB-IC paradigm will make this investigation possible, testing the prediction of a negative within-participants correlation between moments of good focused attention and of good distributed attention.

Experiments 1-8

To begin with, in order to test the first hypothesis in the current chapter, that attention trades off in the form of individual differences in attention style, we report an analysis of combined results from Experiments 1-8. The key prediction is of a between-participants negative correlation between attentional blink errors and illusory conjunction errors. Experiments 1-8 tested a total of 205 participants with a mean age of 24 and an age range of 18 to 40. There were 138 females and 67 males. Across Experiments 1-8, the average T1 error rates were 18.3%, while the average error rates were 12.1% for attentional blinks and 37.3% for illusory conjunctions.

Experiments 1-8 tested a range of hypotheses regarding trade-offs in attention, and as a consequence the experiments differed in a number of ways. First, Experiment 1 and Experiment 8 did not include any manipulations of attention states. On the other hand, Experiments 2-7 included experimental manipulations or task context variations. Some manipulations aimed to induce attentional focus or resulted in it (exogenous cueing, endogenous cueing, slower presentation rates). Others aimed to distribute attention through dual tasking or inducing a

spatially global attention. Task context also had an impact on attention: Experiment 5 probed mind wandering level, but probes themselves may have resulted in a more focused attention. Conversely, Experiment 6 used dual tasking, which may have resulted in a more distributed attention overall. Meanwhile, in Experiment 3b and half of the trials of Experiment 4, a presentation rate of 106.6 ms/stimulus was used, by contrast to the presentation rate of 80 ms/stimulus used in all other experiments. Furthermore, in Experiment 8 a short lag of 3 items between T1 and T2 was used, as opposed to a lag of 2 in all other studies. Finally, Experiment 8 was an EEG study and participants performed the AB-IC paradigm during EEG recordings, which is also a potential factor that may affect their attention state. All of these factors that may have affected attention will be controlled for when analysing the relationship between focused and distributed attention between participants, across Experiments 1-8.

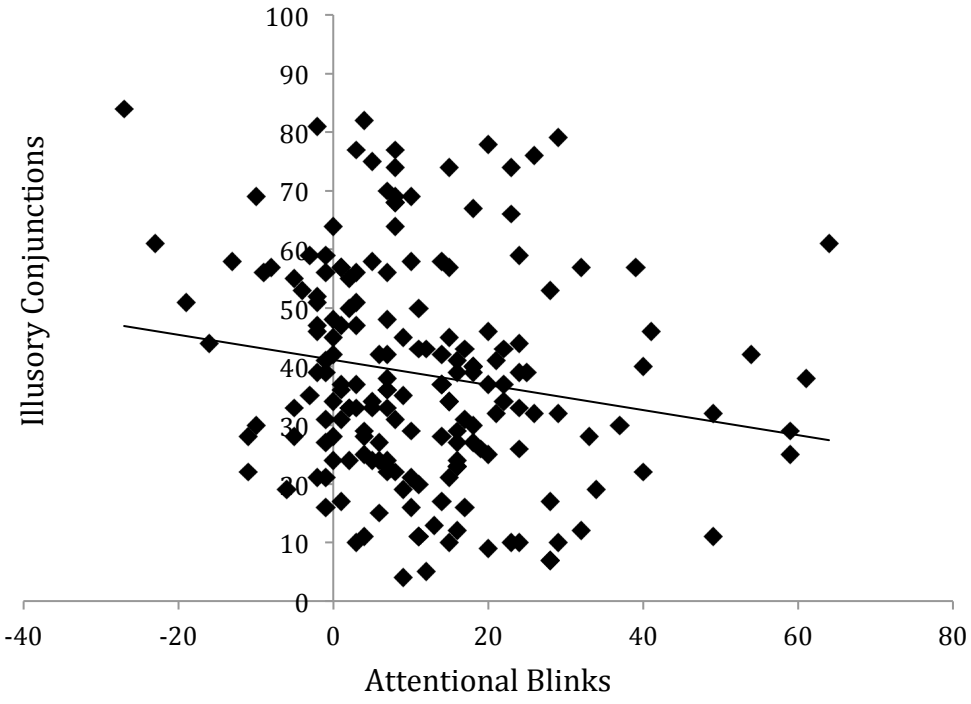

Figure 28. Correlation between attentional blink (AB) and illusory conjunction (IC) error rates in Experiments 1-8, remains significant when all other factors are held constant.

Figure 28 presents a scatterplot across the 205 participants of Experiments 1-8, showing a clear overall negative relationship between errors in the AB vs. IC tasks. The relationship is significant when tested as a simple correlation (r = -.149, p = .032). However, to test this relationship more rigorously given differences across experiments described above, we ran a multiple linear regression analysis. The analysis was conducted on IC error rates as the predicted variable, using the key predictor of attentional blink error rates, and control predictors of: experiment (8 categories: Experiments 1-8), lag (a short lag of 2 vs. 3), task context (Experiments 1 and 8 which involved no experimental manipulations vs. all other experiments which contained manipulations or probes), and type of manipulation (those which aimed or may have resulted in an increase of focus: exogenous cueing, endogenous cueing, slow presentation rate, probes vs. those which aimed or resulted in distraction: dual tasking and global attention induction).

The multiple linear regression showed that the independent variables significantly predicted the illusory conjunctions error rates, $F(5, 204) = 4.22$, p = .001, R^2 = .096. All but two independent variables (experiment and type of manipulation, *ps* > .1) predicted the rate of illusory conjunctions when controlling for all other variables. The short lag length (p = .016) and the task context (p < .001) significantly predicted the rate of illusory conjunctions. Crucially for the trade-off hypothesis investigated in this thesis, attentional blink rates predicted illusory conjunction rates significantly and negatively when all other variables were held constant (*Beta* = -.20, $t(204) = -2.3$, p = .021).

These results indicate the existence of a negative between-participants relationship between focused and distributed attention performance, across all experiments conducted so far within the thesis. The negative association suggested the possibility that there are individual differences in attention style. However, the current analysis is conducted across experiments and is therefore

not conclusive. An experiment conducted specifically to look at the hypothesis of individual differences is needed. Consequently, in Experiment 9 we follow up on the result by looking at individual differences in attention style in a non-blocked version of the AB-IC paradigm.

Experiment 9

Method

Following up the results across Experiments 1-8, the aim of Experiment 9 was to test further the hypothesis of individual differences in attention style in a novel task design. Additionally, the study also aimed to test the hypothesis of fluctuations in attention states, with periods when attention is more focused or more distributed. Crucially, in Experiment 9 we will approach both these hypotheses differently than previous studies in the current thesis, by using a non-blocked version of the AB-IC paradigm in which participants are required to report T1 identity, T1 colour and T2 letter on each trial. With this design, participants should not be able to strategically deploy attention as was possible in previous experiments, and so the current design may allow natural tendencies and fluctuations to be observed more clearly.

Participants

Experiment 9 tested 20 participants from the Oxford community. There were 10 females. The mean age was 26 years (age range 19 to 37). According to selection criteria, none of the participants were colour blind and all had normal or corrected-to-normal vision. Participants were not on any psychoactive medication at the time of the study, and all of them were fluent in English. The experiment received ethical clearance from University of Oxford Central

University Research Ethics Committee. All participants received payment of £10 for taking part in the study.

Procedure

Experiment 9 used a non-blocked version of the Attentional Blink – Illusory Conjunctions (AB-IC) paradigm. Instead of alternating between blocks of the AB task (requiring a report of two letter targets) and IC task (requiring a report of the T1 target and its colour), the current study required participants to make three responses on every trial, identifying the T1 letter and its colour as well as the T2 letter. The procedure for recording responses was the same as in previous studies, such that multiple-choice questions were asked at the end of each trial, requiring participants to choose between 9 response options randomly allocated to response boxes. The order of responses was the same after each trial of Experiment 9: the T1 letter, its colour and the T2 letter, respectively. This order was preserved so as not to confuse the participants and not to load them with the additional task of paying attention to the order of targets to be reported.

At the end of every fourth trial, participants were probed to self-report their levels of mind wandering. They were asked to rate the content of their thoughts during the past few trials on a continuous scale of 0 to 100. The scale contained two orthogonal dimensions: on task vs. off task (horizontal dimension) and aware or not aware of what they were thinking (cf. Christoff et al., 2009). Participants could rate their response anywhere in the rectangular space created by the two orthogonal dimensions (cf. Macdonald et al., 2011). The mind wandering probe procedure was the same as the one used in Experiment 5 in the current thesis.

The experiment followed the same general procedure as previous experiments, with timing of events (including RSVP presentation rate) the same as in Experiments 1-2 and 5-7: at a rate of 80 ms/stimulus and using a short lag of 2 (i.e. 1 distractor item between T1 and T2 at short lag). Participants were

instructed with regard to the task requirements. They were instructed that every few trials they would be probed with regard to their mind wandering level. After 12 practice trials, participants completed 10 experimental blocks for a total of 360 trials. The number of blocks was reduced compared to previous experiments, to compensate for the longer time it took participants to make 3 responses per trial. The experimental session lasted approximately one hour.

Results

The average error rate for reporting the T1 letter was at 28.3%. On trials when T1 was correctly identified, participants erroneously reported T1 colour significantly more frequently (71.1% errors) than the T2 letter (31% errors, $t(19) = 8.15$, $p < .001$). The rate of correctly reporting all three responses (T1, its colour and T2) was only 15%.

A comparison between the general results of Experiment 9 and Experiment 1 revealed that T1 error rates were significantly higher in Experiment 9 (compared to 18.9% errors in Experiment 1, $t(67) = 3.1$, $p = .003$). Similarly, participants made significantly more illusory conjunction errors in Experiment 9, at an error rate of 68.9% (computed using the model fit), compared to 46.6% in Experiment 1, $t(67) = -4.6$, $p < .001$). On the other hand, attentional blink rates measured on the basis of the difference in reporting T2 at short lags and the mean rate of reporting T2 at long lags and T1, did not reliably differ between experiments (10.3% in Experiment 9 vs. 13.3% in Experiment 1, $t < 1$, $p > .1$). This was interesting to note, because the overall task requirements were more demanding than in Experiment 1, since Experiment 9 required 3 rather than 2 responses and this was reflected in higher baseline T1 error rates. Despite this, distributed attention performance was not significantly affected. On the one hand, this suggests again that what is optimal for a focused attention (e.g. reduced task demands) is not always optimal for distributed attention. Moreover, the good performance in distributed attention in Experiment 9 despite overall higher task

demands suggests that when increased demands lead to a trade-off between focused and distributed attention, there may be a bias towards a distributed state. One possibility that will be further discussed later is that distributed attention is the default attention state.

