Attentional Narrowing:
Triggering, Detecting and Overcoming a Threat to Safety

by

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We have two lives.

The second begins when we realize we only have one.

- Confucius-

To maman, papa, bibou, and my guardian angel

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ALL: Novel problem, high task load and incentive scenario .... Chapter 3

AN-Co: Attentional narrowing with a command display intervention .... Chapter 5

AN-None: Attentional narrowing without any intervention .... Chapter 5

AN-St: Attentional narrowing with a status display intervention .... Chapter 5

BAS: Baseline scenario .... Chapter 3

DA I: Detection algorithm I .... Chapters 4 and 5

DA II: Detection algorithm II .... Chapters 4 and 5

DD: Dwell duration .... Chapters 3, 4 and 5

DR: Detection rate .... Chapters 2, 3 and 5

INC: Incentive scenario .... Chapter 3

MATB II: Multi-Attribute Task Battery II .... Chapters 3 and 5

NVP: Novel problem scenario .... Chapter 3

PoF: Percentage of fixations .... Chapters 3, 4 and 5

REMAN: Resource management .... Chapters 3, 4 and 5

RMSD: root mean square deviation .... Chapters 3 and 5

SCHED: Scheduling task .... Chapters 3 and 5

SD: Standard deviation .... Chapters 2, 3 and 5

SYSMON: System monitoring task .... Chapters 3 and 5

TRCK: Tracking task .... Chapters 3 and 5

WKL: High task load scenario .... Chapter 3

ABSTRACT

In complex safety-critical domains, such as aviation or medicine, considerable multitasking requirements and attentional demands are imposed on operators who may, during off-nominal events, also experience high levels of anxiety. High task load and anxiety can trigger attentional narrowing – an involuntary reduction in the range of cues that can be utilized by an operator. As evidenced by numerous accidents, attentional narrowing is a highly undesirable and potentially dangerous state as it hampers information gathering, reasoning, and problem solving. However, because the problem is difficult to reproduce in controlled environments, little is known about its triggers, markers and possible countermeasures.

Therefore, the goals of this dissertation were to (1) identify reliable triggers of attentional narrowing in controlled laboratory settings, (2) identify real-time markers of attentional narrowing that can also distinguish that phenomenon from focused attention – another state of reduced attentional field that, contrary to attentional narrowing, is deliberate and often desirable, (3) develop and test display designs that help overcome the narrowing of the attentional field.

Based on a series of experiments in the context of a visual search task and a multi-tasking environment, novel unsolvable problems were identified as the most reliable trigger of attentional narrowing. Eye tracking was used successfully to detect and trace the phenomenon. Specifically, three eye tracking metrics emerged as promising markers of attentional narrowing: (1) the percentage of fixations, (2) dwell duration and (3) fixation duration in the display area where the novel problem was presented. These metrics were used to develop an algorithm capable of detecting attentional narrowing in real time and distinguishing it from focused attention. A command display (as opposed to status) was shown to support participants in broadening their attentional field and improving their time sharing performance.

This dissertation contributes to the knowledge base in attentional narrowing and, more generally, attention management. A novel eye tracking based technique for detecting the attentional state and a promising countermeasure to the problem were developed. Overall, the findings from this research contribute to improved safety and performance in a range of complex high-risk domains.

Chapter 1

Introduction

Operators in complex event-driven domains such as aviation, medicine or nuclear power have to cope with considerable attentional demands (Vincente, Mumaw & Roth, 2004). During routine operations, they are required to divide their limited attentional resources effectively across several tasks and displays. In safety-critical and/or off-nominal situations, they may need to allocate attention to only one task or problem and engage in focused attention. Focused attention refers to the ability to concentrate, *deliberately*, on one task or source of information while suppressing others. A reduction in attentional scope is observed also when operators experience a phenomenon called attentional narrowing. Attentional narrowing is characterized by an *involuntary* reduction in the range of cues that are utilized by an individual (Mueller, 1976). This state is triggered by high levels of arousal and/or affects high in motivational intensity, such as excessive workload or threat. When experiencing attentional narrowing, operators are unaware of their limited perceptual and cognitive scope and falsely assume that they have a complete picture of the situation. Thus, depending on context, divided and focused attention can be necessary and appropriate mental states whereas attentional narrowing is a condition that needs to be avoided at all times, as illustrated by .accidents in a number of domains, including aviation.

For example, a study by Shappell and Wiegmann (2003) showed that attentional narrowing was a contributing factor to all controlled-flight-into-terrain (CFIT) accidents in the US Air Force. Attentional narrowing was also responsible for the crash of Eastern Airlines Flight 401 in 1972, in which 103 people lost their lives. In this case, a landing gear indicator light failed during approach. All three pilots focused exclusively on diagnosing the problem. As a result, they failed to notice that the autopilot had been disengaged inadvertently, which resulted in the aircraft gradually descending and ultimately crashing into the Everglades (NTSB, 1973). More recently, attentional narrowing was identified as a contributing factor to the crash of Singapore Airlines flight 006 in 2000, which led to the loss of 83 lives. Due to extreme and rapidly degrading weather conditions, the pilots had to rush their preparations for takeoff and narrowed their attention on making sure that the winds were still within safe limits; in the process, they failed to notice that they were lined up on the wrong runway. The Aviation Safety Council of Taiwan stated that “under the severe weather situation experienced by the crew, the flight crew’s attention had overly narrowed […] on the weather information to the detriment of other critical operational information” (ASN, 2008).

These catastrophic events illustrate the importance of addressing the challenge of attentional narrowing. However, to date, surprisingly little is known about the triggers of this potentially dangerous state, its effects on human performance, and promising ways to overcome the problem. These gaps can be explained, in part, by the fact that it is difficult to reproduce attentional narrowing in controlled laboratory settings, hampering research efforts in this area. The ultimate goal of this dissertation is to develop context-sensitive display designs that can overcome attentional narrowing. To this end, the following three research objectives are addressed:

(1) Identify reliable triggers of attentional narrowing in controlled laboratory settings

(2) Identify markers of focused attention and attentional narrowing that help distinguish between the two attentional states in real time

(3) Develop adaptive display designs that help overcome the undesirable state of attentional narrowing.

This chapter will first provide an introduction to the two attentional states of primary interest in this research: focused attention and attentional narrowing. Next, the effects of stress on attention and performance will be discussed, and an overview of proposed triggers of attentional narrowing will be presented. A promising means of detecting and tracing the problematic state in real time - eye tracking - will be described. Finally, possible countermeasures to attentional narrowing will be explored.

Focused attention and attentional narrowing: the importance of distinguishing two attentional states

Operators engage in one of four types of attention while performing tasks, which differ in the amount of resources that are utilized and how they are allocated

(Knowles, 1963): (1) selective attention, (2) sustained attention, (3) divided attention and (4) focused attention. Selective attention is the process in which "the organism selectively attends to some stimuli or aspects of stimuli, in preference to others" (Kahneman, 1973) and can be appropriate, for instance, when one task or subset of tasks becomes more demanding. Sustained attention is also referred to as vigilance, and is defined as "a state of readiness to detect and respond to certain small changes occurring at random time intervals in the environment" (Mackworth, 1957).

Of particular interest to the present research are divided and focused attention. Divided attention refers to "performing two or more tasks or processing two or more sources of information concurrently" (e.g. Zanto & Gazzaley, 2014). This type of attention underlies task sharing or multitasking which is required of operators in most real-world domains.

Focused attention

When the demands associated with a particular task increase or when a novel challenging problem is encountered, operators may need to engage in focused attention which has been defined as a "goal-directed orientation of the (attentional) spotlight which breaks down when processing of selected elements is disrupted by unwanted distractions" (Wickens, 2006). In other words, when engaged in focused attention, operators actively and deliberately suppress unwanted information and interruptions with the goal to maintain or improve performance on the ongoing task or line of reasoning. During final approach, for example, a pilot needs to focus his/her attention on the instruments and outside view and suppress potential disruptions, such as conversations that are not related to the flight. This requirement is reflected in the ‘Sterile Cockpit Rule’, an FAA regulation requiring pilots to refrain from non-essential activities during critical phases of flight.

Provided that operators correctly identify and distinguish critical from irrelevant tasks and stimuli, focused attention is a highly desirable state that should be supported. In addition to training, rules and regulations, display design can help achieve this goal. It has been shown, for example, that attentional focus and information processing can be improved when information is presented in a continuous manner on a display (Broadbent, 1982; Posner, 1980; Tsal & Lavie, 1988). Lowlighting irrelevant cues can also support more efficient focusing of attention by preventing undesirable data-driven shifts of attention (Jonides & Yantis, 1988; Todd, 1979). Finally, displays that support preattentive reference by providing partial information about potential interruptions in an ambient fashion allow the operator to make informed decisions about attention switching without disrupting the ongoing task (Hameed et al., 2006).

Focused attention can fail in at least two ways. One possible breakdown in focused attention is “the failure to attend to a central stimulus while ignoring more peripheral stimuli” (Wickens & Hollands, 2000). This failure can occur when irrelevant stimuli are too salient and require a high level of mental effort to be ignored. Also, when several information sources are presented in close spatial proximity, it may become difficult for the operator to focus on only one while ignoring the other less relevant sources (Holahan, Culler & Wilcox, 1978; Wickens, 1992). This problem may be experienced, for example, with cluttered, configural or object-based displays. Another way in which focused attention can break down is when the importance of a task or piece of information is misjudged by the operator, leading him/her to miss more critical events or diagnostic cues.

On the surface, focused attention and attentional narrowing – the main focus of this research - appear very similar. Both states are characterized by a narrowing of the scope of attention. But while focused attention is deliberate and potentially necessary and appropriate, attentional narrowing is involuntary, undesirable and potentially dangerous. Thus, it is critical to be able to distinguish the two states and to overcome attentional narrowing.

Attentional narrowing

Definition

Attentional narrowing was first discussed and examined in the 1950's (e.g., Bahrick, 1952; Combs & Taylor, 1952; Kohn, 1954; Easterbrook, 1959). At the time, several terms were used to refer to the phenomenon: "narrow strip-maps" (Tolman, 1948), "perceptual selectiveness" (Bahrick, 1952), "breadth of learning" (Bruner, 1955), and "narrow attention" (Callaway, 1958). In 1959, Easterbrook developed the cue utilization theory which posits that high levels of arousal (which Easterbrook described as "drive", i.e. "a dimension of emotional arousal or general covert excitement") and emotions, especially negative ones, lead to a shrinkage of the perceptual visual field, i.e., a "reduction in the range of cues that can be used". At the time, experiments on attentional narrowing were most often conducted using a dual-task paradigm (Wachtel, 1967; Cornsweet, 1969) where participants were asked to perform a main task which was presented in their central field of view. Their second task was to detect lights that were presented in their peripheral visual field. Arousal and negative emotions were varied using a range of manipulations, such as physical discomfort (Callaway & Thompson, 1953), heat and humidity (Bursill, 1958), or electric shock (Wachtel, 1968).

Participants' attentional scope was assessed based on the detection of the peripheral visual stimuli.

Early findings from these studies suggested that attention narrows towards the central point of the visual field. However, later research showed instead that the task or stimuli towards which attention converges depends on additional factors than simply their physical location. In particular, it was found that attention tends to be captured by salient stimuli in the environment (in a bottom-up fashion) or by tasks and stimuli that are perceived to be of high importance or priority (in a top-down fashion), irrespective of their location relative to the person (Bacon, 1974; Weltman et al., 1971; Dirkin & Hancock, 1983). Tasks of perceived lower importance tend to drop off while tasks of perceived higher importance are attended (Houston, 1967; Hockey, 1970; Broadbent, 1971; Bacon, 1974). Additionally, attention narrows towards stimuli that have a higher probability of occurring (Hockey, 1970; Dirkin & Hancock, 1984) and/or that are relevant to the main task (Reeves & Bergum, 1972).

Originally, attentional narrowing was considered a purely perceptual phenomenon that was studied primarily in the visual domain. More recently, a small number of studies has suggested that the phenomenon may affect other modalities as well. For example, a recent study by Dehais (Dehais, Causse, Vachon, Regis, Menant, Tremblay, 2014) found that 40% of pilots missed an auditory alert triggered during a stressful situation (windshear during landing). Still, it appears that the auditory and tactile modalities are less vulnerable to attentional narrowing, compared to the visual channel (e.g., Hess, 2006). Recent studies also demonstrated that narrowing is not a purely perceptual phenomenon but that it occurs at the level of higher cognitive functions (e.g., hypothesis generation) as well (Keinan et al., 1999). In addition, the narrowing of attention can , impair the ability to perceive time (for a review, see Hancock & Weaver, 2005), leading operators to pursue an erroneous solution for longer than appropriate (Cowen, 1952).

These recent findings have led to broader definitions of attentional narrowing, and various terms have been used in the literature to refer to the perceptual and cognitive aspects of the phenomenon. For example, ‘tunnel vision’ was used in early experiments on perceptual narrowing (Williams, 1985) and, more recently, to describe the attentional state in the context of police work (Findley & Scott, 2006). The terms ‘attentional tunneling’, ‘cognitive capture’ and ‘cognitive tunneling’ tend to be employed in research on object-based visual attention, such as studies evaluating the effects of head-up displays (displays that presents information directly on the user’s field of view, as a transparent overlay) and vision enhancement systems (Gish, Saplin & Perel, 1999; Thomas & Wickens, 2001; Wickens et al., 1998; Wickens & Alexander, 2009) on attention. ‘Cognitive narrowing’ is the preferred term in the literature on the effects of affective states on the attentional field (Wachtel, 1967; Gable & Harmon-Jones, 2010), while ‘“perseveration syndrome” and “inattentional deafness” have been used in the aviation literature (Dehais et al., 2010; Dehais et al., 2014)”.

One of the most widely accepted and encompassing definition of attentional narrowing was proposed by Wickens (2005): “the allocation of attention to a particular channel of information, diagnostic hypothesis or task goal, for a duration that is longer than optimal, given the expected costs of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks”. In other words, **attentional narrowing is experienced when (1) attention is allocated to one task for an inappropriately long period of time, and (2) performance on other tasks drops as a result.** This definition of attentional narrowing will be used for the remainder of this document.

Triggers of attentional narrowing

As mentioned earlier, the study of attentional narrowing requires that the phenomenon can be induced reliably in controlled laboratory settings. This requires the identification of effective triggers of this mental state. To date, a wide range of causes have been proposed, many of which relate to the general concepts of ‘stress’ and ‘anxiety’.

<u>The effects of stress on human performance, cognition and attention</u>

Early definitions of stress focused on either external triggers (e.g., Janis & Mann, 1977) or an individual’s response to these stimuli (e.g., Ivancevich & Matteson, 1980). Later definitions (e.g., Hancock, 1989) acknowledged the mutuality of both factors and described stress as resulting from the interaction of: (1) the physical characteristics of the environments, or inputs, (2) the compensatory processes of the individual, or adaptation, and (3) the performance effects, or outputs. The definition of stress that has been most widely accepted was proposed by Lazarus and Folkman (1984), and is the one that will be used in the rest of this document: “Psychological stress is a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being” (Lazarus & Folkman, 1984). In other words, stress is described as the result of the interaction of two factors - environment and person demands - that exceed available resources.

High levels of stress can have terrible effects on human performance (for early findings, see Basowitz et al., 1955) such as (1) induce physiological changes, such as an increased heart rate (Lazarus, Speisman, & Mordkoff, 1963), (2) impair cognitive functions, such as working memory (see, for instance: Berkun, 1964; Wachtel, 1968; Mandler, 1979;

Davies & Parasuraman, 1982), problem solving (see, for instance, Yamamoto, 1984), and decision making (Cohen, 1952; Wright, 1974; Keinan, 1987) and (3) harm social skills, such as the ability to work in teams (Driskell, Salas & Johnston, 1999). Importantly and closely related to the focus of this research, stressors can lead to 'distraction', i.e., the deviation of attention away from task-related cues (Alkov, Borowsky & Gaynor, 1982), and to 'perseveration' or 'problem-solving rigidity' (Zakay, 1993), which is defined as a situation where the individual fails to consider alternative hypothesis or data dimensions (Wright, 1974) and persists with a particular intention or method even though it has proven unsuccessful (Cohen, 1952). Hypervigilance – defined as "an impulsive, disorganized pattern of decision making" (Janis & Mann, 1977) - has also been observed under high stress and identified as a contributor to the observed performance decrements (Johnston, Driskell & Salas, 1997). Last, internal stressors can also lead to "ballistic decision making" (Dörner 1996), where decisions are made without proper consideration of their implications. Distraction, perseveration, hypervigilance and ballistic decision making are stress-induced cognitive changes that are expressions of attentional narrowing.

Anxiety

Over the past 60 years, a wide range of internal stress factors have been proposed to contribute to a narrowing of the attentional scope (for a more complete overview of findings, see, for example, Staal, 2004; Friedman & Foster, 2010). These factors have in common that they trigger anxiety which Matthews & MacLeod (1994) define as follows: “Anxiety is […] defined by response rather than stimulus. […] It is associated with quite a complex cognitive pattern, which includes both a deficit in resources or working memory and a bias in selective attention that prioritizes threat stimuli”. In other words, anxiety is described as an emotional state induced by stress, and characterized by a reduction of the attentional resources available. Anxiety is a concept that has been described as multidimensional (Hodgson & Rachman, 1974; Lang, 1969), and two main dimensions of anxiety have been described: cognitive and somatic anxiety (Davidson & Schwarts, 1976). They each affect human performance in different ways. Cognitive anxiety affects human processes at a cognitive level and has been associated with the concepts of ‘arousal’ and ‘worry’, while somatic anxiety, on the other hand, corresponds to an emotional affect and has been associated with the concepts of ‘high motivational intensity’ and emotionality. Cognitive and somatic types of anxiety are not independent, and their effects on human performance have been studied both independently and in combination (Hardy & Fazey, 1987; Derryberry & Tucker, 1994; Janelle, 2002; Friedman and Foster, 2010; Harmon-Jones, Price & Gable, 2012). The two possible triggers of attentional narrowing that have received the most attention in recent years are arousal and high motivational intensity.

Arousal. Arousal is defined as an energetic state of the organism (e.g., Bourne, 2003; Stokes & Kite, 2001). It is associated with being more alert and awake, highly active and reactive to stimuli (Bourne, 2003). Human performance has been shown to be tightly linked to levels of arousal. This relationship is being described by the Yerkes-Dodson law (Yerkes & Dodson, 1908) which stipulates that performance on complex tasks reaches its highest point at an intermediate level of arousal (see Figure 1.1), and decreases with both lower and higher levels of arousal. The optimum level of arousal depends on the task the person is engaged in and, in particular, on its complexity.

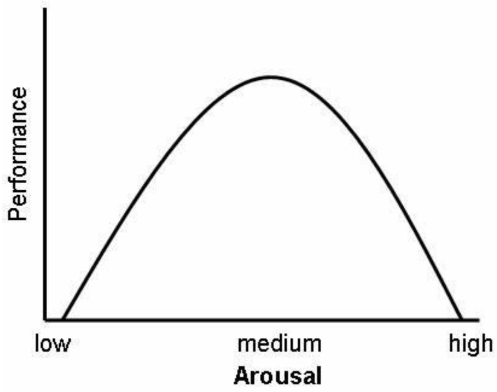


Figure 1.1 - The Yerkes-Dodson law (Yerkes and Dodson, 1908)

Easterbrook's cue utilization theory and the Yerkes-Dodson law both predict that high levels of arousal lead to performance decrements as "arousal restricts the range of cues among which attention may be divided" (Kahneman, 1973). Early on, when arousal starts to increase, only irrelevant cues are missed, but as the arousal level rises further, task-relevant cues are being dropped as well and performance decreases. Complex tasks and multi-tasking rely heavily on divided attention and are therefore more sensitive to high levels of arousal; for these tasks, optimum levels of performance are therefore achieved at lower arousal levels than for simple tasks, as illustrated in Figure 1.2.