Individual differences in attention style

The first key hypothesis in the current study was that there are individual differences in temporal attention style, with some people being more focused and others more distributed. Results supported this, as reflected in a negative between-participants correlation of attentional blinks and illusory conjunction error rates (r = -.53, p = .015, Figure 29). The negative correlation was also observed between AB error rates in odd trial numbers and IC errors in even trial numbers (r = -.52, p = .019) as well as the reverse (r = -.49, p = .028). This replicated the negative between-participants correlation found across Experiments 1-8 reported in the current chapter.

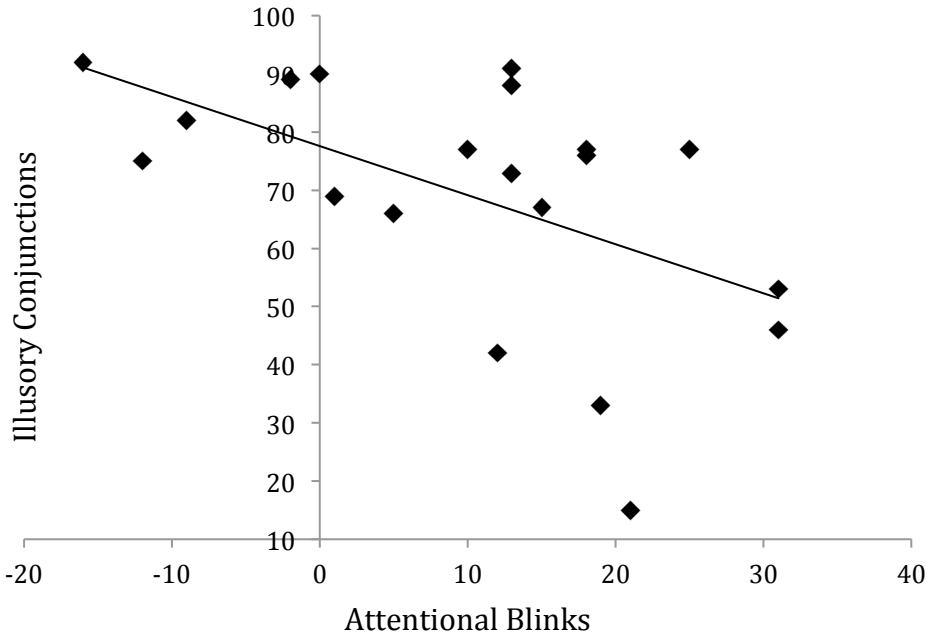

Figure 29. Scatterplot showing the individual difference correlation between attentional blink (AB) and illusory conjunction (IC) rates in Experiment 9.

To further investigate individual differences in attention style, we analysed how attentional blinks and illusory conjunctions were related to mind wandering between participants. The analyses aimed to understand whether participants' attention styles were associated with their tendency to mind wander. Every four trials, participants rated their level of mind wandering during the past few trials. Across participants, there was an average rating of 61% on-task, while the rating for awareness of thought content was 58%.

Between participants, on-task and awareness self-ratings were not correlated (r = .27, p = .242). Thus, analyses looking at individual differences in mind wandering in relation to attention were conducted separately for the two types of mind wandering ratings. However, correlations between mind wandering self-ratings and AB and IC task scores revealed that neither the tendency to be on task nor to be aware of thought content was associated to attentional blink or illusory conjunctions performance (ps > .1). Previously, in Experiment 1 we had reported a trend for mind wandering (retrospectively self-rated after the task) to be differently associated to attentional blinks and illusory conjunctions between participants. But neither Experiment 5 nor the current study could confirm this between-participants dissociation when measuring mind wandering using probes.

Fluctuations in attention states in relation to mind wandering

A second key hypothesis tested in Experiment 9 was that attention states fluctuate, with periods of more focused and periods of more distributed attention. The first analysis to test the hypothesis assessed how focused and distributed attention both fluctuate together with mind wandering levels. We expected that periods of high mind wandering would be characterised by more illusory conjunctions errors and fewer attentional blinks than periods of low mind wandering. To test within-participants effects of mind wandering on performance, mind wandering scores (self-rated every four trials) were split into

Low, Medium and High values using a tertiary split (cf. Experiment 5). Analyses looked at how attentional blinks and illusory conjunctions errors differed in the four trials prior to Low, Medium and High mind wandering ratings. The tertiary split was performed on both aware/unaware and on task/off task scores, because the two types of ratings were not correlated. The mean of within-participants correlation coefficients was .10 (sd = .26), which was not significant as shown by a t-test against zero ($t(19) = 1.67$, $p = .111$).

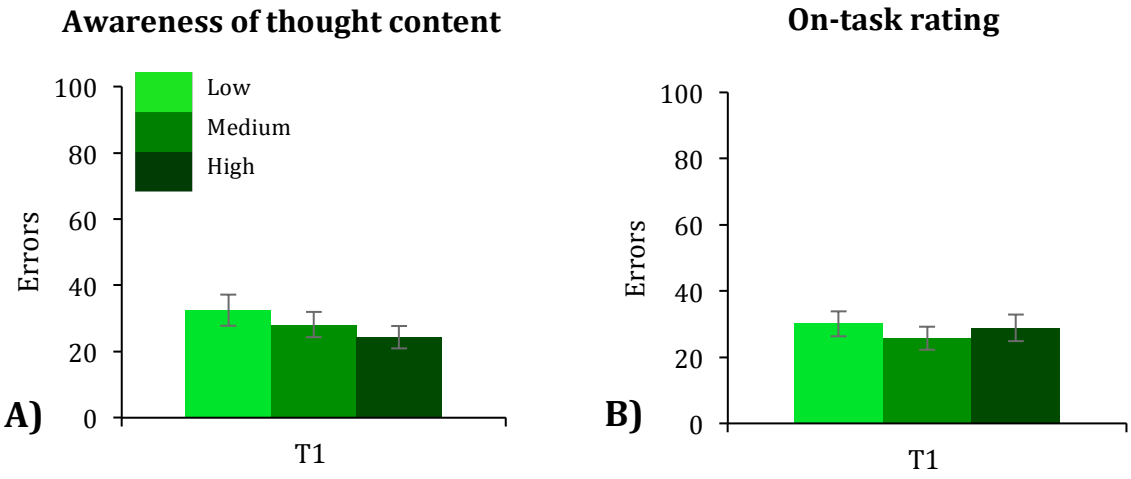

Figure 30. T1 error rates by level of **(A)** awareness of thought content and **(B)** on-task rating.

First, to verify whether self-ratings of mind wandering captured variance in mental states, the relationship between mind wandering and T1 detection accuracy was analysed. The prediction was that target error rates would increase with mind wandering level, as has been shown previously both in other studies (e.g. as reviewed by Smallwood & Schooler, 2015) and in Experiment 5 of the current thesis. A repeated measures ANOVA was conducted to investigate the relationship between self-rated awareness (Low, Medium, High) and T1 accuracy. As expected, T1 detection accuracy improved with increased awareness ($F(2,38)$

= 3.89, p = .029), with a significant linear trend (F(1,19) = 4.96, p = .038; Figure 30A). A similar ANOVA conducted on on-task rating level (Low, Medium, High) also showed that T1 detection varied with on-task ratings (F(2,38) = 3.6, p = .037), although this relationship did not exhibit a significant linear trend (F < 1, p > .1; Figure 30B).

Moving further, to quantify the effects of mind wandering on attentional blinks and illusory conjunctions, we conducted two separate ANOVAs for the two types of mind wandering ratings. First, a repeated measures ANOVA was conducted on awareness level (Low, Medium, High) and type of attention measured (AB vs. IC). There was no main effect of awareness level (F(2,38) < 1, p > .1) nor a reliable interaction between awareness level and attention type (F(2,38) = 2.1, p = .138), although the numerical trends shown by Figure 31A were for AB errors to increase with self-rated awareness of thought content, while IC errors decreased when awareness was rated as high.

A second repeated measures ANOVA was conducted, to investigate the effects of on-task rating (Low, Medium, High) and type of task (AB vs. IC) on error rates. There was a marginal effect of mind wandering level (F(2,38) = 3.03, p = .060) along with a linear trend (F(1,19) = 5.94, p = .025, Figure 31B) but, contrary to predictions, there was no interaction with attention type (F < 1, p > .1). Overall, results suggested that error rates in both attentional blinks and illusory conjunctions were lowest when participants were on task.

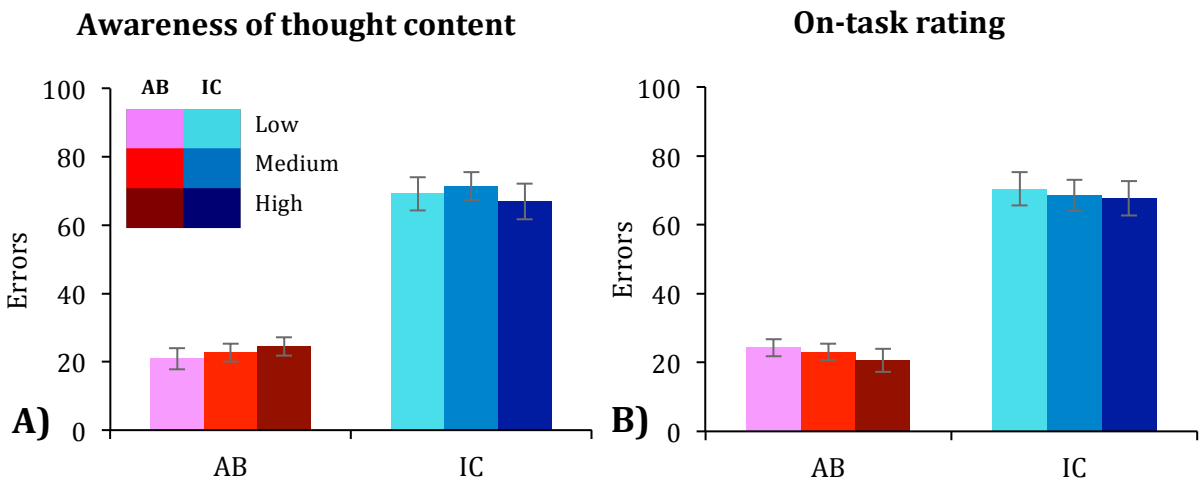

Figure 31. AB and IC error rates by level of **(A)** awareness of thought content and **(B)** on-task rating.