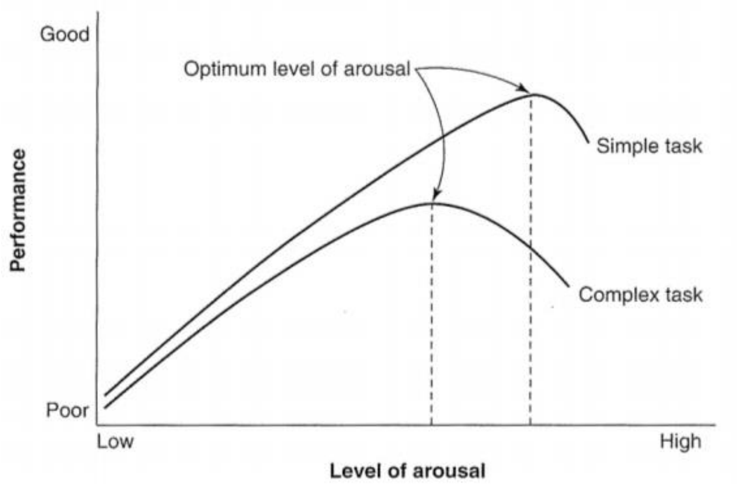


Figure 1.2 - Adaptation of the Yerkes-Dodson Law for simple and complex tasks

Factors leading to an increase in arousal fall into two main categories: environmental factors and task demands. Environmental factors include extreme heat, high humidity, strong vibrations, bright lighting and loud noise (e.g., Hancock et al., 2002; Bursill, 1958; Mackie & O'Hanlon, 1977; Kuller & Laike, 1998). Of these, noise has received the most attention to date. Generally, in loud conditions, the operator's attention will narrow in on those stimuli that are highly salient or presented more frequently (Smith & Broadbent, 1985). For example, Hockey (1970) demonstrated that loud ambient noise impaired task performance and decreased the range of perceived cues, especially for complex tasks. In the case of simple tasks, noise actually led to improved performance. Several later studies (e.g., Smith, 1991; Szalma & Hancock, 2011) confirmed that the effect of noise on attention depends on task features (e.g., whether the task requires the operator to be active or passive). The nature of the noise itself is also an important factor in determining its performance effects. Intermittent and aperiodic noise is particularly harmful (Broadbent, 1958). For example, in a study by Uchtdorf and Heldt (1989), 98% of participating pilots indicated that there are too many auditory cockpit alerts, and that these alerts are too loud and disruptive. The performance costs of loud noise on modern flight decks were illustrated by the accident of a French airliner in 2009 off the Brazilian coast. After pressure measurement devices had failed, erroneous indications of the plane’s airspeed and altitude led the pilots to enter a dangerous stall condition. This resulted in a 92dB aural stall warning that persisted for almost one minute and may have contributed to a narrowing of attention, preventing the pilots from scanning all available and relevant cues to diagnose the situation (BEA, 2012).

High task demands are another factor that contributes to increased arousal. Task demands are a function of the amount of information presented on a display, the complexity of the task and overall workload. Early research by Mackworth (1965) suggested that the more information is presented, the more the field of view is reduced. However, subsequent research found that the amount of data does not, in itself, reduce the scope of attention; instead, it is the associated increased task complexity and workload that trigger attentional narrowing (Ikeda, 1975; Williams, 1982). Also, higher levels of task complexity have been associated with a stronger sense of immersion – the feeling of “becoming physically (or virtually) a part of the experience itself” - (Pine & Gilmore, 1999) which, in turn, is believed to induce increased levels of arousal and therefore breakdowns in attention allocation (Parsons, 2009). More recently, Rantanen (1999) and Murata (2004) confirmed that high workload narrows the field of view and the attentional field.

High motivational intensity. Motivational intensity is defined as “the strength or urge to move towards/away from a stimulus” (Harmon-Jones & Price, 2013). Early research on the role of affect in attentional narrowing suggested that negative emotions trigger the phenomenon (Easterbrook, 1959) while positive affect has the opposite effect of broadening the attentional field. However, more recent studies found that both positive and negative affect can lead to attentional narrowing when combined with high motivational intensity (Gable & Harmon-Jones, 2008; Friedman and Foster, 2010) while broadening the attentional scope when low in motivational intensity (Harmon-Jones & Gable, 2009; Fredrickson & Branigan, 2005; Gable & Harmon-Jones, 2010). An example of a negative affective state of low motivational intensity is sadness; in contrast, disgust and fear are examples of a high motivational negative affect where the person is highly motivated to take action to avoid the stimulus or situation. A wide range of factors can trigger affects high in motivational intensity, including money incentives (Bahrick, Fitts & Rankin, 1952, social stress (Sanders, Baron & Moore, 1978), scary novel situations (Weltman & Egstrom, 1966), conflicts (Mann, 1992), faces expressing negative emotions (Fenske & Eastwood, 2003), ego-threatening tasks and approach/avoidance motor actions (Forster et al., 2006).

Researchers do not agree on the relationship between arousal and motivational intensity, mostly due to their disagreement about the definitions of those concepts. While Harmon-Jones, Price and Gable (2012) suggest that “motivational intensity, rather than arousal per se, is the variable that causes attentional narrowing”, Bradley and Lang (2007) argue that the two concepts are the same. In contrast, Bourne (2003) claims that arousal and motivational intensity are separate phenomena. The effects of both factors on attentional narrowing appear to be affected by personality factors, such as trait anxiety (e.g., Pacheco-Unguetti et al., 2010; see Figure 1.3). Highly anxious individuals are more likely to engage in attentional narrowing (Derryberry & Reed, 1998; Koster et al., 2005).

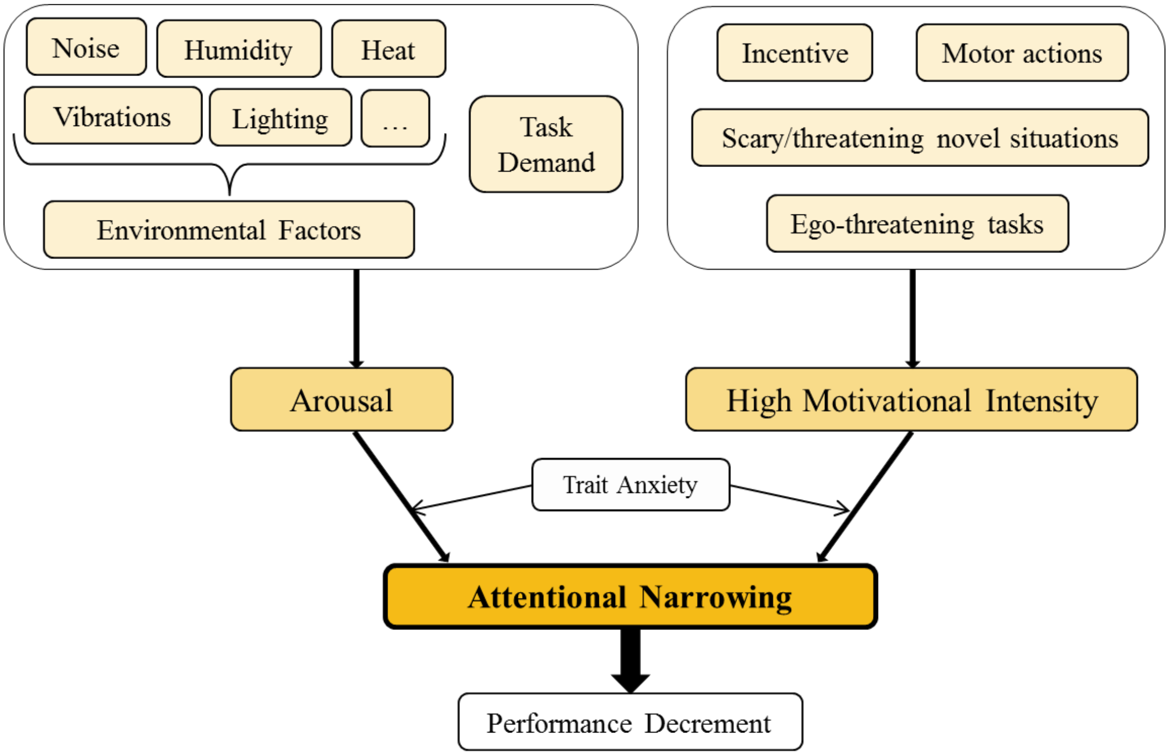


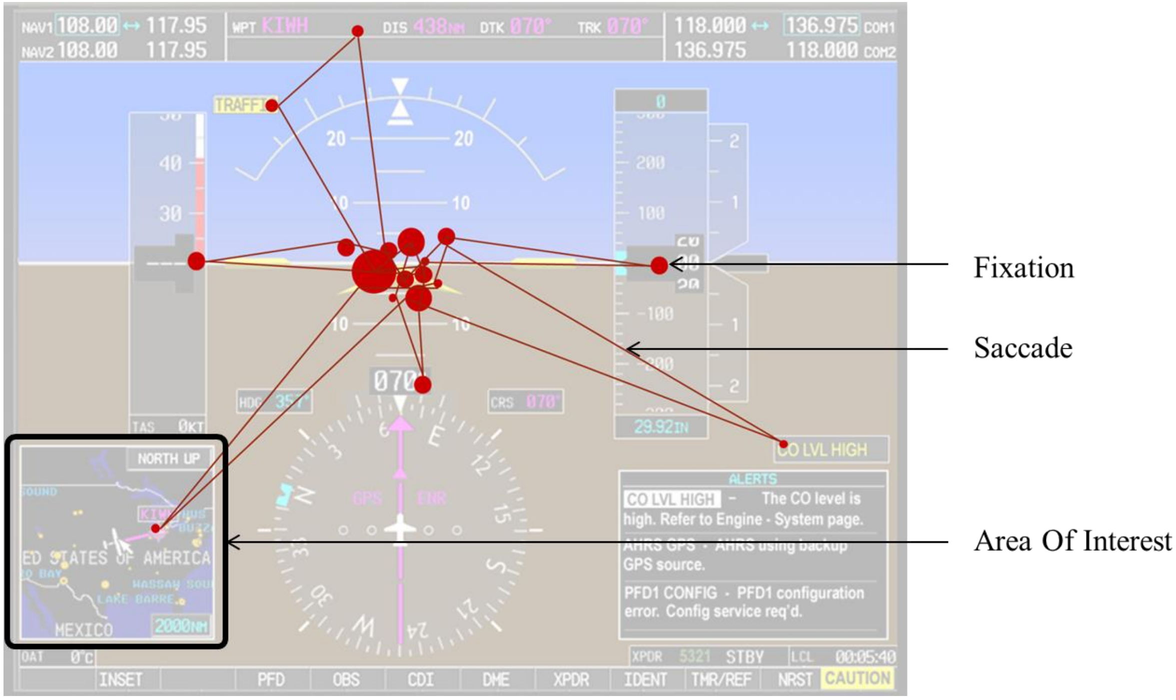
Figure 1.3 - A framework of triggers of attentional narrowing

Eye tracking as a marker of attentional narrowing and focused attention

In addition to understanding when and why attentional narrowing is experienced, it is important to develop means of detecting and correctly identifying this attentional state in a timely fashion. To this end, the proposed research aims to identify valid real-time markers of both focused attention and attentional narrowing. An indirect way of assessing attentional narrowing is to infer it from the level of arousal and motivational intensity experienced by a person. This can be achieved using physiological measures, such as arterial blood pressure and blood flow (Boutcher & Boutcher, 2006), heart rate and heart rate variability (e.g. Bogdonoff et al., 1960; Appelhans & Luecken, 2006), and neuro-imaging techniques, such as positron emission tomography (Simpson et al., 2001), functional near infrared spectroscopy (fNIRS) (Glotzbach et al., 2011), and functional magnetic resonance imaging (fMRI) (Causse et al., 2013). While these measures are indicative of anxiety levels, they do not provide direct evidence of narrowing based on changes in operators' attention allocation. The technique proposed in this dissertation to use for this purpose is eye tracking.

Eye tracking is used to measure a person's point of regard - where the person is looking at on the display - in real time and with high spatial and temporal resolution (Zelinsky & Sheinberg, 1997). It provides information on a person's visual attention (Yarbus, 1967): both on what people purposefully look for in a display (top-down influence) and also what elements attract their attention (bottom-up influence) (Duchowski, 2007). Eye tracking has been widely used in human factors research and, in particular, in the domain of aviation (e.g., Kocian, 1987; Longridge et al., 1989). It has the advantage of being non-invasive and non-intrusive.

One important unit of analysis in eye tracking is a scanpath which consists of a combination of fixations and saccades. Fixations are defined as spatially stable positions of the eye which allow for processing of information in the attended location (Findlay, 2004). Saccades are rapid eye movements that occur between two fixations. It is believed that no information processing occurs during saccades (Yarbus et al., 1967). An area of interest (AOI) is a specific region of the display defined by the experimenter (see Figure 1.4), and a dwell (or gaze) is defined as the time between the first fixation in an AOI and the next fixation outside that AOI.



CO LVL HIGH - The CO level is high. Refer to Engine - System page.

AHRS GPS - AHRS using backup GPS source.

PFD1 CONFIG - PFD1 configuration error. Config service req'd.

Figure 1.4 - Illustration of fixations, saccades and an AOI (Area of Interest)

Combining these building blocks of eye tracking data, a considerable number of eye tracking metrics have been proposed in the literature (see Poole & Ball, 2004 for a review). These metrics can be used to identify or infer the reduction in the operators' attentional scope which characterizes both attentional narrowing and focused attention. First, the number of fixations in one AOI expressed as a percentage of the total number of fixations on the display provides a direct measure of the amount of visual attention allocated to the AOI (Sodhi et al., 2002; Poole et al., 2004; Thomas & Wickens, 2004). The duration of dwells in an AOI can also be used to trace shifts in attention allocation across the display, and have been used to detect attentional shifts (Mello-Thoms et al., 2004; Hauland, 2003; Thomas & Wickens, 2004; Harbluk et al., 2007). Another, more involved metric that could be used for detecting attentional narrowing is the convex hull area (defined as the smallest area that includes all the fixations on the display; Goldberg & Kotval, 1999). A smaller convex hull area indicates a smaller visual scanning pattern, and, as a result, a reduction of the attentional visual field. Fixation duration, a rather simple metric, correlates with information extraction difficulty (Just & Carpenter, 1976) and task load (Di Nocera, Terenzi & Camilli, 2006) and has therefore been associated with attentional narrowing (Janelle, 1999; Cowen & Ball, 2002; Tsai et al., 2007). These eye tracking metrics will be used to develop a tool that can detect attentional narrowing in real time and distinguish it from other attentional states, as described in the sections below. More detail on the use of eye tracking, and additional eye tracking metrics will be described in chapter 3.

Overcoming attentional narrowing

The ultimate goal of this dissertation is to develop an effective means of overcoming attentional narrowing in real time. To date, researchers have explored very few candidate techniques for achieving that objective. One such technique which focuses on the prevention of narrowing is previous experience with anxiety-inducing factors (Hancock, 1986). Some studies also suggest that operators who have been pre-exposed to important alarms (Dehais et al., 2014) are less likely to miss them during a stressful event. However, prior exposure to alarms and anxiety-inducing events is possible only to a limited extent because complex systems in real world domains can fail in a very large number of expected but also unanticipated ways.

Another approach that is concerned with the detection and recovery from attentional narrowing once this state has been entered is to present an alarm that makes the operator aware, and helps them break out of this condition (Dehais et al., 2010). To date, very few studies have explored how to best implement this approach. The alert would need to: (1) be triggered when attentional narrowing is sensed, (2) reliably capture attention without being too salient which might startle the operator and only increase his/her level of anxiety and (3) re-orient attention towards the tasks or pieces of information that have been neglected. The following sections discuss these requirements and challenges in more detail.

Timing of the alert and adaptive displays

Operators who receive too many alarms experience increased fatigue and may silent critical alerts and, as a result, alarm overload may lead to dangerous situations (see, for instance, Hollifield & Habibi, 2010 for a review on alarm management). It is thus important to ensure that the alarm is only triggered when attentional narrowing is experienced to avoid overloading operators with alerts. Context sensitive displays adjust characteristics of the interface– such as the salience, location or timing of its elements - in response to change(s) in the environment, the system or the operator (Parasuraman et al., 1992; Miller et al., 2005). The need for context-sensitive information presentation has been widely acknowledged, especially in complex domains (Bennett & Walters, 2001; Dorneich et al, 2003; Schmorrow & Kruse, 2004; Sarter, 2007). Adaptive displays automatically adjust parameters such as the location, salience, or timing of cues in response to sensed changes in environmental conditions (e.g., ambient noise), task demands or operators' needs and capabilities (Rothrock et al., 2002). Because they do not impose additional workload on operators (Hameed & Sarter, 2009), adaptive displays are thus a promising candidate to support attention capture during the highly stressful and overwhelming situations that are associated with attentional narrowing.

An important challenge for the design of adaptive displays is the choice of an effective invocation technique, i.e., a sensing mechanism able to detect when to trigger the intervention – in this case identify when attentional narrowing is experienced. As described earlier, to achieve this objective, a real-time detection algorithm based on eye tracking metrics will be developed and help decide when it is necessary to trigger the alert. Eye tracking is particularly well suited for this purpose since it provides continuous and real-time information about the user's attention allocation (Parasuraman, 2007) and is not intrusive. Recent studies have found that eye tracking is a promising means of detecting in real time dangerous attentional states such as drowsiness (Azim, Jaffar & Mirza, 2014), or attentional narrowing (Dehais et al., 2015). Detection algorithms use the eye tracking data collected to evaluate if the operator is in a desired or undesired state. The decision can be made by comparing the eye tracking measures to specific thresholds, or using machine learning tools such as support vector machines (Liang, Reyes & Lee, 2007), K-means (Kang, Chung & Lee, 2014) or fuzzy inference systems (Regis et al., 2014).

Capturing attention

The second important step towards capturing attention is to design an alert that can effectively interrupt the operator from his current attentional focus. However, when engaged in attentional narrowing, the amount of cues that can be processed by individuals is reduced and, as a result, it is more likely that alerts will be missed. It is thus recommended to use salient alarms located close to the focus of attention (Pinet, 2015), and simple and direct instructions (Hancock & Szalma, 2003; Dehais et al., 2010). Using alternative sensory modalities has also been suggested as a way to mitigate the effects of attentional narrowing and help alarm detection and attention re-allocation. It has been found that auditory and tactile cues can support interruption more effectively than visual cues (see, for a review, Lu et al., 2013), especially when engaged in attentional narrowing (Hess, 2006).

Guiding attention

Once attention has been captured, the last step towards designing an effective alerting system is to support re-orientation of the attention. The design of decision aids can greatly affect information processing and decision making, and should be carefully defined and implemented (Todd, 1991). When experiencing high levels of anxiety such as the ones associated with attentional narrowing, individuals' decision making abilities are hindered (Cannon-Bowers & Salas, 1998). Specifically, operators that are highly anxious tend to adopt the first choice that was considered during the decision making process (Stokes, Kemper & Marsh, 1992) and their working memory abilities are affected (Diamond et al., 1996). The alerting system should therefore provide information on the recommended course of action that is easy to understand. In addition, shifting attention can lead to increased stress and anxiety (see, for instance, Monsell & Driver, 2000). Two approaches have been discussed to support attentional guidance and decision making through effective display design: status and command. Status displays highlight the source and/or nature of a problem while command displays indicate the course of action that should be taken to solve the issue. For instance, to indicate that the gas level of a car is low and that the driver should stop by a gas station, a gauge system that displays how much fuel is left in the tank would represent a status alert, while an icon shaped as a gas station fuel pump would represent a command alert. Status alerts present the advantage of increasing situation awareness, because they allow the operator to maintain a clear mental picture of the status of the system, and are thus preferable in situations when automation is not fully reliable (Sarter & Schroeder, 2001). On the other hand, command displays help offload operators' working memory by making the decision for them, and are thus promising means of supporting attentional shifts during highly stressful situations such as attentional narrowing. In this dissertation, the effectiveness of status and command alerting systems at re-orienting attention will be evaluated and compared.