Fluctuations in attentional states: further findings

The findings regarding fluctuations in attentional states in relation to mind wandering were not in line with the predictions. However, this might have been due to a lack of a relationship between mind wandering and attention (as reflected in the distinction between focused vs. distributed) rather than a lack of fluctuations in those attentional states. Thus, we conducted investigations of attentional states fluctuations in their own right, both on a trial-by-trial basis and across blocks.

The first set of analyses looked at trade-offs in attention performance in each trial. By hypothesis, correctly reporting the colour of the T1 letter requires a focused attentional state, while reporting the T2 letter at a short lag requires a distributed state. We contrasted T2 error rates on colour-correct trials, looking only at trials when T1 was correctly identified (28.9% of all trials) with T2 error rates on trials in which an incorrect colour was reported (71.1% of trials). We

predicted that participants would be less likely to report T2 letter identity correctly if they reported T1 colour correctly, but only if T2 occurred at Lag 2.

A repeated measures ANOVA investigated the effects of Lag (2 vs. 6) and colour accuracy (correct vs. incorrect) on T2 error rates. There was a main effect of lag ($F(1,19) = 17.48$, $p = .001$) but no main effect of colour accuracy ($F(1,19) < 1$, $p > .1$). Crucially, the predicted interaction between lag and colour accuracy was significant ($F(1,19) = 7.59$, $p = .013$). Follow-up paired-samples t-tests revealed that at lag 2, there were marginally fewer T2 letter errors on trials when the colour was incorrectly reported (35.4%) compared to trials when the colour was correctly reported (40%, $t(19) = -1.9$, $p = .072$; Figure 32A). This was not the case at lag 6 ($t(19) = 1.5$, $p = .144$; Figure 32A), where there were numerically fewer T2 letter errors on colour correct trials (23.3%) compared to colour incorrect trials (26.3%).

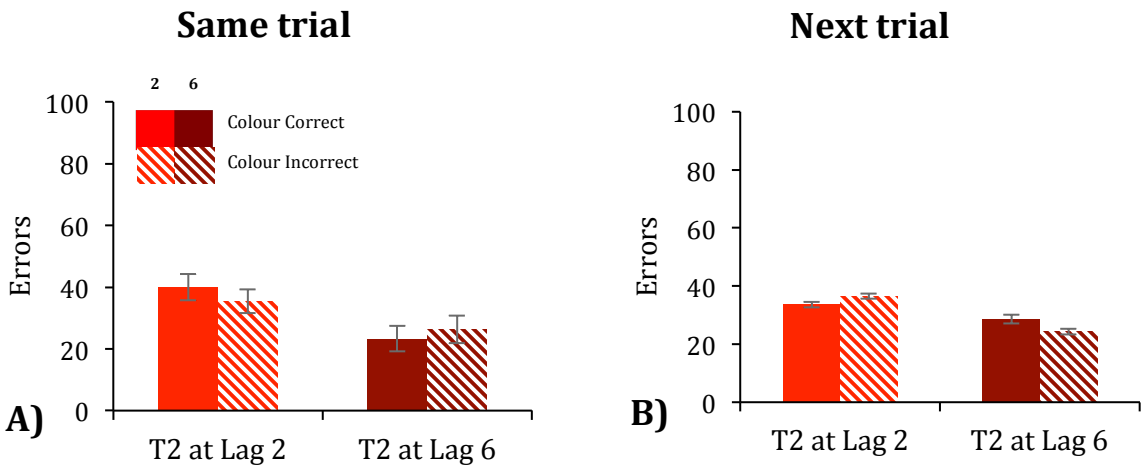

Figure 32. T2 letter detection accuracy in **(A)** same trial and **(B)** next trial, according to whether the colour was correctly identified on a trial or not, when T1 is correct.

Following the interesting trade-off within trials, we continued by investigating whether attention traded off from trial to trial. A repeated measures ANOVA looked at effects of lag (2 vs. 6) and previous trial colour accuracy (T1 and colour correct vs. T1 correct and colour incorrect) on T2 letter accuracy in a trial. There was a marginal main effect of lag ($F(1,19) = 4.15$, $p = .056$) and no reliable effect of colour accuracy ($F < 1$, $p > .1$). Additionally, there was no reliable interaction between lag and colour accuracy ($F(1,19) = 1.9$, $p = .184$). As Figure 32B shows, results suggested that attention states did not trade off from one trial to the next for either T2 lag.

By contrast, we investigated whether attention states are preserved from one trial to the next. The first analysis looked at colour detection. Trials were again split according to colour accuracy (T1 and colour correct vs. T1 correct and colour incorrect), and an analysis looked at the frequency of colour errors on the next trial. Participants were less likely to make T1 colour errors on a trial if they had reported T1 colour correctly on the previous trial (66.2%) than if they made an illusory conjunction error on the previous trial (73%), as shown by a paired-samples t-test ($t(19) = 2.53$, $p = .020$, Figure 33A).

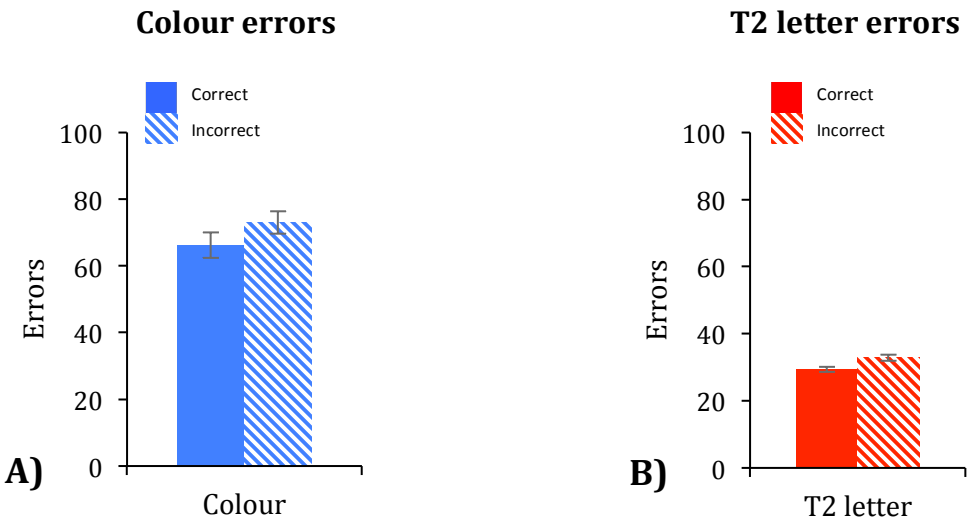

Figure 33. Errors of **(A)** colour detection in trials that follow colour correct vs. incorrect trials; and **(B)** T2 detection in trials that follow T2 correct vs. incorrect trials.

For a similar analysis in the AB task, trials were split according to T2 letter accuracy (T1 and T2 correct vs. T1 correct and T2 incorrect). A repeated measures ANOVA looked at whether T2 error rates on a given trial varied as a function of T2 letter accuracy on the previous trial (T2 letter correct vs. T2 letter incorrect), lag on the previous trial (2 vs. 6) and lag on the current trial (2 vs. 6). There was a main effect of lag on the current trial ($F(1,19) = 19.46$, $p < .001$), with more T2 errors on lag 2 trials (38%) compared to lag 6 trials (24.2%), in accordance with traditional AB effects. In line with the idea that attention states are preserved from one trial to the next, there was a marginal main effect of letter accuracy on the previous trial ($F(1,19) = 4.14$, $p = .056$), such that there were fewer T2 letter errors following T2 letter correct trials (29.4%) compared to those that followed T2 letter incorrect trials (32.8%), as can be observed in Figure 33B. There were no other reliable main effects or interactions ($ps > .1$).

This set of analyses suggested that good performance on each task (AB and IC) was preserved from one trial to the next (Figure 33A-B). The effect was not merely a reflection of preserving good performance between trials in general. As reported above, letter correct trials were not more frequent following colour correct trials. Similarly, a paired-samples t-test showed that colour correct trials were also not reliably more frequent following letter correct trials (71.4% errors) compared to letter incorrect trials (70.5% errors, $t < 1$, $p > .1$).

The previous analyses suggest that attention states traded off within a given trial but were preserved from one trial to the next. The next analyses investigated whether attention traded off across blocks. There were 10 experimental blocks. For each participant and each block, we recorded the frequency of colour correct trials (when T1 and its colour were reported correctly) and letter correct trials (when T1 and T2 were reported correctly). The two frequencies were separately averaged for lag 2 trials vs. lag 6 trials. The key analysis to test the hypothesis of trade-offs in attention state across blocks was correlational. However, before conducting the correlational analyses, we first looked at the effects of block on performance to verify whether performance changed over time, which could become a confound in the subsequent correlational analysis. Therefore, we conducted a repeated measures ANOVA to examine the effects of block (1 to 10), lag (2 vs. 6) and task (colour correct vs. letter correct) on performance (Figure 34). There was a significant effect of block ($F(1,19) = 14.6$, $p = .001$) along with a linear trend ($F(1,19) = 11.73$, $p = .003$), indicating that error rates decreased over time. There were also reliable effects of task and lag and an interaction between task and lag ($ps < .05$), but these have already been discussed elsewhere. Crucially for the current investigation, the effect of block did not differ reliably by task ($F(9,171) = 1.36$, $p = .221$). On the other hand, there was a significant interaction between block and lag ($F(9,171) = 2.75$, $p = .005$), along with a significant three-way interaction between block, lag and task ($F(9,171) = 2.79$, $p = .004$).