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Chapter 2

Exploring the effectiveness of attentional narrowing triggers in the context of a visual search task

One important prerequisite for designing countermeasures to the problem of attentional narrowing is being able to reliably induce the phenomenon in controlled laboratory settings. As described in Chapter 1, arousal and high motivational intensity have been proposed as the two main categories of triggers of attentional narrowing (see, for instance, Janelle, 2002; Gable & Harmon-Jones, 2010; Roets & Van Hiel, 2011). However, there is still uncertainty about the effectiveness of specific triggers in each of these categories, such as loud noise or heat as triggers of arousal and threat or a novel situation as triggers of high motivational intensity. Also, due to the paucity of research on attentional narrowing in settings involving complex tasks and high attentional demands, it is not clear which proposed triggers of narrowing will be most effective in these environments.

High task demand, for instance, has been proposed as a trigger of attentional narrowing because it induces arousal, but recent studies found that its effects vary as a function of the nature of the task. In a study by Sodhi and Reimer (2002), participants were asked to drive a vehicle while performing one of several tasks, including computing a date and a memory task. The date calculation task led to a more pronounced reduction of the area scanned by drivers than the memory task, suggesting that attentional narrowing is not simply sensitive to the level of task demand, but also to specific task demand characteristics, such as the extent to which working memory is required to complete the task. Complexity is another important task characteristic: more complex tasks lead to a more pronounced narrowing of the visual field (Victor, Harbluk & Engstrom, 2005).

Task prioritization needs to be considered also when invoking attentional narrowing. Early studies on attentional narrowing had participants perform a simple primary task such as counting, located in the center of the visual field, and, simultaneously, a secondary peripheral task such as detecting lights. More recent work required participants to timeshare more complex tasks in the context of domains such as flying (Wickens, 2005), driving (Janelle, Singer & Williams, 1999) or multiple unmanned vehicle control (Dehais, 2012). In both cases, when participants were anxious, their attention narrowed towards the task/tasks that was/were perceived as most stressful or of highest priority. However, few studies have examined anxiety-induced attentional shifts when all tasks and search targets are assigned equal importance. It is not clear what the focus of narrowing will be in that case.

Finally, few studies have examined the effectiveness of narrowing triggers when they are combined (Hancock & Pierce, 1985). For instance, will task demand lead to the same attentional field shrinkage when presented alone or when presented concurrently with a threatening situation?

Another important question is how attentional narrowing affects top-down (also referred to as endogenous) versus bottom-up (exogenous) information processing. Top-down information search and processing is driven by knowledge, expectations and previous experiences, while bottom-up processing is determined largely by the salience of external stimuli (Rumelhart, 1977). To date, most studies have focused on the effects of anxiety on bottom-up attention capture and signal detection. In these experiments, participants were asked to detect the onset of peripheral visual cues (bottom-up processing). Detection rates dropped significantly when high levels of anxiety were induced by presenting faces with fearful expressions or by threatening participants to apply electric shocks (Bishop, Duncan & Lawrence, 2004; Cornwell et al., 2007). To date, few studies have explored the effects of anxiety on top-down attention control mechanisms (Russell & Hatfield, 2013).

Chapter 2 presents two experiments that were run in order to address the research gaps described above. In particular, the objectives of these experiments were:

(1) To identify the most reliable triggers of attentional narrowing in the two categories, arousal and high motivational intensity, separately and combined, and examine their possible interactions
(2) To explore attention allocation and attentional narrowing in the context of a search task where all elements on the display have the same importance and priority
(3) To examine the effect of anxiety on top-down versus bottom-up attention control

Air traffic control (ATC) was chosen as the application domain for the two experiments. It requires controllers to monitor large amounts of data and quickly identify abnormal events. ATC exemplifies a fast-changing, high-risk and stressful workplace that imposes high task demands on operators and where breakdowns in attention allocation, such as attentional narrowing, can have catastrophic consequences.

Experiment 1:

Noise and task demand as triggers of arousal and attentional narrowing

The first experiment examined how high levels of arousal – one of two triggers of attentional narrowing that have received the most attention - affects visual attention allocation. In particular, it investigated the effectiveness of two arousal-related stimuli – intermittent and aperiodic loud noise and high task demand – for inducing attentional narrowing, individually and in combination (Murata, 2004; Rantanen, 1999; Mehler et al., 2009). These triggers were chosen because they tend to be experienced in many complex safety-critical real-world domains. Participants in this experiment were asked to perform a visual search task in the context of an air traffic control simulation. All search targets were of equal importance and priority. The task involved mostly top-down attention control. Performance and eye tracking data were recorded, and a number of eye tracking metrics were computed to detect and trace the narrowing of visual attention.

Methods

Participants

The participants in this study were 7 graduate students from the University of Michigan (3 females and 4 males). Their average age was 25.1 years (SD = 4.7). Participants reported normal or corrected-to-normal vision. None of the participants had prior experience with air traffic control (ATC) tasks.

Apparatus and tasks

The study was conducted using a simplified ATC simulation that was displayed on a 20-inch monitor, placed approximately 24 inches from the participants. Green aircraft icons were presented against a black background (see Figure 2.1).

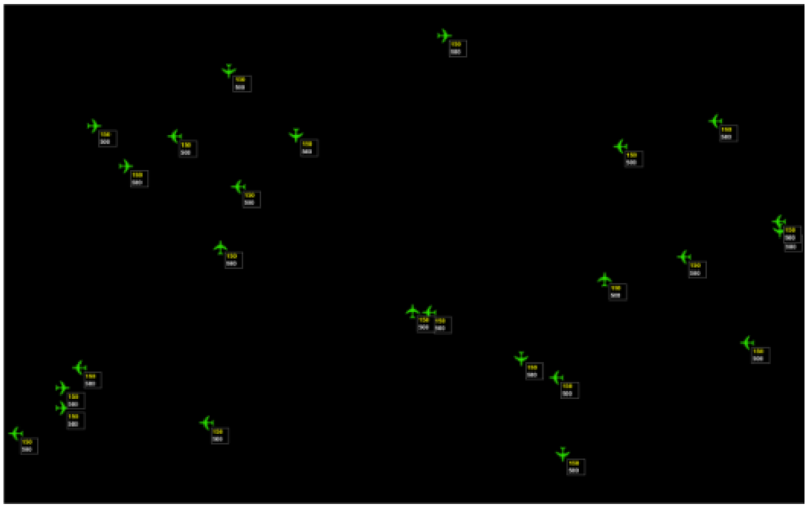


Figure 2.1 - ATC simulation display

Aircrafts were moving across the screen following a straight line, either horizontally or vertically, at a constant speed of 0.15 inches per second. The aircraft speed (shown in yellow) and altitude (shown in white) were presented in a data block to the lower right of the aircraft icon (see Figure 2.2).

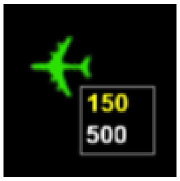


Figure 2.2 - Aircraft icon and data block showing airspeed (150 kts) and altitude (FL (flight level) 500)

All aircraft were assigned an airspeed of 150 knots and an altitude of 50,000 feet (FL 500). Occasionally, airspeed or altitude deviations occurred (airspeed values in the data block changed to 165 kts, 185 kts or 200 kts; altitude values changed to FL 370, FL 435 or FL 465). Participants were asked to monitor for these deviations and to return the airspeed or altitude to their assigned values as quickly as possible. To do so, they had to left-click the aircraft and choose the appropriate correction from three displayed options on a pop-up menu. In the case of airspeed deviations, the options were 15 kts, 35 kts and 50 kts, and in the case of an altitude deviations, the options were 35 (3,500 feet), 65 (6,500 feet) and 130 (13,000 feet). Speed and altitude deviations lasted 6 seconds; if no correction was made during that time, the parameter automatically returned to its prescribed value. If the participant chose the appropriate correction value, the box around the data block turned green for 2 seconds; in case of an inappropriate correction, it turned red. The number and frequency of deviations differed between the two task demand conditions.

Experimental Conditions.

The two triggers that were used to induce attentional narrowing were noise and task demand.

(1) Noise manipulation.

Noise in this study was designed to be loud, intermittent, a-periodic and contained speech, as recommended by Szalma and Hancock (2011). Specifically, in the loud noise condition, a combination of white noise and aviation-related non-speech (e.g., siren sounds or horns) and speech alerts (e.g., “pull up!”, “glideslope!”, “windshear!”) were presented via a headset, at an average amplitude of 95 dBA. The various warnings were presented in an intermittent aperiodic fashion, at a rate of every 3 seconds or less. In the no noise condition, participants were wearing a headset but no sound was presented.

(2) Task demand manipulation. Task demand was varied using the number of aircraft on the screen and the frequency of speed or altitude deviations. In the low task demand condition, 25 aircraft were presented on the screen, and an altitude or speed deviation occurred every 6 seconds. In case of high task demand, 80 aircrafts were presented, and an altitude or speed deviation occurred once per second (see Figure 2.3).

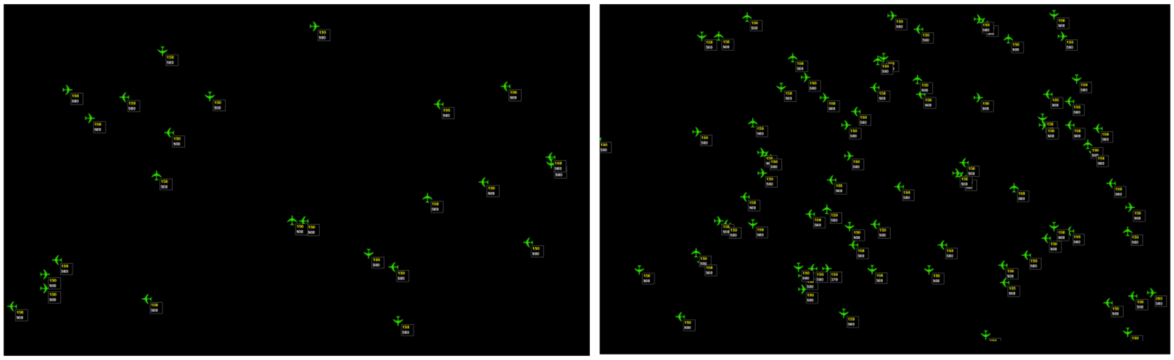


Figure 2.3 - ATC simulation display in the low task demand condition (left) and the high task demand condition (right)

Experiment Design and Procedure

The study employed a 2 (task demand: low or high) x 2 (noise level: no noise or loud noise) within-subject design. The order in which participants were presented with the two noise conditions was counterbalanced.

Participants were given a 10-minute training session to familiarize themselves with the ATC simulator. Next, they were asked to complete a 12-minute practice scenario during which they were asked to report observed airspeed or altitude deviations as fast as possible, and to apply the accurate correction to the data block. Then, the eye tracker was calibrated and the experiment began, requiring participants to complete two 12-minute scenarios. Task demand was varied within each scenario, while noise was varied between scenarios. Each scenario started with a 3-minute low task demand phase, followed by 6 minutes of high task demand, and ending with another 3-minute low task demand period, as illustrated in Figure 2.4.

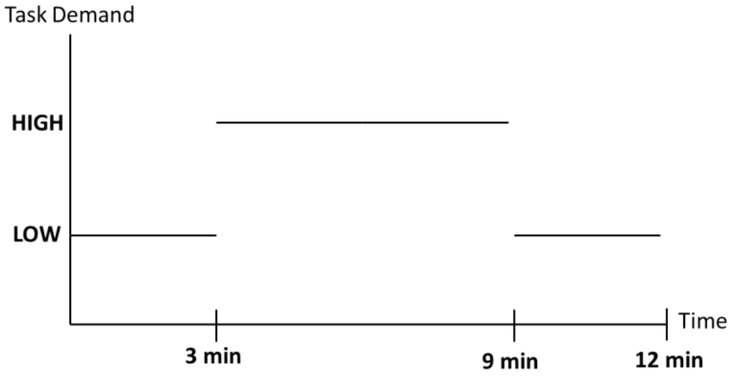


Figure 2.4 - Task demand manipulation within each scenario

Participants were offered a 5-minute break between the two scenarios. The eye tracker was calibrated before each scenario. The entire session took approximately 1.2 hours to complete.

Dependent Measures

Both performance and eye tracking data were collected. To trace visual attention allocation across the display, the screen was divided into 9 sectors of equal size (see Figure 2.5), and the dependent measures were calculated for the overall screen and for each individual sector.

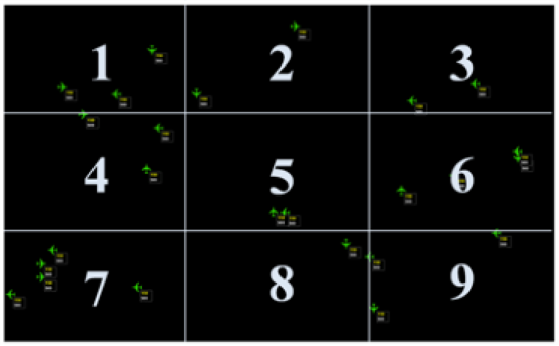


Figure 2.5 - Division of the screen into 9 sectors

Performance data. The performance measure for the air traffic control task was the detection rate for speed and altitude deviations, expressed as the ratio of number of deviations that were noticed to the total number of deviations presented.

Eye tracking data. Eye tracking data was recorded using an ASL Eye-Trac D6 infrared-based, desktop-mounted eye tracker which samples at 60Hz at an accuracy of less than 1 degree visual angle. The eye tracker was placed in front of the participant, underneath the monitor. The following three eye tracking metrics were calculated from the raw data: (1) number of fixations on each of the 9 sectors, (2) mean fixation duration and (3) mean saccade length. The number of fixations on each sector was chosen because it would help trace shifts in attention allocation across the display, and the mean fixation duration and mean saccade length were selected for their ability to suggest the efficiency of the visual search task.

For each dependent measure, the percentage change was computed between (1) the no noise and the loud noise condition, and (2) low task demand and high task demand (see Equation 2.1).

$$\text{(a) Percentage change} = \frac{\text{Value}_{\text{loud noise}} - \text{Value}_{\text{no noise}}}{\text{Value}_{\text{no noise}}} \times 100$$

$$\text{(b) Percentage change} = \frac{\text{Value}_{\text{high task demand}} - \text{Value}_{\text{low task demand}}}{\text{Value}_{\text{low task demand}}} \times 100$$

Equation 2.1 - Percentage change calculation for (a) the noise and (b) the task demand conditions

Results

Performance Data

The average detection rate for speed and altitude deviations across all participants and conditions was 26% (SD = 4%). Performance was significantly lower in the high task demand condition (11%, SD = 2%), as compared to the low task demand condition (42%, SD = 7%; F(1,26) = 177.2, p < 0.001). The change in detection rate was approximately the same across all nine sectors, as illustrated in Figure 2.6.

27%	**20%**	**20%**
39%	**31%**	**31%**
25%	**20%**	**27%**

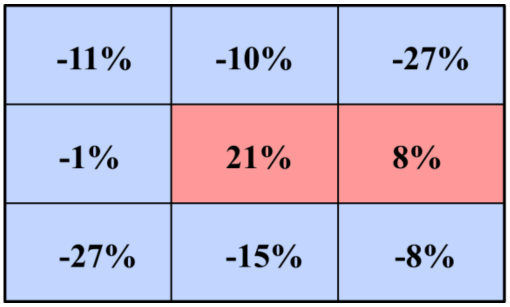
Figure 2.6 - Percentage change in detection rate for each sector between the low and high task demand conditions

The overall detection rate did not differ significantly between the loud noise and no noise conditions (26% in both conditions; in loud noise, SD = 4%, in no noise, SD = 5%). However, detection performance for individual sectors varied somewhat as a function of noise: in the presence of loud noise, performance for sectors 1, 2, 5, 6 and 7 slightly improved; it tended to decrease for sectors 3 and 9 and remained the same for sectors 4 and 8.

Eye tracking

The eye tracker could not be calibrated for 3 of the 7 participants, and eye tracking data were collected and analyzed for the remaining 4 participants only.

<u>Number of fixations.</u> Overall, there was a trend towards fewer fixations in case of high task demand (320, SD = 63), as compared to low task demand (440, SD = 16; F (1, 3) = 7.8, p = 0.07). However, this change did not affect all sectors in the same way. The number of fixations in sectors 5 and 6 increased with high task demand (21% increase in sector 5 and 8% increase in sector 6), while all other sectors showed a decrease in the number of fixations (see Figure 2.7).

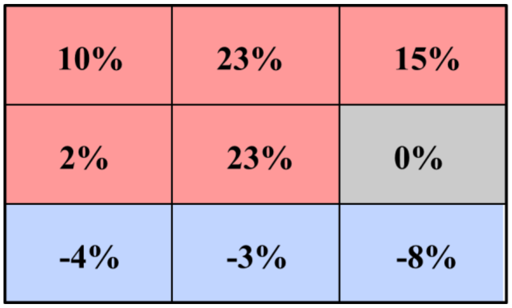


-11%	**-10%**	**-27%**
-1%	**21%**	**8%**
-27%	**-15%**	**-8%**

Figure 2.7 - Percentage change in the number of fixations in each sector between the low and high task demand conditions

Noise did not affect the number of fixations overall or in specific sectors.

Mean fixation duration. The mean fixation duration was significantly higher with high task demand (1.0 s, SD = 0.19s), compared to the low task demand condition (0.7 s, SD = 0.09 s; F (1, 3) = 30.1, p = 0.012). The sectors that showed the strongest increase in the mean fixation duration (23 percentage increase) were sectors 2 and 5 (see Figure 2.8).



10%	**23%**	**15%**
2%	**23%**	**0%**
-4%	**-3%**	**-8%**

Figure 2.8 - Percentage change in the duration of fixations in each sector between the low and high task demand conditions

Noise did not affect mean fixation duration, neither overall or for individual sectors.

Mean saccade length. Mean saccade lengths were smaller under high task demand (65 pixels, SD = 1.75 pixels), as compared to low task demand (75 pixels, SD = 5.14 pixels; F (1, 3) = 25.3, p = 0.015). Noise did not affect the mean saccade length (F (1, 3) = 0.72).

The above mentioned changes for one participant’s scan pattern in the (a) no noise / low task demand condition and the (b) loud noise / high task demand conditions for a 20-second period are illustrated in Figure 2.9. In the latter case, fixations are more closely spaced and longer fixation durations are observed.

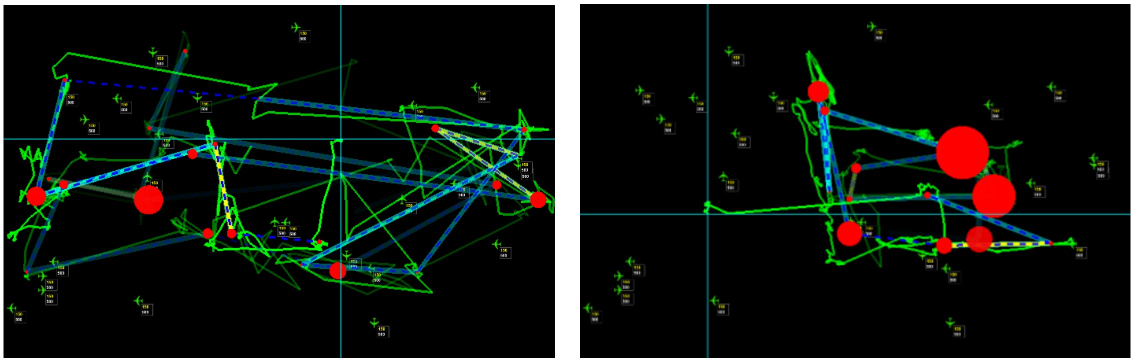


Figure 2.9 - Example of one participant's scan pattern over a period of 20 seconds in (the no-noise, low task demand condition (left) and the noise and high task demand condition (right) (the size of the red circles represents fixation duration)

Discussion

The goals of experiment 1 were to (1) determine the effectiveness of loud noise and high task demand for inducing attentional narrowing and (2) trace how these two factors affect participants' top-down attention allocation in the context of a visual search task where all elements on the display were weighted equally in terms of priority, threat and importance.

Task demand, but not noise, significantly affected participants' performance and attention allocation. In the high task demand condition, significantly fewer airspeed and altitude deviations were detected. The number of fixations in the central sector increased at the expense of the surrounding sectors, and longer fixation durations and shorter mean saccade lengths were observed. In combination, these changes resulted in a slower and more confined visual scan during high task demand. When combined with the observed performance decrements, these findings suggest that participants experienced attentional narrowing in case of high task demand. This finding confirms earlier work that found that increased task load and complexity led to a reduction of the attentional field (Rantanen & Goldberg, 1999; Murata, 2004).

There are several possible reasons why noise did not affect attention allocation and performance as much as expected. First, loud noise has been shown to degrade performance on complex tasks (i.e. multi-tasking or tasks with a high signal rate) but benefit performance of simple tasks (Hockey, 1970). The task used in this experiment - detecting altitude and speed deviations - may not have been sufficiently complex. Also, noise is known to increase arousal which, in turn, is linked to performance by an inverted U-shaped curve (Yerkes & Dodson, 1908). The Yerkes Dodson law states that the highest level of performance is reached at an intermediate level of arousal. The noise level that participants experienced in this study may not have been sufficient to raise their level of arousal to the point where a decrease in performance would be observed. Finally, it has been shown that individuals are capable of adapting to noise exposure (McEwen, 2007) and longer noise stimuli have less effect on performance than shorter ones. Szalma & Hancock (2011) examined over 240 studies on the effects of noise on performance. The median noise exposure of these studies was 1.1 minutes, and more pronounced performance decrements were found for shorter noise stimuli. In the present experiment, noise exposure was 12 minutes long which may have been too long to result in performance effects.

Another important finding from this study is that, in the context of a visual search task where all elements on the display are given the same priority, importance and threat, attention tends to narrow towards the center of the screen/display. This confirms results from early studies on attentional narrowing (see, for instance, Wachtel, 1968).

In conclusion, the findings from this study represent an important first step towards enabling controlled studies of attentional narrowing. High task demand was shown to be an effective manipulation for inducing the phenomenon, and the eye tracking metrics proved useful for gaining insight into underlying attentional processes.

A limitation of this experiment is that task demand was varied via the number of planes and deviations. This may have led to a confound. Smaller saccades were observed in the case of the high task demand (i.e., a large number of aircraft). But rather than being a symptom of narrowing, this effect may simply reflect a search strategy adopted by participants to cope with the increased visual load: because planes were closer to each other, participants' eyes could afford to travel a smaller distance between each fixation. This limitation was overcome in experiment 2.

Experiment 2:

The effectiveness of high motivational intensity and arousal as triggers of attentional narrowing

Experiment 1 found that increased task demand, one factor leading to increased arousal, resulted in a narrowing of participants' attentional field. Recent studies have highlighted that, in addition to arousal, affect and motivation play a crucial role in the control of attention (see, for instance, Friedman & Foster, 2010). The goal of the second experiment was therefore to try to trigger an even larger and more reliable narrowing effect by combining arousal and high motivational intensity. In this case, to address one limitation of the previous study but keep the visual task similar to the first experiment, *arousal* was manipulated using a verbal auditory task. Specifically, high task demand was induced by asking participants to perform a mental arithmetic task (i.e., adding numbers). This type of task has been used frequently to increase workload (see, for instance, Tsai et al., 2007). It has been shown to increase arousal and anxiety (Al'Absi et al., 1997) and lead to a narrowing of attention with associated performance decrements (Harbluk et al., 2007). *High motivational intensity* was induced in participants by means of an ego-threat (i.e. "any event […] having unfavorable implications about the self" (Baumeister, Heartherton & Tice, 1993)). Specifically, participants were given erroneous feedback on their performance, to lead them to believe that they were performing poorly. Recent studies have shown that ego-threat leads to significant increases in negative emotions (see, for instance, Stucke & Sporer, 2002) and resulting performance breakdowns (Schmeichel, Vohs & Baumeister, 2003).

While experiment 1 focused exclusively on top-down attention control (the primary control mode involved in search tasks), experiment 2 examined how high levels of arousal and motivational intensity affect both top-down and bottom-up information processing. To this end, a peripheral detection task was added to the central visual search task used in experiment 1.

The objectives of experiment 2 were thus to:

(1) Determine the effectiveness of an arousal-related stimulus – high task demand – in combination with a stimulus inducing high motivational intensity – ego-threat – for triggering attentional narrowing

(2) Examine the effects of anxiety resulting from a combination of high arousal and high motivational intensity on bottom-up and top-down attention control

Methods

Participants

Five graduate students from the University of Michigan volunteered to participate in the experiment (4 females and 1 male). Their average age was 27 years (SD = 5 years). Participants self-reported normal or corrected-to-normal vision and no hearing impairment in either ear.

Apparatus and tasks

A simplified ATC environment was displayed on a 30” monitor, as illustrated in Figure 0.12, and placed at approximately 24 inches from the participants. It required participants to perform two concurrent noticing tasks of equal importance.

<u>ATC Central Search Task.</u> The search task was displayed in the central sector of the screen (approximately 13.25” by 7.75”) and was similar to the task employed in experiment 1. 20 green aircraft icons were presented flying along straight routes at a constant speed of 0.15 inches per second. A data-block containing the aircraft’s airspeed and altitude

(in white) was displayed on the lower right side of each plane, and participants were asked to look for speed and altitude deviations, as in experiment 1. Aircraft were assigned an airspeed of 150kts and an altitude of FL 300 (flight level 300 or 30,000ft; Figure 0.13). At times, individual aircraft would deviate from this altitude and show FL 170, FL 235 or FL 265 in their data block. When participants noticed the deviation and clicked on the aircraft, they were offered 35, 65 and 130 as possible corrections. If the participant chose the appropriate correction, the box surrounding the data-block turned green for 2 seconds; in case of an inappropriate correction or if no correction was made within 6 seconds, it turned red. This feedback was the same as in experiment 1.

<u>ATC Peripheral Noticing Task</u>. The peripheral noticing task involved the appearance of an aircraft in the airspace surrounding the central sector, as illustrated in Figure 2.10 and Figure 2.11. The aircraft was flying in a straight line towards the central sector, simulating an airplane approaching the ATC sector that the participant was responsible for. Peripheral planes - displayed in green - were flying at a constant speed of 0.15 inches per second. The participants' task was to notice the appearance of these airplanes and acknowledge their presence by pressing the space bar as quickly as possible. Aircraft appeared one at a time, unexpectedly and, on average, once every minute. Peripheral planes disappeared once the space bar was pressed. Planes that were not detected by participants continued on until they reached the central sector; at that point, a data block appeared, and they joined the central sector planes.

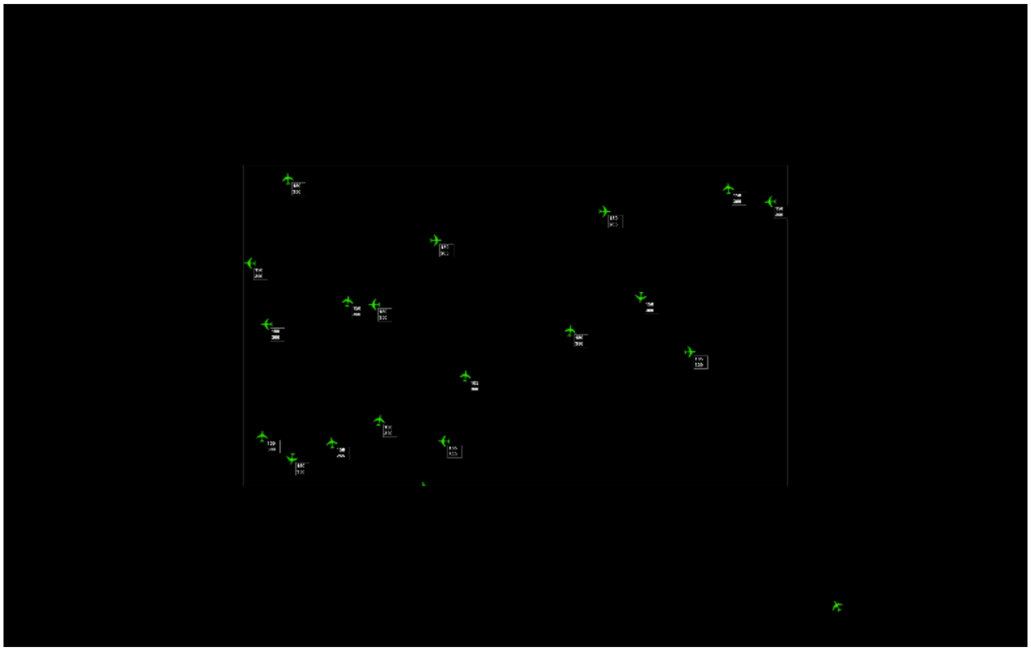


Figure 2.10 - ATC simulator display: central and peripheral sectors

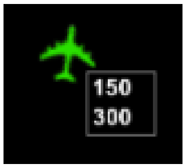


Figure 2.11. Aircraft icon and data block showing airspeed (150 kts) and altitude (FL300)

Experimental Conditions

The variable in this experiment was anxiety, and was manipulated at two levels: low and high.

Low anxiety condition. In the low anxiety condition, participants were asked to complete the two ATC tasks – search for altitude deviations and notice aircraft in the periphery - in a quiet environment.

High anxiety condition. In the high anxiety condition, participants were asked to perform the two ATC tasks and, additionally, they needed to complete paced addition tasks delivered via speakers at an amplitude of about 70dBA. The addition tasks consisted of two two-digit numbers, and participants had 8 seconds to verbally provide the result. Participants were asked to respond as quickly and accurately as possible. They were instructed to give equal importance to the two ATC tasks and the addition task.

To further increase participants' anxiety levels, they were told that, each time they missed an altitude or speed deviation, a loud noise would be played. On average, in an aperiodic fashion, an 80dBA sound was delivered via speakers once every 3 seconds. This exceeded the actual miss rate and was intended to make participants believe that their performance was very poor and thus trigger high motivational intensity through ego-threats.

Experiment Design and Procedure.

The study employed a within-subject factor design, with anxiety being experienced at two levels (low and high). The order in which participants were presented with the two anxiety conditions was counterbalanced.

The experiment took approximately 1.5 hours to complete. Upon arrival, participants filled out the trait section of the State and Trait Anxiety Inventory (STAI). They were then instructed on the two ATC tasks and completed a 5-minute training session to familiarize themselves with these tasks and simulator. Next, participants had an opportunity to practice the auditory addition task, by itself, for 3 minutes.

Finally, the experiment started, and participants completed two 10-minute scenarios, one in the low anxiety, the other in the high anxiety condition. They were offered to take a break in between scenarios and filled out the state section of the STAI immediately following each scenario.

Dependent Measures

Performance measures and subjective ratings were collected to assess participants' anxiety levels and infer the spread of visual attention across the interface.

Central Task. The three performance measures for the central task were (1) the detection rate for speed and altitude deviations (the ratio of detected to total number of deviations), (2) accuracy (the ratio of correct responses to the total number of deviations that were detected and addressed), and (3) completion time (time between the detection of a deviation and the time it was corrected).

Peripheral Task. The two performance measures for the peripheral task were (1) the detection rate for the peripheral planes (the ratio of peripheral planes detected, by the total number of peripheral planes that entered the airspace), and (2) the average response time (time between the appearance of a peripheral plane and when participants hit the space bar).

Addition task. The two dependent measures for the addition task were (1) response rate (the percentage of addition tasks that were performed) and (2) accuracy (the ratio of correct responses to the total number of tasks that were performed).

Anxiety. Participants' anxiety levels were measured using the State and Trait Anxiety Inventory (STAI), a self-report questionnaire commonly used to establish people's general (trait) and temporary (state) levels of anxiety (Spielberger, 2010). Trait anxiety was measured before the experiment, while state anxiety was assessed after each scenario.

Results

Central Task

Anxiety had a significant effect on detection rate: significantly fewer altitude or airspeed deviations were detected in the high anxiety condition (0.20, SD = 0.07), as compared to the low anxiety condition (0.30, SD = 0.05, F (1, 4) = 48.3, p = 0.02). Response accuracy was not affected by anxiety (low anxiety: 0.94, SD = 0.06; high anxiety: 0.87, SD = 0.14). Finally, completion time decreased for all but one participant between the low and high anxiety conditions (0.82 sec (SD = 0.08 sec) and 0.80 sec (SD = 0.04 sec), respectively; F (1, 4) = 0.55, p = 0.50). These results are illustrated in Figure 2.12.

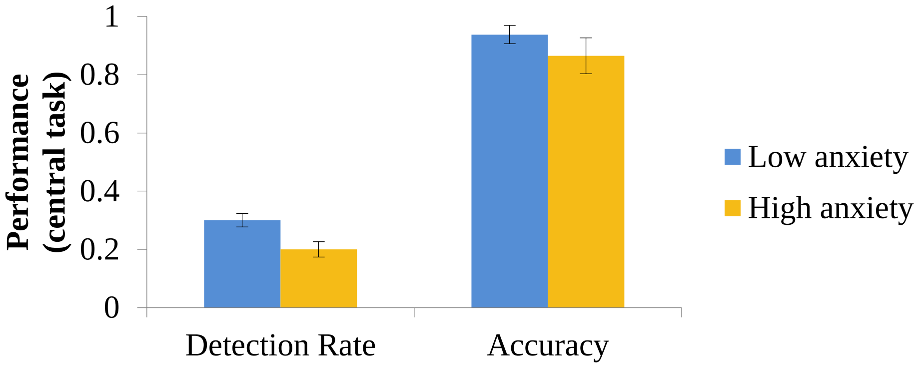


Figure 2.12 - Central task performance - detection rate and accuracy - for the low and high anxiety conditions

Peripheral Task

There was no main effect of anxiety on detection rate (high anxiety: 0.96, SD = 0.055; low anxiety: 0.94, SD = 0.089; F (1, 4) = 0.12, p = 0.75). However, for all but one participant, the response time was longer in the high anxiety condition (9.8 sec, SD = 2.3s), compared to the low anxiety condition (7.6 sec, SD = 3.13s), as illustrated in Figure 2.13 (F (1, 4) = 2.3; p = 0.20).

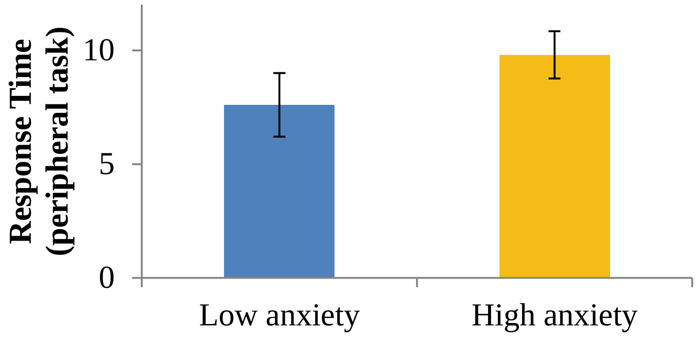


Figure 2.13 - Response time (seconds) for the peripheral detection task for the low and high anxiety conditions

Addition task

For the auditory addition task, baseline performance was assessed during training when participants completed the arithmetic task by itself, without performing concurrent ATC tasks. This baseline was then compared to participants' performance in the high anxiety condition.

The overall response rate significantly decreased from 0.93 in the training condition (SD = 0.46) to 0.67 in the high anxiety condition (SD = 0.22) (F (1, 4) = 10.512, p = 0.03). Also, accuracy was significantly lower in high anxiety, as compared to training (training:

0.76 (SD = 0.13), and high anxiety: 0.62 (SD = 0.18); F (1, 4) = 18.44, p = 0.023). These results are illustrated in Figure 2.14.

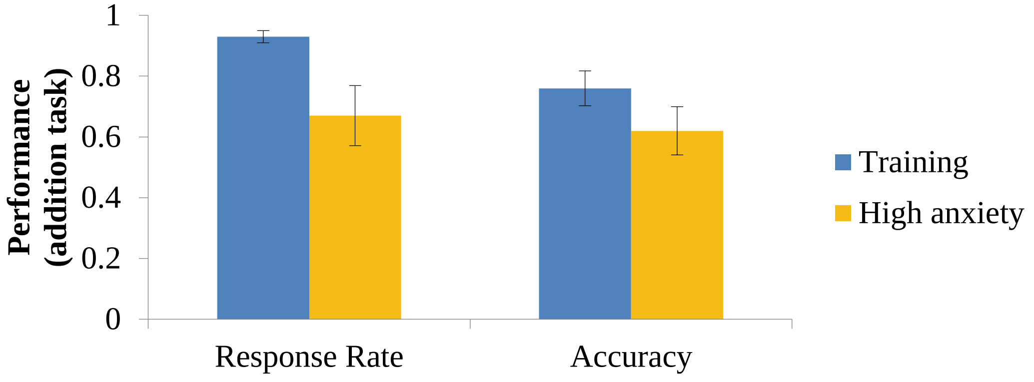


Figure 2.14 - Addition task performance for the low and high anxiety conditions

Anxiety

Data for the State and Trait Anxiety Inventory (STAI) were analyzed using a Wilcoxon Signed-Ranked test for ordinal data. The average trait anxiety score for all participants was 41.4 (SD = 8.5). Results showed a significant effect of anxiety on state anxiety: all participants reported a significantly higher state anxiety level after the high anxiety condition (50.0, SD = 10.5), as compared to the low anxiety condition (39.6, SD = 6.4; z = -2.032, p = 0.042, see Figure 2.15).

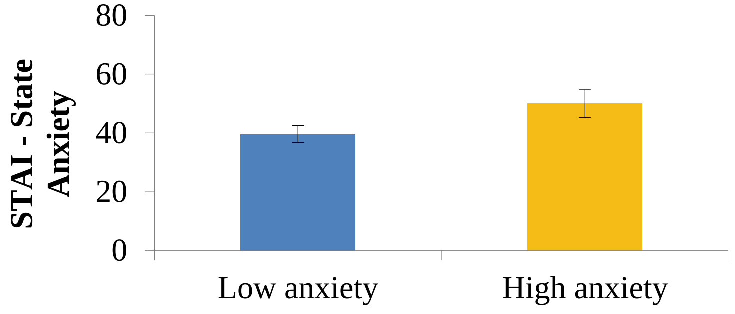


Figure 2.15 – STAI-State anxiety following the low and high anxiety conditions

No correlation was observed between participants' trait anxiety level and the change in state anxiety levels experienced between low and high anxiety conditions (Pearson Correlation Coefficient r = 0.009, p = 0.988). In other words, the state anxiety level of highly anxious participants did not increase more after experiencing high anxiety than it did for less anxious participants. A positive correlation was observed, however, between participants' trait anxiety and the decrease in accuracy on the central task: higher trait anxiety was associated with more pronounced decreases in accuracy on the central task (Pearson correlation coefficient: r = -0.97, p = 0.006). Lastly, there was a positive correlation between trait anxiety and the increase in response time on the peripheral task: higher trait anxiety was connected with stronger increases in response time on the peripheral task (Pearson correlation coefficient: r = 0.987, p = 0.02). No correlation was observed between the other performance measures and trait anxiety. Table 2.1 summarizes the results of the analysis of correlations between trait anxiety, state anxiety and performance on the central and peripheral tasks.