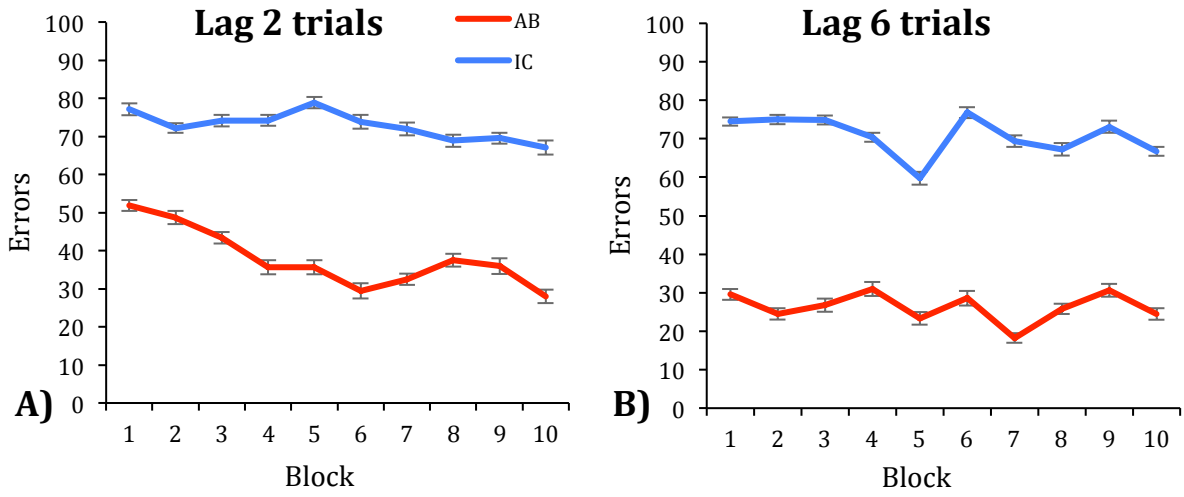

Figure 34. AB and IC task errors across blocks in **(A)** lag 2 trials; and **(B)** lag 6 trials.

Due to the significant effect of block and the linear trend associated with it, along with the three-way interaction that was reported between block, lag and task, we conducted a linear regression to look at the trade-off in attention states across blocks. Specifically, we began by conducting a linear regression on lag 2 trials only, to predict the frequency of colour correct trials, on the basis of T2 letter correct trials and with block number as a control variable. The Beta coefficient for how much T2 letter accuracy predicted colour accuracy, controlling for effects of block, was calculated separately for each participant. Across participants, the average Beta coefficient was -.023. Although the sign of the relationship was overall negative, as would be expected within the framework of trade-offs, the coefficient was not reliable in a t-test against zero ($t < 1$, $p > .1$). By contrast, the equivalent average Beta coefficient for lag 6 trials was .047. Although the sign of the relationship was overall positive, the coefficient was not reliable in a t-test against zero ($t < 1$, $p > .1$). The difference between the two average Beta coefficients was not reliable in a paired-samples t-test ($t < 1$, $p > .1$). One

observation is that there was variability in the size and direction of across-blocks correlations between participants (lag 2: *sd* = .38; lag 6: *sd* = .41). The current sample size was too small for investigating this further, but it remains for future studies to look at trade-offs in attention states across blocks and how these may differ across individuals.

Overall, these analyses revealed interesting findings with regard to fluctuation in attention states. Although attention states did not reliably vary with mind wandering level, there was evidence that attention states do fluctuate in their own right. On individual trials, focused and distributed performance traded off, while attention states were maintained from one trial to the next. It remains for future experiments to further test the idea of trade-offs in attention states over longer timescales.

Discussion

This chapter had two key aims, which were to further investigate individual differences in attention style and to investigate fluctuations in attention states. Results supported the existence of both trade-offs in attention style in the form of individual differences, and trade-offs in attention states in the form of fluctuations, although the latter were not reliably related to self-reported mind wandering in the current experimental setting.

Individual differences in attention style

The hypothesis of individual differences in attention style was first explored in the current thesis in Experiment 1, but with weak results, even after partialling out for potential common variance due to general cognitive abilities. Further experiments in the thesis investigated trade-offs in attention states instead in terms of experimental manipulations affecting focused and distributed attention

differently. The current chapter returned to the data collected across Experiments 1-8 and it was found that a between-participants negative correlation between attentional blinks and illusory conjunctions can be observed across the whole dataset when other factors (e.g. experimental manipulations, task context, design changes) are held constant. This was interesting to note but not conclusive to the question of individual differences, because the analysis was conducted across experiments.

We reasoned that the lack of reliable individual differences in Experiment 1 might have been due to the blocked design of the AB-IC paradigm, which allowed participants to strategically deploy their attention according to task requirements. Although participants might have an underlying trait preference to be focused or distributed, to the extent that they can flexibly shift this mode so that they can do well at both tasks rather than showing a trade-off in performance, the trait preference can no longer be observed experimentally. In fact, there are documented individual differences in the abilities that allow a strategic deployment of attention, such as task-switching or cognitive flexibility (e.g. Allport et al., 1994; Miyake et al., 2000; Friedman et al., 2008; Kane & Engle, 2002), thus leading to a potential confound.

To control for the potential confound of cognitive flexibility, in Experiment 9 we used a non-blocked design of the AB-IC paradigm that required participants to report the T1 identify, the T1 colour and the T2 identity on each trial. Using this design, Experiment 9 aimed to investigate individual differences in attention styles, predicting that some participants would be more distributed in their attention while others would be more focused. Confirming this, reliable individual differences were found in the form of a negative correlation between attentional blinks and illusory conjunctions between participants. The result builds on previous findings regarding stable and reliable individual differences in the attentional blink (Dale & Arnell, 2013b; Dale et al., 2013) that are associated with

individual differences in the trade-off between global and local spatial attention (Zmigrod et al., 2015; Dale & Arnell, 2010; Dale & Arnell, 2015). Although individual differences in both attentional blinks on the one hand, and selective or sustained attention on the other hand have been documented (e.g. for sustained attention Ruff, Lawson, Parrinello & Weissberg, 1990), there has been comparatively little research into how these are associated. Previous studies had reported that some participants can be categorised as blinkers and others as non-blinkers on the basis of their attentional blink error rates (Martens et al., 2006; Willems & Martens, 2016). Comparing these two groups, Willems, Wierda, van Viegen and Martens (2013) found that non-blinkers showed a trade-off in performance because they made more intrusion errors with the stimuli presented near the targets in an AB task. Their results are very similar to what we found in the current thesis regarding a negative association between attentional blinks and illusory conjunctions, the latter being a form of intrusion errors as well. Nevertheless, the current thesis extends their findings by showing a clear trade-off between performing two sets of matched requirements, after having reported throughout this thesis supportive evidence that the two measure a distributed and focused attention in time respectively.

Fluctuations in attention states

The second key aim of Experiment 9 was to investigate fluctuations in attention states, both in relation to mind wandering and in their own right. In terms of fluctuations in attention in relation to mind wandering, there was only a weak trend interaction between the level of awareness of thought content that was self-rated every few trials and performance in focused and distributed attention respectively. This was in contrast to our prior findings from Experiment 5, where we reported that awareness of thought content had reliable opposite effects on the two tasks, being detrimental to focused attention but not to distributed attention. Previous studies reported that mind wandering is detrimental to

sustained attention and working memory (Smallwood & Schooler, 2015; Smallwood et al., 2004; McVay & Kane, 2012; Smallwood, et al., 2008; Mrazek et al., 2012; Macdonald et al. 2011). On the other hand, asking participants to focus less on the task and think about something else reduced blink size (Olivers & Nieuwenhuis, 2005) and furthermore mind wandering propensity during a sustained attention task was predictive of small blinks during an AB task (Thomson, et al., 2015). It was surprising that the current experiment did not replicate results from Experiment 5, despite the fact that we expected that the non-blocked design of the AB-IC paradigm would allow intrinsic fluctuations in attention state to manifest even more clearly, and such fluctuations have been reported to be associated with mind wandering (e.g. Kam et al., 2011). However, there were overall very high rates of illusory conjunctions errors in Experiment 9, perhaps reaching a ceiling effect beyond which mind wandering could not affect performance any further. Future experiments can examine the relationship between mind wandering and attention in the non-blocked AB-IC paradigm with a slower presentation rate, which as shown in Experiment 4 is associated with better IC performance.

Although attention states did not reliably fluctuate with mind wandering levels, Experiment 9 observed attention fluctuations in their own right. First, attention traded off within trials, such that on any given trial, if participants were focused, they were less likely to accurately distribute their attention at the same time. This supported the idea of trade-offs in attention as momentary states. Crucially, the finding suggests that attention is characterised by two different states that are optimal for different contexts, as opposed to the traditional view that performance is good when attention is focused and poor when attention is distracted (e.g. James, 1890), a dissociation that would have predicted a positive association between good performance in both colour detection and T2 detection. Moreover, the finding is not merely the effect of trade-offs due to dual tasking (e.g. Lavie et al., 2004), since it is only observed at lag 2, when a distributed

attention is required. Thus, the finding contributes to the literature on attention fluctuations by showing momentary trade-offs, with moments of focused attention and moments of distributed attention. In a previous study, Macdonald et al. (2011) found that momentary fluctuations in performance in a sustained attention task occurred, with moments of selective attention and moments when the mind wandered. Interestingly, van den Brick, Murphy and Nieuwenhuis (2016) found that the best performance in sustained attention tended to occur at times when pupil diameter was of medium size, potentially corresponding to periods of phasic LC-Na discharge (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Murphy, Robertson, Balsters & O'Connell, 2011). However, both studies measured a sustained attention, and it remains beyond the scope of the current thesis to map sustained attention on the focused-distributed temporal attention trade-off. Nevertheless, an interesting avenue for further research is to look at pupil dilation in relation to fluctuations in focused and distributed temporal attention.