Table 2.1 – Correlations between trait anxiety, state anxiety and task performance for the low and high anxiety conditions (the change is expressed as a percentage of the value in the low anxiety condition)

		Average change (%)	**Pearson correlation coefficient (r)**	**p-value (p)**
STAI	**State anxiety**	27%	0.009	0.988
Central Task	**Hit Rate**	-35%	-0.722	0.169
	Accuracy	**-8%**	**-0.97**	**0.006 ***
	Completion Time	-2%	-0.071	0.91
Peripheral Task	**Detection Rate**	3%	-0.636	0.249
	Response Time	**40%**	**0.987**	**0.02 ***

Discussion

The two main objectives of experiment 2 were to (1) determine the effectiveness of an arousal-related stimulus – high task demand – used in combination with a high motivational intensity-related stimulus – ego-threat – for inducing high levels of anxiety and attentional narrowing, and (2) examine the effect of high levels of anxiety on bottom-up and top-down attention control.

To determine whether this led to attentional narrowing, it is important to recall our definition of the phenomenon: attentional narrowing is experienced when (1) performance breakdowns are observed, and (2) visual attention is reduced to one task or area of the display. In this study, performance on the central task suffered when high levels of anxiety were experienced: not only did participants detect fewer deviations but it also took them longer to correct the deviations. The peripheral task – noticing the appearance of aircraft in the periphery and acknowledging them as soon as possible – provided an indirect measure of the spread of participants' visual attention, and thus offered insights in to the effect of high levels of anxiety on the size of the peripheral visual field. The overall detection rate for aircraft in the periphery did not differ significantly between the two anxiety levels; however, with high anxiety, the average detection time increased by about 2 seconds, indicating that participants tended to notice peripheral planes when they were already closer to the center of the screen (by approximately 0.30 inches). Figure 2.16 illustrates the reduction of the peripheral visual field experienced by participants. The observed reduction of the visual field confirms findings from earlier studies (see, for instance, Bursill, 1958; Yoon et al., 2015). In addition, the results from the STAI questionnaire suggest that high levels of task demand and ego-threat were effective at increasing participants' levels of anxiety. Thus, in summary, high task demand and ego-threat proved to be effective triggers of attentional narrowing in the context of the simulated ATC task used in this experiment.

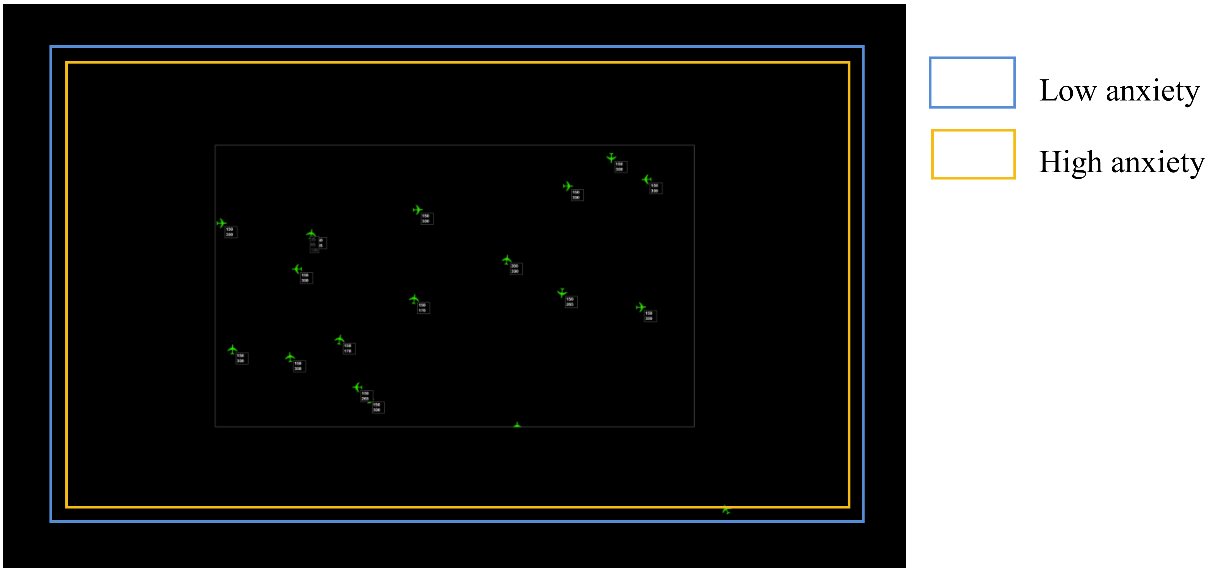


Figure 2.16 - Average eccentricity of peripheral aircraft when detected by participants in the low and high stress conditions

One limitation of this study is that the restriction of the visual field was inferred from the time it took participants to notice aircraft appearing in the periphery. No precise information is available on the shape or size of the visual field in the low and high anxiety conditions. Williams (1995) demonstrated that the narrowing of the visual field is not necessarily equal in all directions of regard. More precisely, the north meridian is affected the most by attentional narrowing, followed by the south meridian and last, the east - west axis. In other words, when engaged in attentional narrowing, individuals tend to drop peripheral cues located in the upper areas of the screen earlier than cues located in the lower and left and right areas of the display. Later studies confirmed these results (Rantanen &

Goldberg, 1999; Park & Reed, 2015). An illustration of the shape of the visual field while experiencing high attentional demands and attentional narrowing is presented in Figure 2.17.

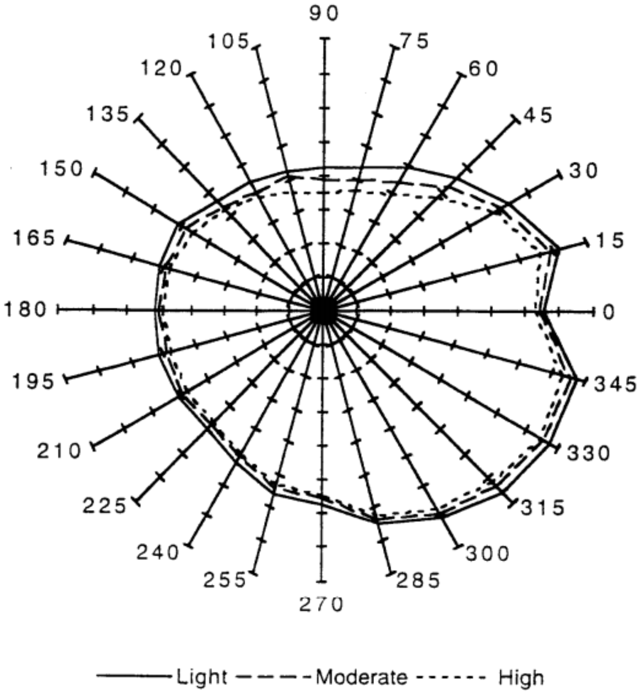


Figure 2.17 – Changes in the visual field (here, the right eye) under high task demand conditions (from Rantanen and Goldberg, 1999)

The observed correlation between high trait anxiety and poor performance on the two tasks confirm findings in the literature on individual differences in response to anxiety (see, for a review, Bar-Haim et al., 2007). Earlier studies have shown that, when highly anxious individuals are presented with a threatening stimulus, the initial shift of their attention towards that stimulus is more pronounced than for less anxious participants (Amir, Foa & Coles, 1998; Mogg et al., 1997).

Discussion

The objectives of the two studies reported in chapter 2 were to (1) identify reliable triggers of arousal and high motivational intensity and, in turn, attentional narrowing, (2) explore attentional narrowing in the context of a search task where targets are assigned the same importance and priority and (3) examine, separately, the effect of anxiety on top-down and bottom-up attention control. In summary, high levels of task load and ego-threat were identified as the most promising triggers of attentional narrowing, affecting both performance and the size of participants' visual field. Participants with high trait anxiety suffered more pronounced performance breakdowns, and high levels of anxiety affected both top-down and bottom-up attention control.

The next step towards a better understanding of attentional narrowing is to explore the phenomenon in the context of a more complex and realistic setting in which participants are required to engage simultaneously in multiple tasks of a different nature. Also, in order to detect and counteract attentional narrowing in real time, reliable and diagnostic markers of this dangerous attentional state need to be identified. Chapter 3 will describe the efforts that were conducted to address these objectives.

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Chapter 3

Inducing and tracing attentional narrowing in the context of a demanding multitasking environment

The experiments described in Chapter 2 suggested two promising triggers of attentional narrowing: high levels of attentional load and ego-threat. However, these studies involved only one simple visual search task where all elements had the same importance and priority. The next step towards better understanding attentional narrowing in real-world domains and designing countermeasures to this dangerous state is to evaluate and confirm the role of these two factors – high levels of attentional load and ego-threat - on attention and performance when individuals are performing multiple tasks in more complex and faster pace environments. More precisely, ego-threats that take the form of novel and unsolvable problems have been found to impair operators' attention allocation and lead to attentional narrowing in complex systems (Martin et al., 2016; Dehais et al., 2012). In addition, several studies observed performance breakdowns on tasks located in the periphery when money rewards were provided (Bahrick, Fitts & Rankin, 1952; Mobbs et al., 2009; Gable & Harmon-Jones, 2010; Fröber & Dreisbach, 2014). Monetary incentives will thus be evaluated in this study as a potential attentional narrowing factor. A second pre-requisite towards developing solutions to attentional narrowing is to identify markers of that dangerous state to be able to detect it and trace it. As previewed in Chapter 1, eye tracking is a promising method to trace shifts in attention allocation because eye movements have been shown to be effective and real-time indicators of a person's visual attention. Therefore, the effectiveness of several eye tracking metrics as real-time markers of attentional narrowing will be evaluated in this study.

In summary, the objectives of the study reported in this chapter were:

(1) to determine the most effective manipulations of anxiety – more specifically high levels of attentional load, ego-threat and monetary incentive - for inducing attentional narrowing in the context of a complex multi-tasking environment
(2) to identify eye tracking metrics that enable us to detect early on attentional narrowing and distinguish between divided attention, focused attention and attentional narrowing.

The expectations were that the experimental condition that presented all three anxiety factors at once would lead to attentional narrowing, and that an increase in attention would be observed toward the novel and unsolvable problem location on the display, while performance on the other tasks would be impaired. In addition, it was anticipated that participants with high levels of trait anxiety would be the most likely to experience attentional narrowing.

Methods

Participants

35 students at the University of Michigan (19 females and 16 males) volunteered to participate in this study. Three females and two males had to be excused because the eye tracker could not be calibrated, or the percentage of samples with data point was less than 60%. The average age of the remaining 30 participants was 21 years (SD = 1.9 years).

Apparatus and tasks

MATB II tasks

The experiment employed an adaptation of the computer-based Multi-Attribute Task Battery II (see Figures 3.1 and 3.2). MATB II simulates a multi-tasking environment that requires the simultaneous performance of monitoring, dynamic resource management, and tracking tasks (Comstock & Arnegard, 1992). The simulation was displayed at the center of a 30-inch monitor with a resolution of 1280 x 1024 pixels. The interface had a width of 16 inches and a height of 12 inches, and was placed at a distance of 24 inches from the participant, making for a visual angle of approximately 26 degrees in the horizontal direction, and 34 degrees in the vertical direction.

Participants were asked to perform 4 tasks on the display: (1) system monitoring, (2) tracking (3) scheduling and (4) resource management (see numbered areas in Figure 3.1).

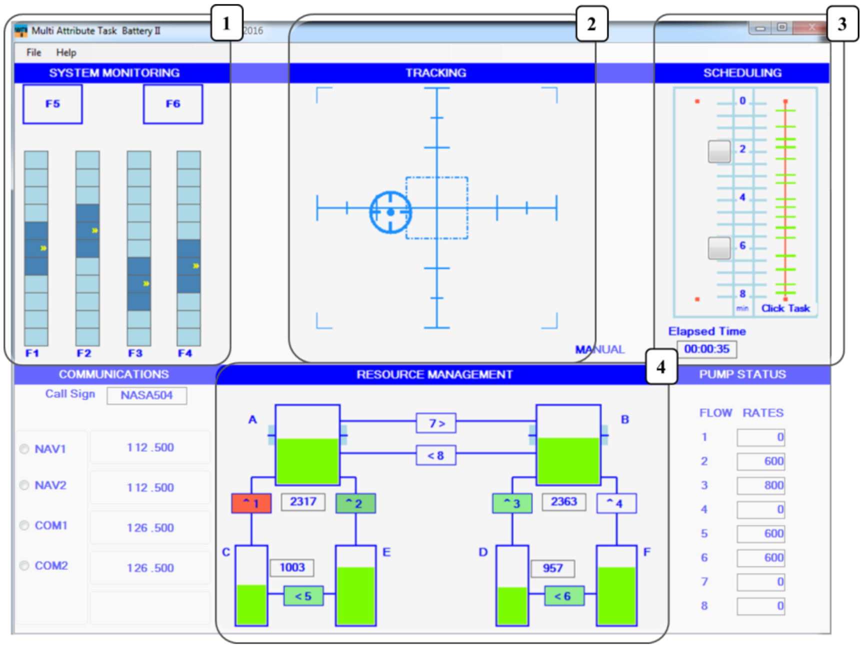

Figure 3.1 MATB II display and tasks. The four areas highlighted on the display correspond to the four tasks that participants were asked to complete: (1) system monitoring, (2) tracking (3) scheduling and (4) resource management

(1) The system monitoring task (SYSMON) was located in the upper left corner of the MATB II display and consisted of monitoring 4 moving scales. Participants had to detect when a dark blue region on any of the four scales deviated from its central position. They were asked to click on the respective scale as soon as they noticed the deviation. This returned the blue region to its central position. If a deviation was not detected and/or responded to, the blue area automatically returned to its central position after 7 seconds.

(2) The tracking task (TRCK) was displayed in the upper middle window of the display. Participants were asked to use a joystick to keep a continuously moving target at the center of the window.

(3) The scheduling task (SCHED) was displayed in the upper right corner of the MATB display. Irregularly spaced green marks were slowly moving up along a vertical axis.

Participants had to detect when the green marks aligned with the blue marks located next to the number ‘2’ or ‘6’ on a parallel vertical scale to the left, and respond by clicking on a button located to the left of the corresponding number.

(4) The resource management task (REMAN) was located in the lower middle window of the MATB II display. The objective of this task was to maintain the fuel levels in two of six tanks – tanks A and B - as close to 2,500 units as possible. To do so, participants activated one or several of 8 pumps by clicking on them in order to transfer fuel from one tank to another. Occasionally, a pump failed. This was indicated by the pump symbol turning red. Participants were not able to use the pump until it recovered on its own, which was indicated by the symbol turning white again.

Peripheral light detection task

In addition to performing the four MATB II tasks, participants were asked to acknowledge when one of two red LED lights on the left and right side of the monitor illuminated, at a visual angle between 30 - 56 degrees, depending on the participant’s visual focus at the time (see Figure 0.2). They responded by clicking as quickly as possible on one of two buttons located on the corresponding left and right side of the joystick they used for the tracking task. Participants were instructed to rely on their peripheral vision to detect the lights, rather than divert their visual attention away from the MATB II tasks. Overall, participants were asked to give equal priority to all tasks – the MATB II tasks and the peripheral lights.

Eye tracker

The eye tracker used in the experiment was a desktop-mounted ASL Eye-Track D6 eye tracking system (sampling rate = 60 Hz, accuracy < 1 degree visual angle) which was placed below the monitor, at a distance of 24 inches from the participant (see Figure 3.2).

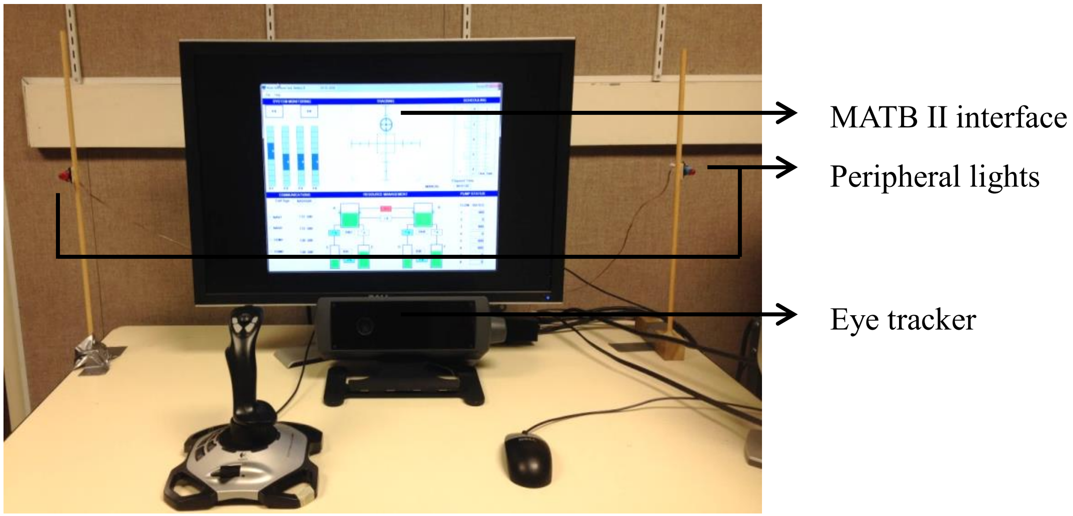

Figure 3.2 - Experimental setup: the MATB II interface, peripheral lights and eye tracker as viewed by the participant

Experimental Conditions

Three candidate triggers of attentional narrowing were evaluated in this experiment: high workload, a novel and unsolvable problem and an incentive.

(1) High workload (WKL): High workload was induced by asking participants to perform an arithmetic task in addition to the MATB II and peripheral light detection tasks. Specifically, they were asked to add two two-digit numbers, presented to them through speakers over the course of four seconds. Participants were given six seconds to respond (by

saying out loud the result) before the next arithmetic task was presented. The answers were recorded by the experimenter throughout the scenario.

(2) Novel and unsolvable problem (NVP): The novel and unsolvable problem consisted of several pump failures on the resource management task. Two types of failures occurred. First, some pumps stopped responding, and did not activate when participants clicked on them. Second, other pumps appeared active and were colored in green but no fuel was being pumped into the tanks. Participants could not solve these problems and it was thus impossible for them to maintain the fuel level in tanks A and B at 2,500 units. Participants had not experienced this failure condition during training.

(3) Incentive (INC): In the incentive condition, participants were told that the participant with the highest final score would receive a bonus of $200, in addition to the regular compensation.

The fourth condition - focused attention - was induced by asking participants to concentrate exclusively on the resource management task. The other tasks and the peripheral lights were still presented but participants were told to actively suppress/ignore them.

The four MATB II tasks differed with respect to the frequency of events requiring participant responses/intervention. Specifically, the system monitoring task and the scheduling task were comparable – both involved approximately 4 events per minute; the tracking task required continuous input from participants; and the resource management (REMAN) task presented, on average, one failure per minute (see Table 3.1 for a summary of the various events frequency).

Table 3.1 - Frequency of events for the various tasks that participants were asked to

complete

		Average frequency	**Duration of event**
MATB II	**System monitoring**	4 deviations / minute	7 seconds
	Tracking	Continuous task	
	Scheduling	4 alignments / minute	~ 4 seconds
	Resource Management	1 failure / minute	20 seconds
Peripheral light detection		3 lights / minute	1 second
Arithmetic task		6 additions / minute	4 seconds

Experiment design and procedure

The four independent variables in this study were workload, novel problem, incentive and focused attention. The experiment employed a fractional factorial design, including only 6 of the 16 (2 x 2 x 2 x 2) possible combinations of factors, as summarized in Table 3.2. The baseline condition was designed to trigger divided attention, while the 4 conditions with an anxiety factor (high workload, novel problem, incentive and ALL) were designed to potentially trigger attentional narrowing. The 6th condition triggered focused attention.

Table 3.2 – Summary of the six experimental conditions employed in this study

		Independent variable			
Experimental condition		**Workload**	**Novel Problem**	**Incentive**	**Focused attention**
	Baseline (BAS)	No	No	No	No
Anxiety Factor	High workload (WKL)	Yes	No	No	No
	Novel problem (NVP)	No	Yes	No	No
	Incentive (INC)	No	No	Yes	No
	All (ALL)	Yes	Yes	Yes	No
	Focused attention (FOC)	No	No	No	Yes

Upon arrival, participants were asked to complete the State Trait Anxiety Inventory questionnaire. They were then introduced to the MATB II simulation, the peripheral light detection task, and the arithmetic task. Participants were told that all tasks were of equal priority and importance. Next, they completed a minimum of three 5-minute practice scenarios to ensure that they were proficient on all tasks. The eye tracker was calibrated, and the experiment started. Each participant was asked to complete the MATB II and peripheral light detection tasks for 5 minutes in each of the 6 different experimental conditions. Following each 5-minute scenario, they were asked to fill out the state section of the STAI questionnaire and the Nasa Task Load Index (TLX; Hart & Staveland, 1988) to assess their level of anxiety. Participants were offered a 2-minute break after the third scenario. The order in which participants were presented with the 6 experimental conditions was counterbalanced. After completion of all experimental conditions, participants were asked to complete a debriefing questionnaire to assess their strategies and self-reported performance.

The total duration of the experiment was approximately 2 hours, and participants were compensated $30 for their time.

Dependent measures

Performance measures, eye tracking data and subjective ratings were collected to assess how the different experimental conditions affected participants' level of anxiety and ability to timeshare the various tasks and to trace their visual attention allocation.

Performance.

For the MATB II, peripheral light detection and arithmetic tasks, accuracy and/or detection rate were measured. In addition, the response time for the peripheral light detection task was recorded. Performance for each of the anxiety conditions was compared to performance in the baseline condition. In the focused attention condition, performance was measured only computed for the resource management task. An overall score was computed to estimate performance on all tasks. Linear regression was used to convert, for each task, detection rates or accuracy measures to a score comprised between 0 and 1. The lowest performance on a task was assigned a value of 0 while the highest performance was allotted a value of 1. The overall score was calculated as the average of all five tasks' score.

Eye tracking data.

Raw gaze data were collected and used to compute two types of eye tracking metrics: global metrics and local metrics. Global metrics were calculated over the entire MATB II display, and used to trace shifts in attention allocation and distinguish divided attention from attentional narrowing. Local metrics were computed for the resource management area only, and served to identify markers of focused attention and attentional narrowing.

Global metrics. Seven global metrics were calculated for each of the four anxiety conditions and compared to the baseline.

(1) **The percentage of fixations** in each task area was computed as the total number of fixations in each of the four task areas expressed as a percentage of the total number of fixations on the display. This metric was used to quantify and compare shifts in attention allocation across the various tasks in the different experimental conditions. Areas that required more attention from participants would lead to higher fixation percentages.

(2) **The average dwell duration** in each of the four task areas corresponded to the average period of time between when a fixation was first observed in one area, and the first next fixation that was measured outside the same area. This metric was employed to reflect participants' strategy when attentional shifts were observed: an increase in dwell durations in one area would indicate that participants spent more time trying to complete the task in that zone. Dwell duration increases have been associated with higher difficulty to extract information (Jacob & Karn, 2003) as, for instance, can be experienced when experiencing a novel and unsolvable problem.

(3) **The average duration of fixations** was computed across the whole display. Longer fixation durations have been observed when task difficulty increases and it is more difficult to extract information (Jacob & Kam, 2003; Henderson & Pierce, 2008). In addition, research has found that high levels of anxiety led to poorer efficiency when processing information. As a result, highly anxious individuals demonstrate less efficient eye

movements, and, as a result, shorter fixations (see, for instance, Williams et al., 2002; Murray & Janelle, 2003; Wilson, Vine & Wood, 2009).

(4) **The average saccade length** was calculated as the distance between two successive fixations. As described in Chapter 1, no information processing occurs during saccades, and, as a result, higher saccade lengths have been associated with less efficient visual strategies - specifically under highly anxious conditions (Bradley et al., 2011).

(5) **The convex hull area** is defined as the minimum area that contains all the fixations. A reduction of the visual attention span, as experienced in attentional narrowing or focused attention for instance, should thus result in a smaller convex hull area.

(6) **The nearest neighbor index (NNI)** is computed as the ratio between the average minimum distance between fixation points and the value that minimum distance would have if the distribution of the fixation points were random. The NNI is equal to 1 when the distribution of the fixations is random, while values smaller or larger than one indicate grouping or regularity, respectively. High levels of attentional load have been associated with random fixation distributions and NNI values close to 1 (Di Nocera, Terenzi & Camilli, 2006).

(7) The last eye tracking metric that was computed was the **ratio of fixation durations to saccade durations**. This metric was first introduced by Goldberg and Kotval (1999) to describe whether more time is spent processing information – as expressed by the fixation durations - or searching for it – as expressed by the saccade durations, and has been used in the literature on attentional narrowing (Regis et al., 2012; Dehais et al., 2015).

Local metrics. Two local metrics were computed for the resource management area: (1) the **average duration of fixations** and (2) the **ratio of fixation durations to saccade durations**.

Subjective ratings.

The State and Trait Anxiety Inventory (STAI) was used to assess participants' general (trait) and temporary (state) anxiety levels. Participants filled out a questionnaire at the end of all experimental sessions to record their strategies and self-reported performance in each experimental condition.

Results

Performance

A repeated-measures analysis of variance (ANOVA) was used to analyze the performance effects of the various experimental factors for the MATB II tasks, the peripheral light detection task, the arithmetic task, and a score reflecting the overall performance on all tasks. Bonferroni corrections were applied for multiple statistical tests. The error bars on the graphs represent the standard error of the mean.

System monitoring (SYSMON)

Overall, the various anxiety factors significantly affected participants' performance on the system monitoring task, as measured by the detection rate (DR) of the deviation of the darker blue areas from their central position (with a Greenhouse-Geisser correction: F (2.8, 83.7) = 8.66, p = 0.000, η_p^2 = 0.23; see Figure 3.3). The novel and unsolvable problem and the ALL condition led to a drop in performance (novel problem: DR = 0.53, SD = 0.21; ALL: DR = 0.52, SD = 0.22), compared to the baseline (DR = 0.65, SD = 0.2; p = 0.003 and p = 0.000, respectively).

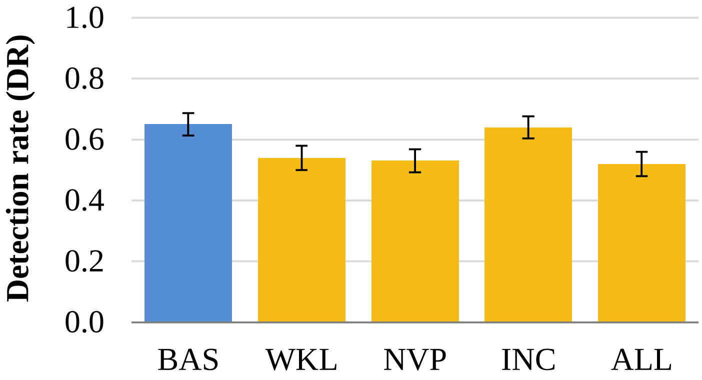

Figure 3.3 - Detection rates (DR) for the system monitoring task in the various conditions

Tracking (TRCK)

Overall, there was a main effect of anxiety on participants' performance on the tracking task, as measured by the root mean square deviation (RMSD) of the target from the center of the axes (F (4, 116) = 5.6, p = 0.000, η_p^2 = 0.161; see Figure 3.4). The novel and unsolvable problem led to a significant drop in performance in the tracking task (RMSD = 63 pixels) as compared to the workload condition (RMSD = 51 pixels; p = 0.001). None of the other conditions differed from the baseline.

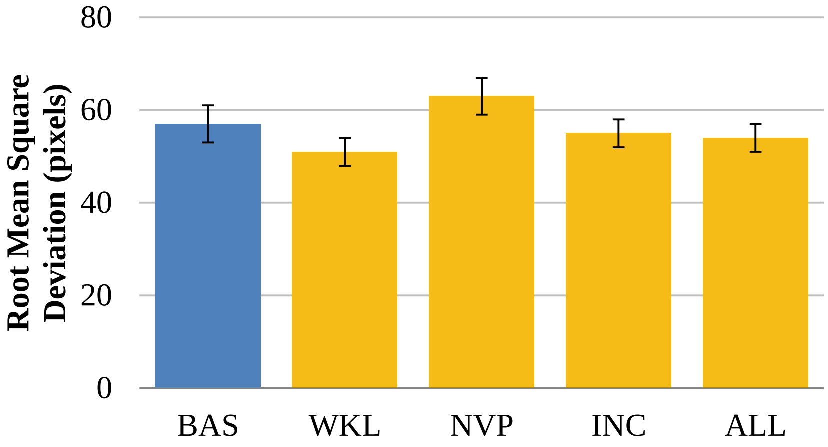

Figure 3.4 - Root Mean Square Deviation (RMSD) from the center target for the tracking task in the various conditions

Scheduling (SCHED)

Anxiety significantly affected performance on the scheduling task, as measured by the detection rate (DR) for bar alignments (F (4, 116) = 20.4, p = 0.000, $\eta_p^2 = 0.413$; see Figure 3.5). The high workload condition, novel problem and ALL conditions led to a drop in performance, as compared to the baseline condition (baseline: DR = 0.68, SD = 0.20; high workload: DR = 0.52, SD = 0.28; novel problem: DR = 0.54, SD = 0.26; ALL: DR = 0.47, SD = 0.28; p = 0.000 in all cases).

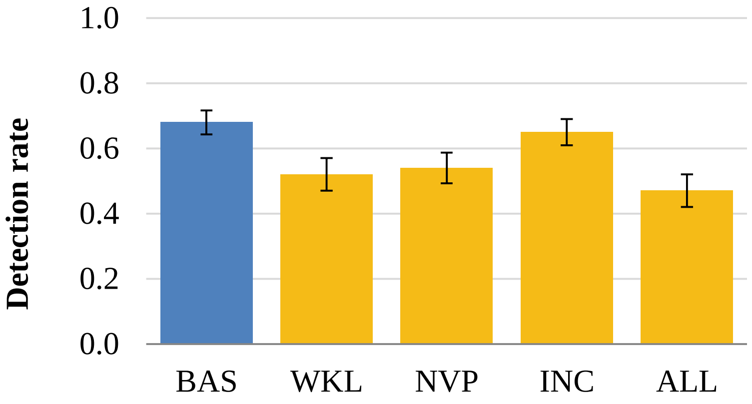

Figure 3.5 – Detection rate for the scheduling task in the various conditions

Resource management (REMAN)

Overall, there was a main effect of anxiety on performance for the resource management task, as measured by the average deviation of tanks A and B from the target of 2,500 units (with a Greenhouse-Geisser correction: F (1.7, 50.0) = 267.3, p = 0.000, η_p^2 = 0.90; see Figure 3.6). The average deviation from the target was 20 units in the baseline condition (SD = 11 units), 55 units in the high workload condition (SD = 34), 277 units in the novel and unsolvable problem condition (SD = 71), 22 units in the incentive condition (SD = 13 units), 398 units in the ALL condition (SD = 120), and 18 units in the focused attention condition (SD = 12 units). The only two conditions that differed significantly from the baseline were the novel problem and the ALL condition (p = 0.000 in all cases).

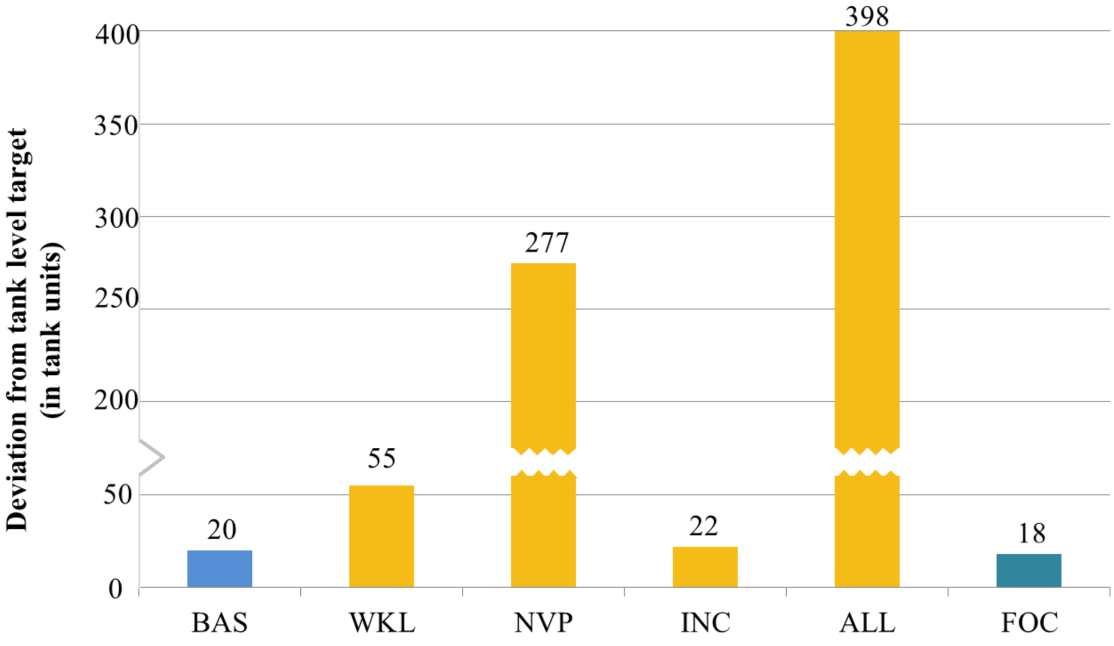

Figure 3.6 – Average deviation of the levels of tanks A and B from the target of 2,500 units for all conditions

Peripheral light detection task

Detection Rate. Overall, anxiety significantly affected the detection of the peripheral lights (F (4, 116) = 4.7, p = 0.002, η_p^2 = 0.139; see Figure 3.7). The detection rate was 0.54 in the baseline condition (SD = 0.20), 0.43 in the high workload condition (SD = 0.21), 0.46 in the novel and unsolvable problem condition (SD = 0.20), 0.53 in the incentive condition (SD = 0.24), and 0.38 in the ALL condition (SD = 0.24). The detection rate was significantly smaller in the ALL condition, compared to baseline (p = 0.004).

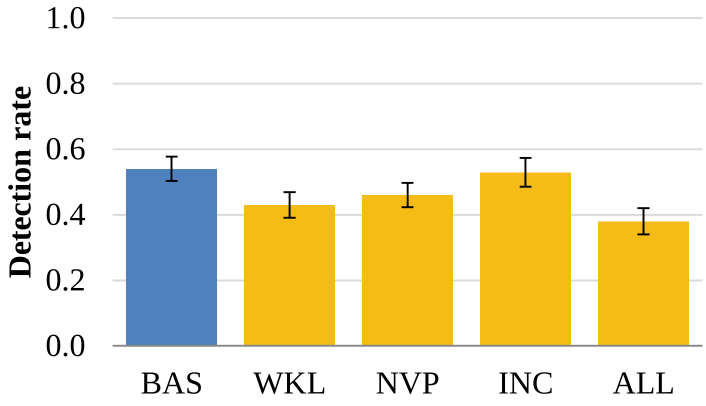

Figure 3.7 - Detection rate for peripheral lights in all conditions

Response Time. There was no main effect of anxiety on response times to peripheral lights (with a Greenhouse-Geisser correction: F (4, 116) = 1.16, p = 0.33).

Arithmetic Task

Accuracy on the arithmetic task did not differ significantly between the ALL condition (accuracy = 0.62, SD = 0.19) and the high workload condition (accuracy = 0.65, SD = 0.17; F (1, 50) = 2.33, p = 0.133, η_p^2 = 0.045). This task was performed in only those two conditions.

Overall score

Anxiety significantly affected the overall score (F (26, 4) = 95.5, p = 0.000, η_p^2 = 0.936; see Figure 3.8). Compared to the baseline condition (0.72, SD = 0.11), the overall score was significantly lower in the high workload (0.65, SD = 0.12; p = 0.001), novel problem (0.58, SD = 0.11; p = 0.000), and ALL conditions (0.54, SD = 0.12; p = 0.000).

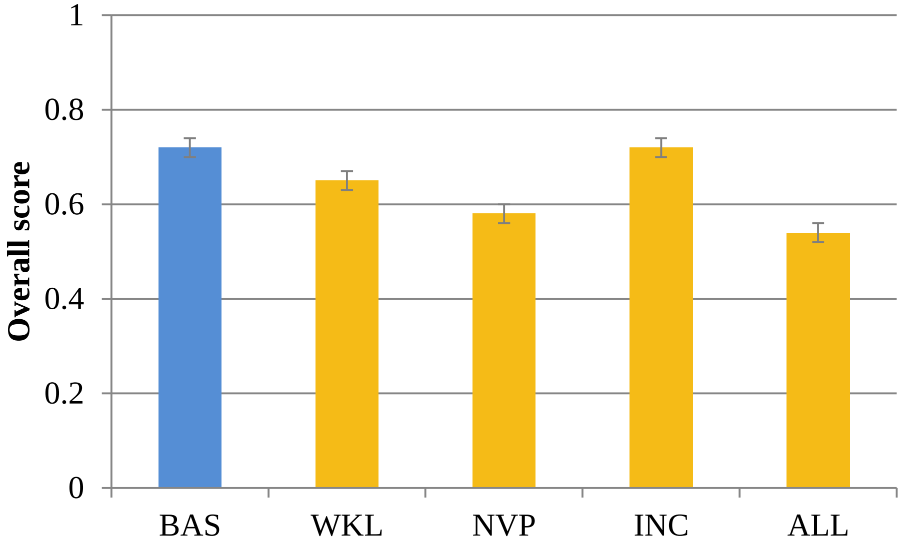

Figure 3.8 - Overall score in all conditions

Eye tracking

A repeated-measures analysis of variance (ANOVA) was performed to analyze the effects of anxiety factors on eye tracking metrics. Bonferroni corrections were applied for multiple statistical tests. The error bars on the graphs represent the standard error.

Percentage of fixations in each task-area (PoF)

System monitoring (SYSMON). The percentage of fixations in the SYSMON area was significantly affected by anxiety (F (4, 116) = 13.91, p = 0.000, η_p^2 = 0.32). Specifically, there was a significant decrease in the percentage of fixations in the SYSMON area in the novel problem condition and in the ALL condition, compared to the baseline (baseline: PoF = 20% (SD = 8%); Novel problem: PoF = 12% (SD = 6%), p = 0.000; ALL: PoF = 15% (SD = 8%), p = 0.032; see Figure 3.9).

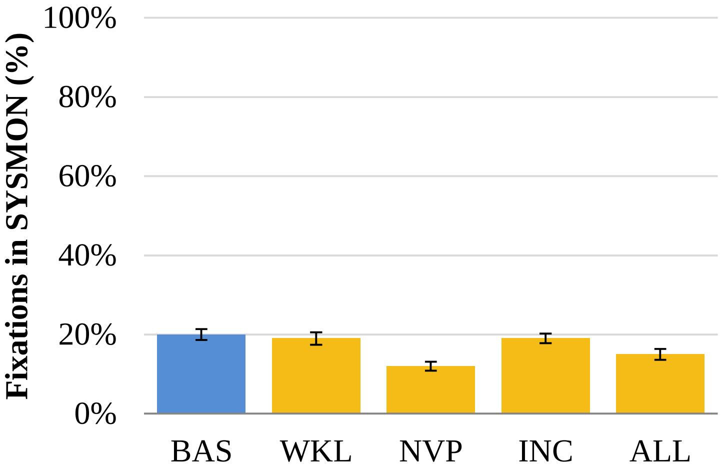

Figure 3.9 – Percentage of fixations on the SYSMON task for all conditions

Tracking (TRCK). The percentage of fixations in the tracking area was also significantly affected by anxiety (F (4, 116) = 20.68, p = 0.000, η_p^2 = 0.42; see Figure 3.10). As compared to the baseline condition (PoF = 22%, SD = 8%), the novel problem condition led to a significant drop in the fixation percentage in the TRCK area (PoF = 15%, SD = 6%, p = 0.000), while the high workload condition led to a significant increase in the fixation percentage (PoF = 27%, SD = 10%; p=0.018).