To better understand how long momentary attention states last, we next investigated how these changed from one trial to the next. Rather than trading off from one trial to the next, we found that attention states tended to be maintained, with better IC performance after correct IC trials and better AB performance after correct AB trials. The result confirmed previous findings with regard to attention fluctuations, which have been found to occur in the order of minutes, displaying cycles of 1.5 to 5 or 7 minutes in sustained attention tasks (Smith, Valentino & Arruda, 2003; Arruda et al., 2009; Macdonald et al., 2011). Interestingly, fluctuations in attention in the order of minutes, at least in the case of sustained attention, have also been proposed to reflect trade-offs between periods of exploration and exploitation and potentially relate to activity in the LC-Na system (Arruda et al., 2009), because tonic LC-Na discharge is also periodic (Foote, Bloom & Aston-Jones, 1983; Rajkowski et al., 1994; Swick, Pineda, Schacher & Foote, 1994).

The finding of fluctuations in the temporal attention trade-off in the AB-IC paradigm opens new avenues for investigating neural correlates of fluctuating attention. In the case of sustained attention, fluctuations were found to correlate to the periodicity of beta oscillations (e.g. Arruda et al., 2009) and power of alpha oscillations (Macdonald et al., 2011). Moreover, oscillations in both alpha and beta frequencies have been previously linked to performance in the attentional blink task (e.g. Martens et al., 2006; Kranczioch et al., 2007), and in Chapter 5 we reported a trend difference in alpha power before AB and IC blocks, but no study to date has looked at how brain oscillations vary with fluctuations in both focused and distributed temporal attention. The AB-IC non-blocked paradigm provides an experimental context for the further study of neural correlates of fluctuations in attention states, both as momentary states and as fluctuations in the order of minutes.

A final observation is that although overall task demands were higher in Experiment 9 compared to Experiment 1, and both T1 error rates and illusory conjunctions error rates increased, there was no increase in attentional blink error rates in comparison to Experiment 1. One possibility is that this reflects a tendency for distributed attention to be a 'default' state, which is more likely to be adopted in cases when participants need to choose between being focused and distributing their attention. In the spatial attention literature, a global bias and a global precedence suggest a default distributed state (Navon, 1977; Hoffman, 1980; Miller, 1981; Pomerantz, 1983). However, current results are not conclusive with regard to the question of whether a distributed attention is a default state, because the higher performance in attentional blink rates may simply occur because avoiding illusory conjunctions is more difficult and potentially more affected by the overall higher task demands.

A crucial contribution of Experiment 9 is that it introduced a new variation to the AB-IC paradigm using a non-blocked design. The new design allowed for intrinsic

variations in attention to manifest, and thus reliable individual differences in attention style and fluctuations in attention states were observed. Furthermore, the non-blocked AB-IC paradigm provides a context for continuing the investigation of trade-offs between focused and distributed temporal attention in a number of interesting ways. Avenues for future research include analyses of how attention fluctuates over longer periods such as over blocks, investigations of how brain oscillations and pupil dilation patterns track fluctuations in attention states and studies of how mind wandering may relate to fluctuations in attention in the AB-IC paradigm using a slower presentation rate. Furthermore, future studies may use the non-blocked AB-IC paradigm to further investigate the interesting finding of individual differences in attentional style, for example by looking at how it relates to personality and other types of individual differences as well as whether it may predict risk of pathologies in attention such as ADHD.

Chapter 7

Discussion

The focused-distributed temporal attention trade-off and beyond

This thesis has explored trade-offs between focused and distributed temporal attention within a novel Attentional Blink – Illusory Conjunctions paradigm. This work was motivated by accumulating evidence of trade-offs in behaviour in various contexts ranging from exploitation–exploration dilemmas to trade-offs in attention. Drawing on multiple lines of evidence, the novel paradigm was designed and tested to deliver reliable measures of focused and distributed attention in time. A series of experiments used the AB-IC paradigm to investigate behavioural and neural dissociations between the two attention modes. A central line of research looked into different types of trade-offs in attention, ranging from modes to states and individual differences. Finally, the thesis closed with an experiment that used a variation on the AB-IC paradigm, exemplifying how the paradigm can be flexibly used and changed to test a wide range of hypotheses.

The AB-IC paradigm

A central contribution of the current thesis is the design and testing of the Attentional Blink – Illusory conjunctions (AB-IC) paradigm as a test that measures focused and distributed temporal attention in visually identical ways. The necessity to design this paradigm was prompted by debates around the existence of trade-offs in cognitive states and attention modes, coupled with the lack of a well-controlled experimental setting in which to test such hypotheses. Such trade-offs have been explored in various contexts: sustained attention (e.g. Kurzban et al., 2013), decision making (e.g., Daw et al., 2006), and visual attention (Manohar & Husain, 2013). However, the trade-off between focused and distributed attention has been little researched within a single integrated task that allows comparisons to be made (cf. Chong & Treisman, 2005a, 2005b). In the spatial domain, such single tasks have been used to look at global-local attention, for example using Navon stimuli (Navon, 1977), hierarchical shapes, or high and low spatial frequency gratings (Dale & Arnell, 2013a), but the reliability of global-local attention across these tasks has been questioned (Dale & Arnell, 2013a). To our knowledge, a similar single task enabling investigation of attentional trade-offs has not been proposed prior to this thesis.

The novel paradigm proposed in this thesis employs visually identical tasks to capture focused and distributed attention by identifying promising results within the field of temporal attention. In the time domain, focused attention is optimal for detecting a single target (Kingstone, 1992; Coull & Nobre, 1998). On the other hand, distributed attention may be beneficial in other tasks such as the Attentional Blink task, in which participants often miss the second of two visual targets presented at a short interval in an RSVP stream (Raymond et al., 1992, Olivers & Nieuwenhuis, 2005; 2006). Taking this hypothesis as a starting point, we designed a novel task, the Illusory Conjunctions task, with the same visual set-up as the Attentional Blink task, but with the aim of measuring focused temporal attention. The novel task was inspired by results from the spatial attention

domain, where it has been repeatedly shown that illusory conjunctions between features of visual objects occur as a result of an unfocused attention (Treisman & Schmidt, 1982; Treisman & Paterson, 1984). In the temporal domain, similar conjunctions have been observed between features of nearby items within AB streams (Vul et al., 2008a; 2008b).

Within the novel AB-IC paradigm, we hypothesized that focused attention in time would help to avoid these conjunctions, but would increase the frequency of attentional blinks. In Experiment 1, we found that intrinsic variations in task design that have been previously known to impact attention (e.g. saliency of a visual target, Treisman & Gelade, 1980; Weichselgartner & Sperling, 1987; Chua, 2005) affected the two tasks in the expected opposite directions, with manipulations that aided selective attention leading to improved performance in the IC task but impaired performance in the AB task.

Having designed the novel paradigm, the first experiment also aimed to find reliable measures for the two attention states. A large sample of participants was used for this purpose. Attentional blink rates, considered to reflect failures of distributed attention, have often been measured as a difference between rates of reporting the second target when occurring at a long vs. short lag from the first target (e.g. Raymond et al., 1992). In the current thesis, the rate of reporting the first target was also factored in, which we found to increase the reliability of the measure. On the other hand, the Illusory Conjunctions task was a novel one without prior established measures. Previous research had found that within RSVP streams, colour mis-report responses were spread around the target (Vul et al., 2008a; 2008b). Indeed, the most reliable measure evaluated was a fitted model that took into account both the accuracy of reporting the first target and the spread of colour responses around the target, as well as further away from the target. As such, this thesis proposed a novel paradigm that not only included two tasks for measuring focused and distributed attention using visually identical stimuli, but also delivered a set of reliable measures of the two types of attention.

The visually-matched, valid and reliably-measured novel paradigm provided a context for the investigation of behavioural and neural hypotheses related to attentional trade-offs. To begin with, the paradigm was appropriate for the study of individual differences, because of the way performance was quantified by always relating the ability to focus or distribute attention (i.e. lag 2 performance or colour response spread) to participants' general ability (reflected in T1 accuracy), thus making sure that the final score does not merely reflect general ability. Moving further, because the two tasks were visually matched, we were able to assume that any manipulation only affected attentional modes and thus that the reported effects—behavioural or neural—can shed light on how the temporal attention trade-off works.

As well as opportunities created through the matched visual design, the AB-IC paradigm was also advantageous due to tapping into temporal rather than spatial attention trade-offs. Within the framework of trade-offs in cognitive performance and the exploitation-exploration dilemma, there are several reasons to believe that temporal attention is important. As Summerfield et al. (2011) observed, perceptual decision-making strategies are affected by the volatility of the environment. This again suggests that the dimension of time may be important in exploitation-exploration dilemma. Furthermore, within the adaptive gain theory, Aston-Jones and Cohen (2005) proposed that temporal attention acts as a gating mechanism for accumulating evidence, which shapes decision-making within the exploitation-exploration trade-off. Finally, if we conceive of attentional trade-offs as related to the trade-off between exploration and exploitation, then it becomes important to look at how a momentary state of exploitation affects participants' ability to monitor subsequent events. The AB-IC paradigm does this through highlighting how focusing on the first visual target reduces participants' ability to report the second target. The paradigm also opens avenues for testing other relevant questions such as how cognitive states shift on a moment-by-moment basis between exploiting or focusing and exploring or distributing attention. If exploitation and exploration behaviours have a rapidly changing cognitive

substrate that relates to attention, then the AB-IC paradigm can help tap into their fine-grained neural bases using techniques such as EEG recordings.

Along with the opportunities it offers, the paradigm also has a drawback. A recent observation about the Attentional Blink task is that it generally involves stimuli presented at the rate of 100 ms/stimulus, which falls within the alpha band. This could raise concerns because brain oscillations synchronize to the rhythm of presented stimuli, as evidence suggests (Muller et al., 1997). This happens especially when participants attend to the presented stimuli (Muller & Hillyard, 2000). Moreover, it has been reported that attentional blink rates increase when alpha-band oscillations entrain to presentation rates especially during T1 presentation (Martens et al., 2006; Keil et al., 2006; Keil & Heim, 2009; Petro & Keil, 2015). A potential consequence of this is that results may be confounded, such that both attentional blinks and modulations of alpha band activity during the task may reflect alpha entrainment rather than cognitive effects.