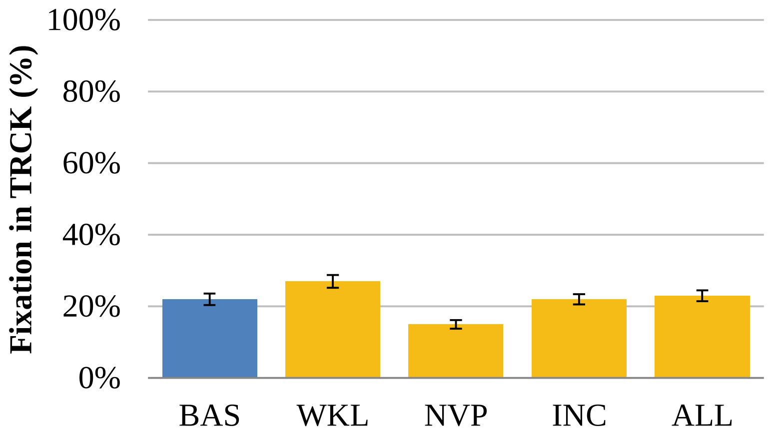

Figure 3.10 - Percentage of fixations on the TRCK task for all conditions

Scheduling (SCHED). A main effect of anxiety was observed also for fixation percentages on the scheduling task (F (4, 116) = 16.22, p = 0.000, $\eta_p^2 = 0.65$; see Figure 3.11). Significantly fewer fixations were observed in this area in the high workload (PoF = 14%, SD = 8%), the novel problem (PoF = 12%, SD = 6%) and the ALL conditions (PoF = 12%, SD = 6%), compared to baseline (PoF = 17%, SD = 5%; p = 0.012, p = 0.000, p = 0.000, respectively).

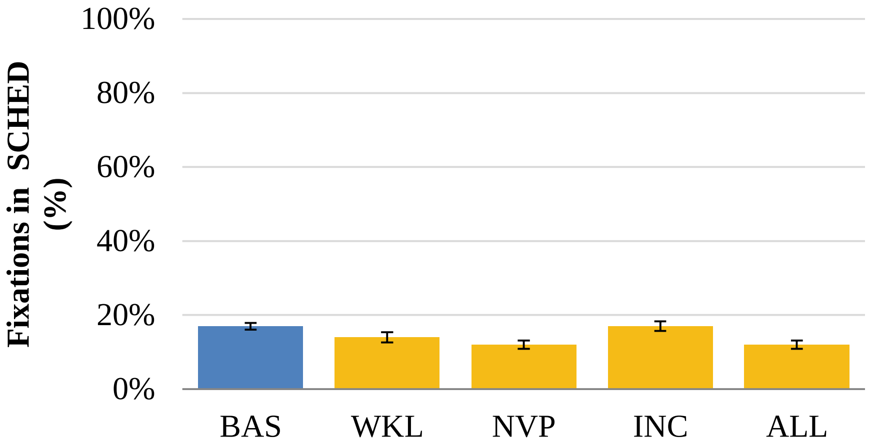

Figure 3.11- Percentage of fixations on the SCHED task for all conditions

Resource Management (REMAN). The fixation percentages in the resource management area were significantly affected by anxiety factors (F (4, 116) = 30.11, p = 0.000, η_p^2 = 0.51; see Figure 3.12). In particular, there were significantly more fixations on the REMAN task in the novel problem (PoF = 59%, SD = 13%) and the ALL conditions (PoF = 48%, SD = 13%), compared to baseline (PoF = 40%, SD = 12%; p = 0.000 and p = 0.010, respectively).

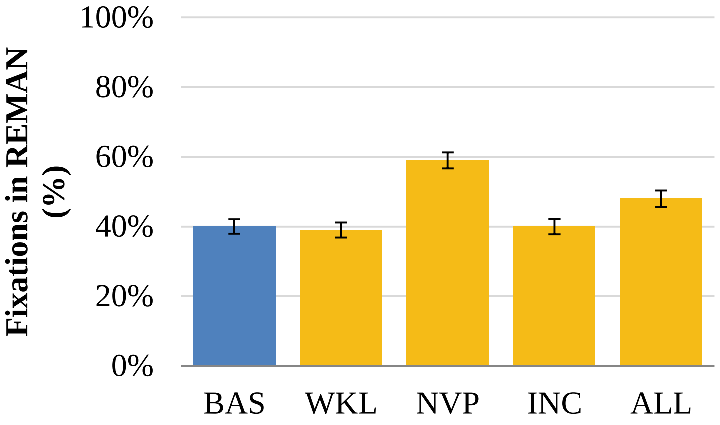

Figure 3.12 - Percentage of fixations on the REMAN task for all conditions

The fixation percentages on all MATB II tasks across all experimental conditions are summarized in Figures 3.13 and 3.15. Note that the percentages for the 4 task regions do not add up to 100 % because some fixations were located outside of these areas (e.g., when transitioning from one task-sector to another).

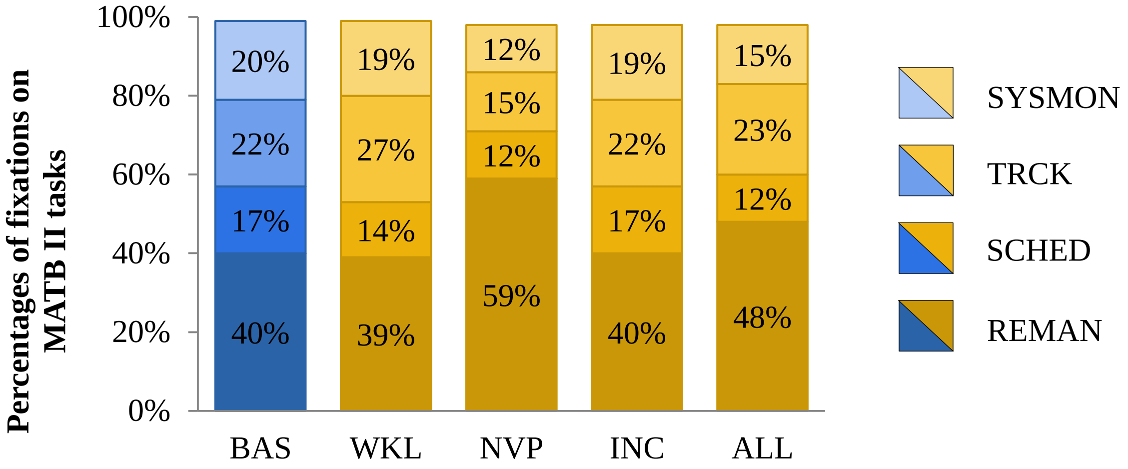

Figure 3.13 – Fixation percentages in all task areas for all conditions

Average dwell duration in each task-area (DD)

System monitoring (SYSMON). There was a main effect of anxiety on dwell duration in the system monitoring area (with a Greenhouse-Geisser correction: F (3.8, 110) = 5.1, η_p^2 = 0.15), but none of the anxiety conditions significantly differed from the baseline. The average duration of dwells in SYSMON was 0.85s in the baseline (SD = 0.28s), 1.1s in the high workload condition (SD = 0.41s), 0.79s in the novel problem condition (SD = 0.28s), 0.76s in the incentive condition (SD = 0.22s), and 0.96s in the ALL condition (SD = 0.4s).

Tracking (TRCK). The average dwell duration was significantly affected by anxiety (with a Greenhouse-Geisser correction: F (2.02, 58.5) = 27.5, p = 0.000, η_p^2 = 0.49). The high workload and ALL conditions led to a significant increase in the duration of dwells in the tracking task, as compared to the baseline (baseline: DD = 0.67s (SD = 0.41s); high workload: DD = 1.42s, (SD = 0.97s), p = 0.000; ALL: DD = 1.31s (SD = 0.69s), p = 0.000), while the novel and unsolvable problem condition was associated with significantly shorter dwells than the baseline (novel problem: DD = 0.51s, SD = 0.28s, p = 0.019).

Scheduling (SCHED). There was no significant effect of anxiety on the average dwell duration in the scheduling task (F (4, 116) = 1.51, p = 0.20, η_p^2 = 0.050).

Resource management (REMAN). The anxiety factor significantly affected the average dwell duration in the resource management task (F (4, 116) = 11.25, p = 0.000, η_p^2 = 0.28). The novel problem condition led to significantly longer dwells than the baseline (baseline: DD = 2.7s (SD = 1.3s); novel problem: DD = 3.9s (SD = 2.1s); p = 0.000).

The average duration of dwells on all MATB II tasks in all experimental conditions is summarized in Figures 3.14 and Figure 3.15.

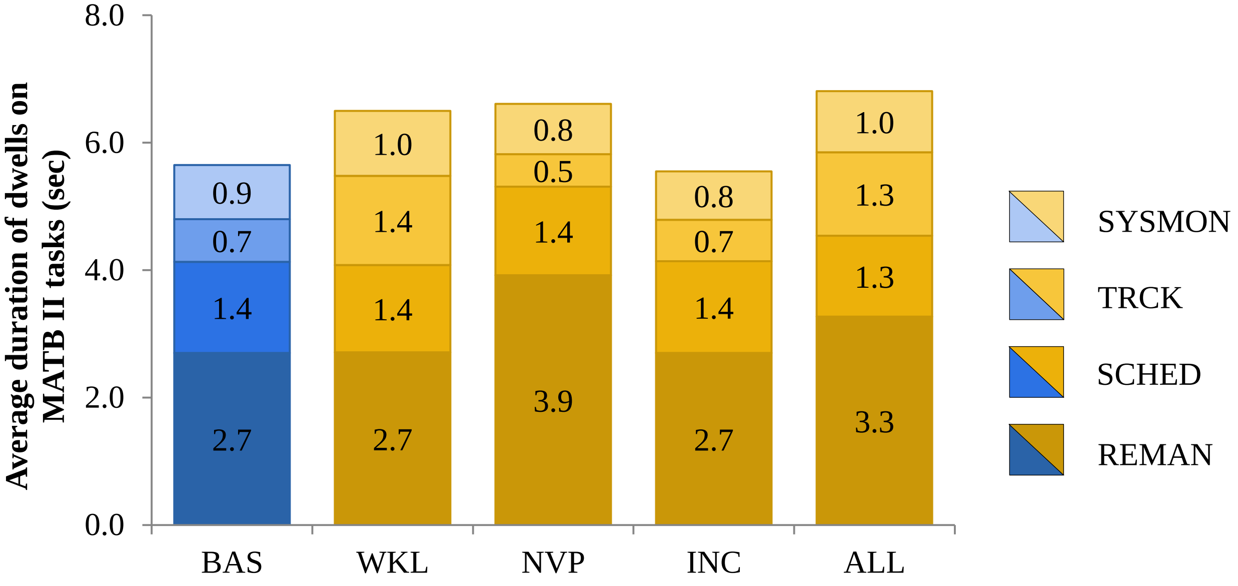

Figure 3.14 - Average duration of dwells on all areas for all condition

s

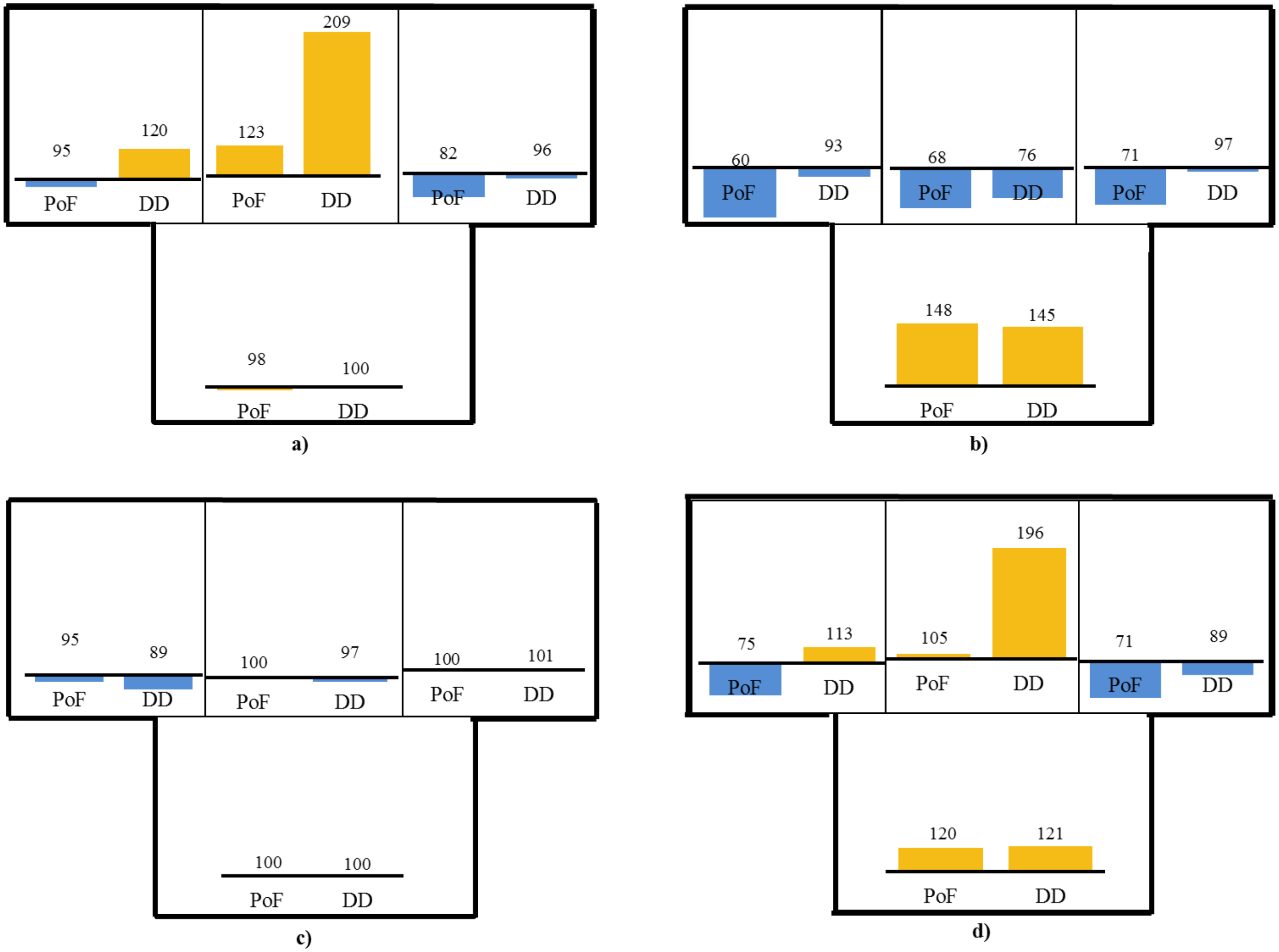

Figure 3.15 - Summary of the visual attentional shifts within the MATB II display, as compared to the baseline, in (a) high workload, (b) the novel problem, (c) the incentive and (d) the ALL conditions. The bars indicate the change in the percentage of fixations (PoF) and in the duration of dwells (DD) in each respective area, as compared to the baseline.

Average fixation duration

Anxiety had no significant effect on the average duration of fixations on the overall screen (F (4, 116) = 1.6, p = 0.178, η_p^2 = 0.052; see Table 3.3).

Average saccade length

The average length of saccades varied significantly as a function of anxiety (F (4, 116) = 36.03, p = 0.000, η_p^2 = 0.554; see Table 3.3). The high workload (average length = 32.4 pixels, SD = 5.1 pixels), novel problem (average length = 33.5 pixels, SD = 4.9 pixels) and ALL (average length = 32.0 pixels, SD = 5.1 pixels) conditions led to significantly shorter saccades, compared to the baseline (average length = 37.5 pixels, SD = 5.2 pixels; p = 0.000 in all cases).

Convex hull area

Anxiety had no significant effect on the convex hull area (F (4, 116) = 1.32, p = 0.27, η_p^2 = 0.044; see Table 3.3).

Nearest Neighbor Index (NNI)

There was a main effect of anxiety on the NNI (F (4, 116) = 3.89, p = 0.005, η_p^2 = 0.118; see Table 3.3). As compared to the baseline condition (0.29, SD = 0.049), the high workload condition led to a significantly higher NNI (0.32, SD = 0.062; p = 0.024) and the ALL condition led to a marginally higher NNI (0.33, SD = 0.07; p = 0.051).

Ratio of fixation duration to saccade duration

Anxiety had no significant effect on the ratio of fixation duration to saccade duration (F (4, 116) = 1.31, p = 0.27, η_p^2 = 0.043; see Table 3.3).

Table 3.3 - Eye tracking results for the MATB II display

	BAS	WKL	NVP	INC	ALL	Main effect of anxiety factor
Average fixation duration (sec)	0.29 (0.05)	0.30 (0.06)	0.28 (0.036)	0.28 (0.04)	0.29 (0.06)	F (4, 116) = 1.60, p = 0.178, $\eta_p{}^2$= 0.052
Average saccade length (pixels)	37.5 (5.2)	**32.4** **(5.1) ***	**33.5** **(4.9) ***	37.7 (4.8)	**32.0** **(5.1) ***	F (4, 116) = 36.03, p = 0.000, $\eta_p{}^2$ = 0.554
Convex hull area (pixels^2)	15,009 (6,118)	19,641 (12,854)	17,571 (9,553)	16,356 (5,835)	19,838 (13,493)	F (4, 116) = 1.32, p = 0.270, $\eta_p{}^2$ = 0.044
Nearest Neighbor Index (NNI)	0.29 (0.05)	**0.32** **(0.06) ***	0.30 (0.07)	0.30 (0.05)	**0.33** **(0.07) ***	F (4, 116) = 3.89, p = 0.005, $\eta_p{}^2$ = 0.118
Fixation duration / saccade duration	1.95 (0.99)	2.17 (0.88)	1.95 (0.87)	1.87 (0.84)	1.97 (1.01)	F (4, 116) = 1.31, p = 0.270, $\eta_p{}^2$ = 0.043

* denotes that this value was significantly different from the baseline condition ($p<0.05$)

Average duration of fixations on REMAN

There was a main effect of anxiety on the average duration of fixations in the resource management (REMAN) area (with a Greenhouse-Geisser correction: F (2.8, 82.0) = 24.51, p = 0.000, η_p^2 = 0.46). The focused attention condition led to significantly longer fixations (0.47 seconds, SD = 0.13) than any other condition (baseline: 0.38 seconds, SD = 0.11 seconds; high workload: 0.36 seconds, SD = 0.067 seconds; novel problem: 0.36, SD = 0.054 seconds; incentive: 0.35 seconds, SD = 0.037 seconds; p = 0.000 in all cases; see Figure 3.16).