A presentation rate of 106.6 ms/stimulus that falls within the alpha range was only used in Chapter 3, with results showing a benefit to IC performance at the expense of AB performance, compared to a presentation rate of 80 ms/stimulus. The increase in attentional blink size at slower presentation rates may have reflected alpha entrainment. On the other hand, Shapiro et al. (2017) observed entrainment effects associated with increased attentional blink rates within both the alpha band range (where the rate of 106.6 ms/stimulus falls) and the beta band range (where the rate of 80 ms/stimulus falls), which was not in line with current results. Moreover, the involvement of alpha entrainment does not contradict the trade-off explanation, because entrainment and attentional blink frequency were both reduced by the presence of a secondary concurrent task in a previous experiment (Wierda et al., 2010) in line with the overinvestment theory (Olivers & Nieuwenhuis, 2006). Furthermore, alpha entrainment need not be seen as a drawback, but an opportunity for future investigation. To this end, the AB-IC

paradigm can be used to examine the roles of both alpha and beta entrainment in relation to both focused and distributed attention.

A final observation about the AB-IC paradigm is its flexibility. Although most of the current thesis used a blocked design, presenting participants with intermixed blocks of AB and IC tasks, the paradigm allows for other set-ups. An illustrative example is the final experiment, in which participants had to report both target letters as well as the colour of the first target in each trial. This new set-up allowed us to observe natural fluctuations in attentional states and was more appropriate for the investigation of individual differences, because it controlled for participants' tendency to adapt to task requirements, which may have happened in the blocked design. Future research might explore other novel variants. For example, participants could be presented with a random alternation of trials of the AB and IC tasks to investigate their ability to switch between attention modes (Monsell, 2003) and to look at whether having a focused or distributed attention in one trial affects stability of preserving an attention mode or the flexibility of switching, respectively (Fallon & Cools, 2014; Froeber & Dreisbach, 2016).

The temporal attention trade-off: strategy, state and trait

The central conclusion of the current thesis is that there are trade-offs between focused and distributed attention in time, such that circumstances that favour one of them may be detrimental to the other. This was the case throughout the current thesis, where almost none of the experimental manipulations or factors measured were beneficial (or detrimental) to both the focused and distributed mode simultaneously. The only exception was delay length in Experiment 3, which may relate to preparation effects and will be discussed below. In addition, the idea of a trade-off was strengthened by the fact that focused and distributed attention modes were not simply two different manifestations of superior cognitive ability, as revealed by the finding that they did not both correlate with the AH5 measure of intelligence. Instead, the trade-off was revealed in terms of attentional modes, states, strategy and perhaps even traits.

One strong argument in favour of trade-offs in temporal attention modes is that they can be manipulated experimentally. This was found throughout Chapters 3 and 4 of the current thesis, which aimed to either increase focus or to broaden attention. In Chapter 3, focused attention was induced through exogenous cueing towards T1, as well as through slower presentation rates. Both manipulations led to decrements in AB performance. Exogenous cueing through salience has previously been found to benefit processing of one stimulus at the expense of further stimuli in temporal attention (Weichselgartner & Sperling, 1987; Chua, 2005). By contrast, bottom-up orienting through pop-out stimuli benefitted processing of individual items but not mean size of items in spatial attention (Chong & Treisman, 2005a). To our knowledge, speed of presentation manipulations have not been researched in relation to attention trade-offs before. Moving further, Chapter 4 investigated manipulations to broaden attention and reported that a secondary concurrent task benefitted the AB task but not the IC task. Benefits to AB were previously reported by Olivers and Nieuwenhuis (2005, 2006) when participants were engaged in a secondary free-association task,

listening to music or a working memory task. By contrast, Lavie et al. (2004) found that working memory load negatively affected performance in a selective spatial attention task. Overall, to our knowledge, this thesis is the first to provide evidence that manipulations can affect the temporal attention trade-off in either direction.

While experimental manipulations show that attentional modes can be externally determined, the current thesis also brings some evidence that participants can strategically deploy attention within the trade-off. Most of the thesis used a blocked design of the AB-IC paradigm, alternating between AB and IC blocks, which might have motivated participants to strategically deploy their attention according to task demands. Indeed, it is commonly observed that participants strategically prepare before each task block, as shown for example in task switching experiments (Poljac & Yeung, 2014). In Chapter 3, we found that both the AB and the IC task performance benefitted from long delays between RSVP onset and T1 onset. We interpret this as a result of task preparation. In Chapter 5, we observed that power of neural oscillations in the gamma and theta bands decreased before RSVP onset, while there was a marginal difference in pre-trial alpha before AB and IC trials. Such neural modulations have been previously reported in task preparation experiments (e.g. Poljac & Yeung, 2014). Neural correlates of strategic task preparation for focused vs. distributed attention tasks can be further investigated by asking participants to voluntarily repeat or switch cf. Poljac & Yeung, 2014; Froeber & Dreisbach, 2016) between AB and IC trials in a non-blocked AB-IC design.

The discussion thus far has referred to focused and distributed attention as ‘modes’, implying that these are cognitive tools that are intentionally deployed, but there are reasons to believe that focused and distributed attention can also manifest as naturally fluctuating cognitive and neural states. While an attention ‘mode’ as a cognitive tool can be used strategically, by contrast a mental state may arise spontaneously and influence behavior at a systemic level. A first strand of

evidence for distinct attention states is how they relate to mind wandering. Experiment 5 measured levels of mind wandering, distinguishing between mind wandering episodes that occurred with or without awareness (Smallwood & Schooler, 2006; Smallwood et al., 2007; Christoff et al., 2009). Rates of illusory conjunctions decreased at high levels of awareness, but this was not the case for attentional blinks. The results extended previous findings of a negative impact of mind wandering on sustained attention (Smallwood et al., 2004) and a potential positive association with performance in AB tasks (Thomson et al., 2015). But more importantly to the notion of attention states, the dissociable association between mind wandering and focused and distributed attention suggests that the potential spontaneous occurrence of mind wandering may affect attention states, perhaps by activating a default state of the brain. Indeed, most often, mind wandering is believed to occur spontaneously (Smallwood & Schooler, 2015; Smallwood 2013) and to involve activity in a default mode network of the brain (e.g. Buckner et al., 2008; Andrews-Hanna, 2012; Mason et al., 2007). However, it has recently been noted that mind wandering can also occur with intention (Seli et al., 2016) and that intentionality and awareness of mind wandering are distinct (Seli et al., 2017). To further understand the association between spontaneous mind wandering and attention states, future experiments could measure both the awareness and intentionality of mind wandering episodes and how these relate to attention and its neural correlates within the AB-IC paradigm.

A second line of evidence for trade-offs in attention states is in how they spontaneously fluctuate. In Chapter 6, we found that performance traded off within each trial between correctly reporting T1 and its colour and reporting the two targets. Moreover, participants maintained a good performance of avoiding either illusory conjunctions or attentional blinks from one trial to the next, whereas the maintenance of good performance did not carry over across tasks. Meanwhile, the EEG study in Chapter 5 found marginal differences between alpha power before the AB and IC tasks, potentially reflecting a preparation of attention

for the subsequent task (e.g. Engel et al., 2001), but found no reliable association between pre-trial alpha power and performance in the two tasks. The hypothesis of spontaneously occurring attentional states would have predicted that alpha power tracks the natural fluctuations between optimally focused and optimally distributed states, on the basis of previous studies showing an association of alpha power to performance in both selective attention tasks and the AB task (Hanslmayr et al., 2007; van Dijk et al., 2008; Janson & Kranczioch, 2011). To further test the neural correlates of spontaneously occurring attention states, future EEG studies can look at alpha power in relation to AB and IC performance in a non-blocked version of the AB-IC paradigm in which natural fluctuations in attention state can be better observed.

On top of trading off as states, focused and distributed attention may also trade off as traits. Individual differences in attention were investigated in Experiment 1, but performance in the AB and IC tasks did not significantly negatively correlate across participants, even when partialling out the common variance due to cognitive abilities. This was surprising, based on previous findings of reliable individual differences in spatially global and local preference (Zmigrod et al., 2015; Dale & Arnell, 2010), which furthermore predicted reliable individual differences in the size of the attentional blink (Martens et al., 2006; Willems & Martens, 2016; Dale & Arnell, 2013b; Dale et al., 2013). We followed up on this discrepancy in Chapter 6, where we reported a negative AB and IC correlation between participants across all experiments (while controlling for other differences across experiments). This correlation was replicated in a single sample in Experiment 9, using a non-blocked version of the paradigm. Thus, the current thesis demonstrates individual differences in the temporal attention trade-off.

A final interesting question refers to the nature of trade-offs in temporal attention. Specifically, these could be between two discrete attention modes or states, or fall along a continuum. The results of the current thesis do not provide

conclusive evidence, but tend to favour the interpretation that attention trades off along a continuum. First, plotting colour responses in the IC task suggested a continuum between correct identification of T1 colour, inaccurate reports of colours of nearby items and random responses reflecting distraction. Additional evidence comes throughout the thesis from the fact that external manipulations can shift attention towards either focused or distributed modes. Finally, evidence for a continuum may also come from neural correlates of attention. Chapter 5 found that event-related potentials to T1 differentiated between attention modes, being higher in focused attention. Previous studies found that P3 event-related potentials that occurred earlier and that were smaller related to fewer attentional blinks (Sergent et al., 2005; Martens et al., 2006), suggesting a graded phenomenon. On the other hand, Sergent and Dehaene (2004) observed that performance in the attentional blink task has at least some characteristics of an all-or-none phenomenon, such that the second target either reaches conscious perception or not. However, this effect refers primarily to conscious perception, which is believed to be different from attention (e.g. Baars, 1997), and thus may not discard the hypothesis of a continuum in attention. Consciousness may be an all-or-none phenomenon even if it is affected by attention states that vary continuously. Future experiments can use the AB-IC non-blocked paradigm to further investigate this topic, for example by comparing the neural correlates of gradual effects of different manipulations on the two attention modes.

Characteristics of focused and distributed temporal attention

Apart from providing evidence for trade-offs between focused and distributed attention in time, the thesis also sheds more light on the characteristics of both focused and distributed attention modes or states. The following sections will describe how focused and distributed temporal attention were characterised in the thesis, in relation to previous notions of focused and distributed attention in space and time, previous findings and theories, and finally in terms of a possible dissociation between focused attention as object-based and distributed attention as broader in scope.

Characteristics of focused temporal attention

Focused attention has been previously defined as both selective and beneficial to perceptual processing (e.g. James, 1890; Broadbent, 1958; Eriksen & Hoffman, 1973; Desimone & Duncan, 1995) and as involving integration of stimulus features into a coherent visual object (Treisman & Gelade, 1980; Treisman & Schmidt, 1982). Research specifically on temporal attention has highlighted similar key aspects, such that on top of accurate and rapid responding to targets (e.g. Wundt, 1887), focused attention in time involves perceptual discrimination of features of a target (Griffin et al., 2002; Correa et al., 2005; Rolke & Hofmann, 2007). In line with these definitions and findings, in the present thesis focused temporal attention within the Illusory Conjunctions task involved accurate perception of a target, along with binding its features correctly and avoiding illusory conjunctions with features of nearby objects.

A key characteristic of focused attention as previously researched is that it can benefit from both exogenous and endogenous cueing, but only the former was reliably found in Chapter 3. Exogenous cueing involved increasing the salience of T1 through presenting a box around the stimulus, a manipulation that had been employed in both spatial and temporal attention experiments (Handy et al., 1999; Prinzmetal et al., 2005; Weichselgartner & Sperling, 1987). Endogenous cueing

involved instructing participants with regard to the time of T1 target onset (cf. Kingstone, 1992; Coull & Nobre, 1998; Correa et al., 2004; 2006; Trivino et al., 2010). However, despite using established methods, only exogenous cues benefitted focused temporal attention within the AB-IC paradigm, while there were no consistent effects of endogenous cues.

One potential explanation for the lack of reliable effects of endogenous cueing in the IC task compared to prior temporal attention tasks is the way that temporal expectations are coded in the brain. As Nobre (2010) noted, there are brain cells that code for a specific location in space, but not for a specific moment in time. This may make it difficult to build temporal expectations in the same way as spatial expectations, but it would not affect exogenous stimulus-driven orientation. As temporal expectations may be coded through oscillatory activity in neural networks (Nobre & O'Reilly, 2004; Karmarkar & Buonomano, 2007; Oprisan & Buhusi, 2014), building an expectation of a target in time could yield task-unspecific brain readiness, as reported in a study (Fischer et al., 2013). While target detection efficiency, measured in previous experiments (e.g. Coull & Nobre, 1998) may still benefit, it remains unclear whether brain readiness benefits feature integration. To further clarify this issue, future studies could investigate the neural correlates of endogenous cueing effects on the IC task. Furthermore, studies can compare between two types of top-down cueing that either involve instructions regarding the time of onset (as has been done in this thesis) or other symbolic instructions regarding the T1 target, for example to look for a word that describes an animal in an RSVP containing word stimuli. In this case, the prediction is that the latter type of endogenous cueing would reduce illusory conjunction rates, but temporal expectation would not. However, irrespective of the results, the dissociation between effects of temporal expectation on target detection in prior experiments and on illusory conjunctions in this thesis suggests that focused attention may not be defined through a strict set of characteristics but rather through a spectrum of features that different methods can capture.

Characteristics of distributed temporal attention

Distributed attention has been comparatively less widely-researched in both the spatial and temporal domains, but the thesis provides new evidence that a distributed attention is optimal in different circumstances than a focused attention, as well as providing support for the overinvestment theory of the Attentional Blink, which portrays the task as one in which a distributed attention is optimal (Olivers & Nieuwenhuis, 2006).

Despite the traditional view that attention is 'good' when focused and selective, as opposed to distracted (e.g. James, 1890), the present thesis brings evidence that a distributed attention is optimal in certain circumstances. A look at previous research on distributed attention reveals that a distributed or broad attention in space has been found to be beneficial for a range of tasks, including the perception of global Navon stimuli (Navon, 1977), averaging the size of multiple objects in a display, and parallel processing of visual stimuli (Chong & Treisman, 2005a; 2005b). Crucially, a local or spatially focused attention was not beneficial to any of these tasks, but was beneficial to visually similar control tasks. In temporal attention, Olivers and Nieuwenhuis (2006) suggested that a distributed attention, as opposed to an overinvested attention to T1, was optimal within the Attentional Blink task.

A key contribution of the present thesis was to provide stronger evidence that a distributed attention is optimal within the AB task by comparison to the novel IC task, and more broadly that a distributed and a focused attention are distinguishable. Indeed, dissociable effects on the AB and IC tasks were found as a result of manipulating both focused attention (exogenous cueing, slower presentation rates) or in association with distributed attention (dual tasking, mind wandering). It was particularly striking that slower presentation rates, which improved both T1 detection and the avoidance of illusory conjunctions, had the opposite effect on attentional blinks. This suggested that circumstances when it is easier to focus are not beneficial to the AB task, and that a distributed

attention is indeed distinguishable from a focused attention. Another interesting finding was that in Experiment 9 in which we used the non-blocked version of the AB-IC paradigm, detection of both letter targets was less frequent on trials when the colour of T1 was correctly identified. This showed that a focused attention was not indiscriminately beneficial for performance, since it led to decrements in AB performance. Overall, results in the thesis suggest that distributed attention is optimal in different circumstances to a focused attention, rather than attention being 'good' only when focused. Due to the visually matched tasks employed in the thesis, the results provide stronger evidence for the existence of a dissociable distributed attention state than many previous studies in both spatial and temporal attention.

As apparent from the foregoing discussion, the assumption behind designing the AB-IC paradigm is that the AB task is best performed under a distributed attention. This was proposed by Olivers and Nieuwenhuis (2006) after finding that participants were better at reporting both targets while performing a secondary concurrent task or while thinking task-unrelated-thoughts. More specifically, the authors argued that an overinvestment of attention in T1 processing led to attentional blinks. Similarly, Olivers and Meeter (2008) proposed that blinks occur when there is a strong cognitive boost to targets followed by a strong bounce leading participants to miss the second target. Along the same lines, a neural theory proposes that attentional blinks result from a refractory neural period after phasic firing of LC-Na neurons (Aston-Jones & Cohen, 2005; Nieuwenhuis et al., 2005). The present findings are consistent with these theories. By contrast, the findings challenge an earlier but still prevailing theory regarding the Attentional Blink that the failure in detecting the second target reflects a limited attentional capacity (Raymond et al., 1992; Chun & Potter, 1995; Arnell & Jolicoeur, 1999). This theory would predict that exogenous cueing or slower presentation rates that facilitate T1 processing should result in more free capacity for T2 processing, but current results showed decrements to T2 detection in these conditions. Moreover, mind wandering or performing a

concurrent secondary task would be expected to put a strain on the limited attentional capacity and increase attentional blink rates, but the opposite was observed.

Object-based vs. Broader scope

A further question regarding the nature of focused vs. distributed temporal attention was raised by results regarding speed of presentation. Specifically, it was found that slower presentation rates reduced illusory conjunctions (i.e. benefitted focused attention), whereas faster presentation rated reduced attentional blinks (i.e. benefitted distributed attention). One interpretation of this result is that at slower presentation rates, participants were better able to focus attention, at the expense of attentional blinks (Olivers & Nieuwenhuis, 2006). A further, albeit not contradictory explanation is that at slow presentation rates participants can perceive items within the RSVP as individual objects, whereas at faster presentation they may treat the entire stream as a single object. This interpretation is in line with Treisman's definition of focused attention as feature-binding and object-based (Treisman & Gelade, 1980; Treisman & Schmidt, 1982). Indeed, the fact that endogenous cueing of the time of onset remained ineffective at slow presentation rates may suggest that focused attention is not directed towards a moment in time, but is rather object-based.

Findings in this thesis support the view that attentional blinks are reduced when there is less investment in individual stimuli. While most of the reported results show that less task investment benefitted the AB task, in fact less task investment may also involve less investment in the processing of each individual stimulus object. Chapter 4 reported that AB performance was not disrupted by mind wandering, and mind wandering involves a decoupling of attention from the current task (Schooler et al., 2011; Kam & Handy, 2013). Additionally, dual tasking, which is associated with less involvement in each task (Miyake et al., 2000; Lavie et al., 2004), was found to be beneficial to AB performance. Furthermore, Chapter 5 also reported that event-related potentials to the T1

target, which track target processing (Polich, 2007; Miniussi et al., 1999), were markedly reduced in the AB task. Without excluding the idea of less investment overall, this result suggests that distributed attention involves less investment in individual stimuli. Results in Chapter 3 supported this, as it was found that exogenous orienting to T1, widely believed to focus attention and improve object processing (Posner, 1980; Treisman & Gelade, 1980; Treisman & Schmidt, 1982) is detrimental within the AB task. Finally, findings from a previous study also support the interpretation that the AB is best performed when object stimuli are not individualized. Raymond (2003) reported that attentional blinks were eliminated when the whole RSVP stream was perceived as a single moving object, while attentional blinks occurred when distractors between T1 and T2 were objects that became differentiated. An interesting question for future research is how this hypothesis relates to the proposal that while focused attention individualizes objects, distributed attention favours statistical processing (Chong and Treisman, 2005a; 2005b; Summerfield et al., 2011). For example, within the AB-IC paradigm we might study whether participants are more likely to correctly identify statistical properties of the RSVP stream during the AB or IC task.

Temporal attention trade-offs and the exploration–exploitation dilemma

The current thesis has investigated focused and distributed attention in time within the larger literature on trade-offs in cognition and behaviour. Thus, animals face a trade-off in their foraging behaviour, between the need to exploit a source of food and continue to explore or monitor their environment for new opportunities or threats (Charnov, 1976). Machine learning scientists have tried to solve the dilemma and find the right moment when one should stop exploring options and start exploiting a certain task goal (Gittins & Jones, 1974; Gittins, 1979; Kaelbling et al., 1996). The question of how humans make decisions to solve the exploitation-exploration dilemma has likewise been studied behaviourally (Daw et al., 2006; Manohar & Husain, 2013) and in terms of neural correlates (Kolling et al., 2012; Fallon & Cools, 2014; Froeber & Dreisbach, 2016). A conceptual link between exploitation-exploration and temporal attention was proposed by Aston-Jones and Cohen (2005), who argued that temporal attention acted as a gating mechanism for decision making along the exploitation-exploration continuum. Furthermore, phenomena that were previously believed to exemplify failures of attention or performance, such as mental fatigue or lapses of vigilance (Kahneman, 1973) have recently been described as potentially reflecting the cost of exploiting the current task at the expense of lost opportunities (Kurzban et al., 2013).

While not directly investigating the link between temporal attention trade-offs and the exploitation-exploration dilemma, research in this thesis has found similar attributes. A key shared attribute is that the two states in each pair involve both benefits and costs alike. Exploitation decisions may carry the benefit of a stable working memory and enable the pursuit of rewards, but there may be less flexibility of integrating new information (Fallon & Cools, 2014). Exploration may be associated with increased flexibility of behaviour, but reaction times are increased (Froeber & Dreisbach, 2016). Within the AB-IC paradigm, focusing one's attention on one target carried the cost of failing to perceive other targets,

while processing both targets decreased the ability to report specific features of one of them. This trade-off was observed within each trial in Chapter 6. Additionally, participants who had a trait-like tendency to be more focused were on the other hand less able to distribute their attention, and the reverse.

The associations between mind wandering and focused vs. distributed attention in time are also relevant within the discussion of trade-offs in behaviour and cognitive states. Mind wandering illustrates such trade-offs, being costly to current task goals (Smallwood & Schooler, 2006; 2015; Killingsworth & Gilbert, 2010), but being beneficial in a range of contexts (Smallwood & Andrews-Hanna, 2013) including delaying gratification (Smallwood et al., 2013, Bernhardt et al., 2014), thinking creatively (Baird et al., 2012) and exploring opportunities or planning for future goals (Baird et al., 2011; Smallwood et al., 2009). Of these, the latter may be conceptually mapped onto the exploitation-exploration trade-off as a form of internal exploration. Interestingly, it was found that cognitive control may determine when people mind wander, such that participants with good cognitive control abilities only mind wandered when the external environment did not necessitate their attention (Kane & McVay, 2012; Unsworth & MacMillan, 2013; Levinson et al., 2012; Rummel & Boywitt, 2014; Smallwood & Andrews-Hanna, 2013). Within exploration-exploitation, individual differences in behaviour were also found (Kayser, Mitchell, Weinstein & Frank, 2015). Participants with a more external perceived locus of control showed more uncertainty-driven exploration behaviours, while a pharmacological manipulation of dopamine increased exploration but not exploitation behaviours in participants with a particular dopamine-related genotype. In the present thesis, individual differences in the temporal attention trade-off were reported in Chapter 6, but the thesis did not investigate individual differences in the ability to calibrate attention along the focused-distributed trade-off. Future studies may use the blocked AB-IC paradigm to investigate whether individual differences in cognitive control are related to how much participants mind wander during the

IC vs. the AB task, considering that mind wandering is detrimental to the former but not the latter.

A further similarity between exploitation-exploration and focused-distributed temporal attention is their alternating or fluctuating nature. In decision-making, Daw et al. (2006) observed fluctuation between periods of exploitation of the option with the best reward and periods of exploration, when the next-to-best reward options were chosen. A similar alternation was observed in the present thesis. While attention traded off within each trial between either being focused on T1 and its colour or being distributed across the visual stream, on the other hand attention states were preserved from one trial to the next. Trials when identification of T1 and its colour were correct followed after other such trials, and the same was the case for trials when both letters were correctly identified.

As well as fluctuating in similar ways, attention and other cognitive states may share a similar bias. In Chapter 6, we found that AB performance was unaffected by the increased task load (having to make three responses) as compared to Experiment 1, although T1 errors and illusory conjunctions were increased. One possibility is that this finding reflects a preference for a distributed attention state, although the results are not conclusive because they may be explained by the IC task being more difficult and more likely to be affected by task load. Nevertheless, a potential preference for distributed attention fits within the larger context of biases in cognition, especially because of the association between distributed attention and mind wandering found in Experiments 1 and 5. Mind wandering has been related to activation of the default mode network of the brain (Buckner et al., 2008) and may thus represent a default mental state, given its very frequent occurrence (Kane et al., 2007; Killingsworth & Gilbert, 2010). A preference for distributed attention in space was suggested by findings of global precedence in Navon tasks (Navon, 1977; Hoffman, 1980; Miller, 1981; Pomerantz, 1983).

There are several lines of evidence supporting the existence of an 'exploration bias' in decision making. In machine learning Kaelbling (1993) found that an exploration bias, or 'uncertainty bonus' that favours choosing uncertain options may be beneficial for performance. Studying human behaviour in the multi-armed bandit task, Daw et al. (2006) did not report such an exploration bias. However, this bias may be context-dependent. As McClure et al. (2006) explain, an exploration bias may be necessary in the early stages of decision-making, when it acts as an annealing mechanism adding noise to the system such that new associations can be learnt on top of older associations (Cohen et al., 2007). In terms of neural mechanisms, McClure et al. (2006) suggest that the dopaminergic system computes reward, while frontal regions together with the locus-coeruleus noradrenergic system (LC-Na) act as the annealing mechanism. Interestingly, the dopaminergic reward system has been found to be modulated by novelty-seeking, which may potentially be a reflection of an exploration bias (Bardo et al., 1996; Kakade & Dayan, 2002). Overall, there are interesting links between biases in attention state and exploration or novelty biases, and these may be investigated for example by looking at the fMRI correlates of periods of distributed attention bias during the AB-IC non-blocked tasks, compared to an exploration-exploitation task.

Finally, an interesting link between the current thesis and the exploitation-exploration dilemma comes from the literature on the locus coeruleus – noradrenergic system (LC-Na). The system has been proposed to have a key role in mediating exploitation and exploration, but also to be involved in temporal attention (Aston-Jones & Cohen, 2005). Of particular interest, Nieuwenhuis et al. (2005) proposed that the LC-Na system mediates the attentional blink, which occurs due to a refractory period of LC neurons that follows phasic firing. Evidence for this hypothesis from pharmacological manipulations has been mixed (Jepma et al., 2010; Warren et al., 2017; Nieuwenhuis et al., 2007; De Martino et al., 2008), perhaps because pharmacological manipulations cannot directly

influence phasic and tonic firing of the LC-Na. However, pupil dilation, which is considered to be a proxy of LC-Na activity (Murphy et al., 2014), has been associated with the exploitation-exploration trade-off as well as temporal attention. Pupil dilation is observed before periods of exploration compared to exploitation (Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011; Hayes & Petrov, 2016) and following target detection for either single temporal targets as well as both targets within the AB (Kihara et al., 2015; Wierda, van Rijn, Taatgen & Martens, 2012; Wolff, Scholz, Akyurek & van Rijn, 2015), but overall pupil dilation was smaller when targets were presented at a short lag (Zylberberg, Oliva & Sigman, 2012).

These findings may suggest a potential connection between the LC-Na and both exploitation-exploration and temporal attention trade-offs, but the precise mapping of pupil dilation size and attention state remains unclear. Interestingly, pupil diameter has also been found to vary with other factors studied throughout the thesis. Of relevance to the theme of focused attention, Akdogan, Balci and Van Rijn (2016) reported that pupil dilation was more rapid when temporal targets were expected at short delays compared to long delays. Furthermore, in relation to distributed attention, Konishi et al. (2017) found that a large pupil size was associated with external distraction, while a small pupil size was related to mind wandering. A range of further hypotheses with regard to pupil dilation can be tested within the AB-IC paradigm. Pupil diameter could be compared before correct AB and IC trials within the non-blocked AB-IC paradigm, with the prediction that larger pupil diameters would precede correct AB vs. IC trials (cf. Jepma & Nieuwenhuis, 2011). On the other hand, pupil diameter size can be studied in relation to mind wandering episodes during the AB-IC paradigm, predicting that high mind wandering levels would be associated with small pupil dilation and reduced attentional blink sizes (cf. Konishi et al., 2017; Zylberberg et al., 2012). Collectively, these studied would provide useful insight into a possible

psychopharmacological mechanisms underpinning the trade off between focused and distributed attention.

Conclusions

To conclude, the present thesis contributes to our understanding of temporal attention and to the larger literature on trade-offs in focused vs. distributed processing in a number of ways. First, it introduces the novel AB-IC paradigm to provide reliable measures of focused and distributed attention in time in two visually matched tasks. Second, it provides evidence for the existence of trade-offs between focused and distributed attention in time, which are affected in opposite ways by a number of experimental manipulations that aim to induce focused or distributed attention, as well as by mind wandering levels. Additionally, focused and distributed attention are dissociable in terms of their neural correlates. Crucially, the thesis provides evidence that focused and distributed attention are each optimal in different task circumstances, rather than a 'good' attention being always focused and selective, as has been often argued or implied (James, 1890). Findings in this thesis suggest that attention can trade off in the form of modes, states or traits, and that attention fluctuates naturally but may also be strategically deployed by participants. The results raise interesting questions regarding the nature of focused and distributed attention in time, for example whether these differ in a binary way or vary on a continuum, and whether the two attention types can be described as involving the processing of single objects in the case of focused attention vs. higher-level processing in the case of distributed attention. Finally, the thesis closed on an experiment that introduced a novel variation to the AB-IC paradigm, exemplifying how the flexibility of AB-IC design can be useful to investigate a range of further questions with regard to the trade-off between focused and distributed temporal attention and how this may relate to the trade-off between exploitation and exploration.

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Appendix A

Table 1. Example questions from the AH5 general intelligence test used in Experiment 1.

Q1.	Which one of the five words on the right bears a similar relation to each of the two words on the left? Order. Immediate. 1. Plan 2.Instruct 3.Tidiness 4.Direct 5.Command
Q2.	Write down the number of the word which would come in the middle, if the following words were arranged in order of magnitude: 1. Street 2.Continent 3.Room 4.Country 5.Universe 6.Town 7.County 8.Planet 9.House

Table 2. Items from the Digit Symbol mental speed test used in Experiment 1.

1	2	3	4	5	6	7	8	9
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Table 3. Example item from the Beck Depression Inventory used in Experiment 1.

Sadness	
0	I do not feel sad.
1	I feel sad much of the time.
2	I am sad all the time.
3	I am so sad or unhappy that I can't stand it.

Table 4. Example item in the mind wandering self-report questionnaire used in Experiment 1.

On the below scale, please rate to what degree you have mind wandered in the task just completed:				
1	2	3	4	5
Not at all	A little	Average	A lot	All the time