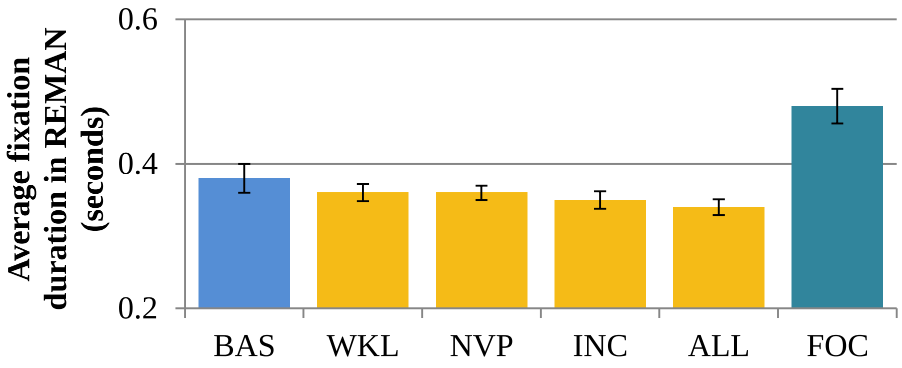

Figure 3.16 - Average duration of fixations in the REMAN area

Ratio of fixation duration to saccade duration on REMAN

There was no main effect of anxiety on the ratio of fixation duration to saccade duration in the REMAN area (F (5, 145) = 2.15, p = 0.062, η_p^2 = 0.069).

Subjective ratings

Non-parametric Friedman tests were used to examine differences between repeated measures on the STAI and TLX rankings.

STAI anxiety

The average trait anxiety of participants was 36.6 (SD = 8.3). Anxiety significantly affected participants' state anxiety ($\chi^2(5) = 75.6$, $p = 0.000$). Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied (the significance level was set at $p < 0.008$). Wilcoxon signed-rank tests showed that the high workload, novel problem and the ALL conditions led to a significant increase in state anxiety, as compared to the baseline condition (baseline: 36.7 (SD = 7.7); high workload: 43.4 (SD = 10.1), Z = -3.95, p = 0.000; novel problem: 44.8 (SD = 9.9), Z = -4.3, p = 0.000; ALL: 47.1 (SD = 11.9), Z = -4.28, p = 0.000; see Figure 3.17).

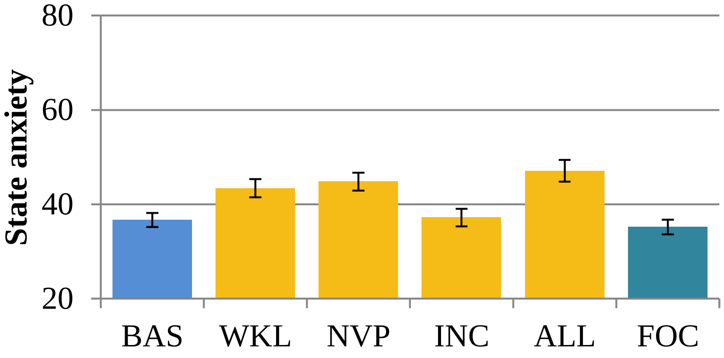

Figure 3.17- State anxiety experienced after each experimental condition

A marginally significant correlation was observed between trait anxiety and the change of percentage fixations in the REMAN area between the baseline and the novel problem condition: the percentage of fixations in the REMAN area tend to increase more for participants that showed higher levels of trait anxiety (Pearson coefficient $r = 0.337$, $p = 0.078$). None of the other percentage changes (for PoF and DD) in the other conditions were correlated with trait anxiety ($p > 0.118$ in all cases).

There was no correlation between the percentage change in state anxiety (calculated between the baseline and each of the high anxiety conditions) and the percentage change in percentage of fixations or dwell durations in REMAN ($p > 0.158$ in all cases).

Self-evaluation of task performance

There was a significant effect of anxiety on self-reported performance on the MATB II tasks ($\chi^2(4) = 78.1$, $p = 0.000$; see Figure 3.18). Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied (the significance level was set at $p < 0.01$). Compared to the baseline, participants reported a perceived significant performance decrement in the high workload condition (baseline: 6.9, SD = 2.0; high workload: 4.6, SD = 1.7; Z = -4.5, p = 0.000), the novel problem condition (4.7, SD = 2.0, Z = -4.4, p = 0.000) and the ALL condition (2.9, SD = 1.6, Z = -4.5, p = 0.000).

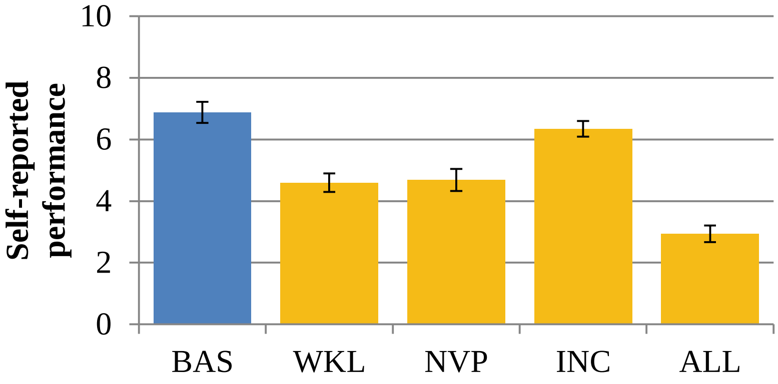

Figure 3.18 - Self-reported performance on the MATB II tasks in all experimental conditions

Discussion

The goals of this study were (1) to determine the most effective manipulations of anxiety – more specifically high levels of attentional load, ego-threat and monetary incentive - for inducing attentional narrowing in the context of a complex multi-tasking environment, and (2) to identify eye tracking-based markers of divided attention, attentional narrowing and focused attention. To that end, participants were asked to timeshare several tasks in the presence or absence of potential triggers of narrowing, and to engage in focused attention (focused on one of the four tasks) in another condition. Their performance and eye movements were recorded. The following sections first summarize and discuss the findings related to the effectiveness of various triggers for inducing attentional narrowing and then examine the ability of the various performance and eye tracking metrics to distinguish between three attentional states.

Inducing attentional narrowing

As described in Chapter 1, a person is considered to experience attentional narrowing when two conditions are met: (1) their performance drops, and (2) visual attention is allocated, involuntarily, to a single task or display region for an extended period of time. Of the 4 possible triggers of narrowing that were examined and compared in this experiment, the novel and unsolvable problem and the ALL condition led to the largest performance decrements on the MATB II tasks. Specifically, these two conditions affected the system monitoring, scheduling and resource management tasks. The monetary incentive, on the other hand, was ineffective at degrading performance. The latter result can be explained, in part, by the fact that, while monetary incentives tend to increase the amount of effort invested in accomplishing tasks, this may not always result in increased anxiety (Bonner & Sprinkle, 2002), due to individual differences in personalities (Locke & Braver, 2008) or economic status (Griskevicius, Tybur, Delton & Robertson, 2011). Also, during the debriefing, several students reported that they did not think their performance would be the best of all participants and, as a result, they gave up and did not try any harder during the incentive condition.

The novel and unsolvable problem and high workload also significantly affected visual attention allocation, as indicated by the eye tracking data. Specifically, in the high workload condition, attention shifted towards the tracking task while, in the presence of a novel problem, it was allocated mostly on the resource management task. Combined, the performance and eye tracking data suggest **that the novel and unsolvable problem was the most effective means of triggering attentional narrowing**. This conclusion is further supported by debriefing data showing that participants believed their performance dropped in the novel problem and ALL conditions, as compared to the baseline, but wrongly stated that their performance was worse in the ALL condition, compared to the novel problem condition. This suggests that participants were not aware of the extent of their performance decrements and the underlying narrowing of attention in the presence of a novel problem which is a hallmark of the involuntary nature of attentional narrowing. The success of this manipulation at inducing attentional narrowing can be explained by a combination of factors. First, the fact that the problem was novel unexplained and unsolvable could have led participants to experience difficulties with attribution - the process of inferring causes (e.g., interactions, characteristics) from their effects (e.g., actions, behaviors) (Deschamps, 1973).

In this case, it may have been difficult for participants to decide whether the problem was due to the system or themselves. In this case, it may have been difficult for participants to determine whether the problem was due to a failure of the system or their own poor performance. If they attributed the problem to their own performance, they may have experienced ego-threat. In addition, because participants did not know that the problem was unsolvable, they continued to try to solve it which increased their workload and, in turn, their arousal which is a known trigger of attentional narrowing.

In the high workload condition, eye tracking data indicated a strong increase of attention on the tracking task – expressed by an increase in the percentage of fixations and dwell duration in this area. The fact that participants neglected the resource management task can be explained, in parts, by Wickens' multiple resource theory (2002). The arithmetic and resource management task both drew from the same pool of attentional resources and required them to work with numbers. As a result, performing them together was very difficult. Despite the instructions to give the same weight and importance to all tasks (MATB II, peripheral lights and arithmetic task), participants reported prioritizing the arithmetic task over the others. Quotes from the debriefing questionnaire include: "when thinking about the questions I wouldn't pay attention to the [other] tasks. I didn't mean to do this", "I had to stop monitoring the tasks to replay the numbers I was being asked to add in my head", "my main focus was on the auditory tasks the whole time", and "I forgot about most of the other tasks completely and tried to answer the math questions that I could". Participants had been instructed to look at the MATB II display at all times. Therefore, when trying to solve the arithmetic problems, they stared at the screen without actively engaging in any task. Because the tracking task was located at the center of the display front of their eyes, it was most natural for participants to look in this area. One participant reported: “I often felt I was blankly staring through the screen when given an auditory task”.

Contrary to our expectation, the ALL condition – when a mental arithmetic task, a novel problem and incentive were presented simultaneously - did not lead to the most pronounced signs of attentional narrowing. This can be explained by the fact that while the arithmetic task led participants to stare at the tracking task for longer durations, the novel and unsolvable problem increased their attention towards the resource management task. The effects of the auditory workload and the novel problem on participants’ attention cancelled each other out. Participants would either prioritize the arithmetic task and, as a result, not notice the novel problem in the resource management area, or, on the contrary, engage in the resolution of the novel problem and drop the arithmetic task.

Participants who exhibited higher levels of trait anxiety experienced a marginally larger increase in fixations on the resource management task. This result confirms that highly anxious individuals are more likely to engage in attentional narrowing (see, for instance, Derryberry & Reed, 1998; Koster et al., 2005). Studies in neuro-cognition have found that high levels of trait anxiety hindered the control of attention (Bishop, 2009; Telzer et al., 2008) and, more specifically, the executive control network (Pacheco-Unguetti et al., 2010). It is interesting to note that the average trait anxiety of participants, as measured by the STAI questionnaire, was of 36.6. Other researchers have estimated this value as reflecting low trait anxiety (see, for instance, Koster et al., 2005). This could help explain why the correlation between trait anxiety and attentional narrowing was only marginally significant: our study was, overall, ran on students who were not very anxious.

Distinguishing between divided attention, focused attention and attentional narrowing

In an effort to identify the most diagnostic marker of attentional narrowing, the eye tracking data were analyzed to establish which metrics were best able to distinguish between the states of divided attention (as experienced in the baseline condition), focused attention, and attentional narrowing (as experienced in the novel and unsolvable problem condition).

First, the findings from this study indicate that, when engaged in attentional narrowing, (1) the percentage of fixations in the resource management area significantly increased, (2) the duration of dwells in the resource management area significantly increased, and (3) the average length of saccades on the entire MATB II display was shorter than when engaged in divided attention.

Second, when participants were engaged in focused attention (the focused attention condition), fixations were significantly longer than when they were engaged in divided attention (baseline) and attentional narrowing. This finding can be explained by the fact that the focused condition imposed low levels of attentional load on participants, a situation that has been associated with longer fixation durations (Tsai, 2007; Matthews et al., 2015). The average duration of fixations did not differ between the baseline divided attention condition and the attentional narrowing during the novel problem. This result may be explained, in part, by the fact that, on the one hand, the novel and unsolvable problem imposed high levels of attentional load and operators, and therefore tended to reduce the duration of fixations. In addition, fixation duration has been found to decrease under high levels of anxiety (see, for instance, Williams et al., 2002). On the other hand, situations when it is more difficult to extract information have been associated with longer fixation durations (Jacob & Karn, 2003). In the present study, in the condition where participants were presented with a novel and unsolvable problem, participants experienced both high levels of workload and anxiety, but also difficulties with extracting information, since they were facing a very difficult problem on the resource management task. The two effects may thus have combined and cancelled each other out.

In conclusion, this study showed that (1) a novel and unsolvable problem is an effective trigger of attentional narrowing, and (2) three eye tracking metrics - percentage of fixations, dwell duration and fixation duration in the area presenting the novel problem can be used to detect when individuals experience this attentional state and distinguish it from divided attention and focused attention. In order to develop real-time countermeasures to the problem of attentional narrowing, the next step of this line of research is to develop an algorithm that can detect, over a short interval of time and using the metrics identified in this study, when participants engage in attentional narrowing. The efforts made towards this objective are described in Chapter 4.

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Chapter 4

Developing an eye tracking-based algorithm for detecting attentional narrowing

The study described in Chapter 3 identified several eye tracking metrics that responded differently when participants experienced attentional narrowing versus when they were engaged in either divided or focused attention. To accomplish the ultimate goal of this dissertation research – namely to detect and counteract attentional narrowing real time –, the next step is to determine which of these metrics can distinguish most reliably between the three attentional states and to develop a detection algorithm based on these metrics. Also, in order to detect attentional narrowing as early as possible and be able to prevent performance breakdowns caused by this attentional state, it is important that the window of time over which the metrics need to be calculated before a determination can be made be as short as possible. It is likely that there will be a tradeoff between the length of that time window and the accuracy of the algorithm's assessment of a person's attentional state.

Development of the algorithm

The detection algorithm will use as input (observations) eye tracking data collected in real time, and provide as output (categories) the attentional state of the participant: divided attention, attentional narrowing or focused attention (see Figure 4.1).

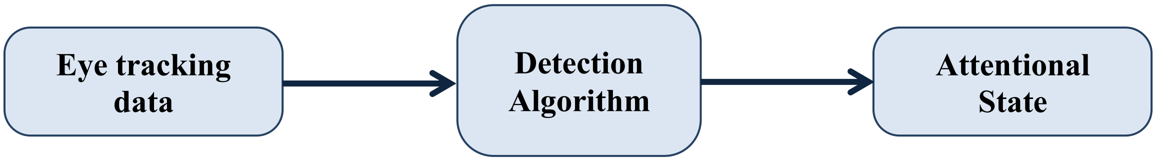

Figure 4.1 – Basic structure of the detection algorithm

Constraints of the detection algorithm

Several constraints had to be met in the development of the detection algorithm. First, the study reported in Chapter 3 revealed large inter-individual variability for the various eye tracking metrics. This confirms previous work which has shown that eye movements can greatly vary from one person to another (Andrew & Coppola, 1999; Chua, Boland & Nisbett, 2005; Rayner et al., 2007; Castelhano & Anderson, 2008) and that greater detection accuracy can be achieved by using detection algorithm parameters that are specific to each individual (Jin et al., 2013).

Second, the detection algorithm ultimately needs to perform well not only in controlled laboratory settings but also in complex real-world domains, such as flight decks or process control. In those environments, attentional narrowing is experienced very rarely, and therefore the detection algorithm cannot rely on any a-priori knowledge of a particular operator’s eye movements when she/he experiences this undesirable attentional state. At best, baseline data on eye movements when engaged in divided attention – the default attention state in these domains – may be available.

Finally, it is critical that the detection algorithm can detect attentional narrowing as soon as possible, before it can lead to performance breakdowns. Therefore, it is important to determine the minimum number of eye tracking metrics needed to achieve this goal while minimizing required computing time. At the same time, since the algorithm’s output will ultimately be used to trigger countermeasures to attentional narrowing, data need to be collected and processed over a sufficiently long period of time to ensure high accuracy and avoid unnecessary interventions.

Structure and logic of the detection algorithm

Machine learning is one approach for developing algorithms that are capable of making decisions and predictions based on empirical data. More specifically, there are two main types of machine learning: (1) supervised and (2) unsupervised learning. Supervised learning tools (“classifiers”, such as support vector machines (SVM), or logistic regression) assign observations (input – in this case, eye tracking data) into categories (output – in this case, attentional states), based on a “training set” - a set of observations that have already been associated with their corresponding output. Unsupervised learning tools (“clustering algorithms”, such as K-means) can achieve a similar categorization without any training set, by grouping new inputs into categories based on their distance from previous inputs.

To date, most researchers who developed eye tracking-based detection algorithms have employed supervised learning (Liang, Reyes & Lee, 2007; Judd et al., 2009) because, in those cases, a full training set was available. However, the training set for the detection algorithm developed as part of this dissertation contains data points for only one of three possible outputs, namely “divided attention”. It does not have a training set for the outputs “attentional narrowing” and “focused attention”. Supervised learning is therefore not an option. At the same time, most unsupervised learning tools require several data points before they can reliably categorize new observations. Because attentional narrowing is a rare and dangerous state, it is not possible to wait and gather sufficient data points before making any decision; thus, unsupervised learning cannot be employed either.

Instead, the algorithm will build on the fact that both attentional narrowing and focused attention differ from divided attention in that they involve a reduction in the visual attentional field, and compare values of the metrics with set thresholds measured during divided attention. Therefore, the detection algorithm presented in this chapter involves two stages: DA I and DA II. First, Detection algorithm I (DA I) will serve to detect a reduced attentional field – i.e., it will distinguish between divided attention on the one hand and focused attention and attentional narrowing on the other hand. Second, once DA I has detected a reduced attentional field, Detection algorithm II (DA II) will then be employed to further distinguish between attentional narrowing and focused attention.

Detection algorithm I (DA I): detecting a reduced attentional field

The experiment described in Chapter 3 identified three eye movement-based metrics that respond differently to attentional narrowing than to divided attention: (1) the percentage of fixations (PoF) on the resource management (REMAN) task (increase), (2) the average dwell duration (DD) on the REMAN task (increase), and (3) the average saccade length (decrease). Focused attention was also characterized by higher fixation percentages (PoF) and longer dwell durations (DD) in the REMAN area, as compared to the divided attention condition. The average saccade length was shorter in the high workload condition also; it is therefore not sufficiently diagnostic of a reduced attentional field. For that reason, DA I will use only (1) the percentage of fixations and (2) the average dwell duration on the REMAN task as inputs. The output of this algorithm will be binary: (1) divided attention or (2) attentional narrowing or focused attention, as illustrated in Figure 4.2.

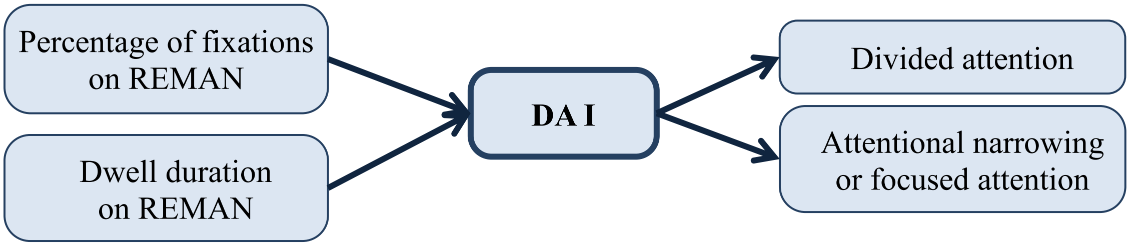

Figure 4.2 - Detection Algorithm I structure diagram

Attentional narrowing or focused attention will be assumed when one or both of the two input values - percentage of fixations and dwell duration in the REMAN task - calculated over a specific window of time, w - exceed certain thresholds. Observations that are below the threshold for both measures will be categorized as divided attention. The thresholds are set based on the data collected in the divided attention condition for each individual, using the formula described in Equation 4.1.

$$\text{Threshold DA I (PoF)}$$
$$= \text{Average PoF during divided attention} + \boldsymbol{\alpha}\,.\,\text{standard deviation}$$

$$\text{Threshold DA I (DD)}$$
$$= \text{Average DD during divided attention} + \boldsymbol{\beta}\,.\,\text{standard deviation}$$

Equation 4.1 - Calculation of each individual’s thresholds for DA I

Detection algorithm II (DA II): distinguishing between focused attention and attentional narrowing

Once a reduced attentional field is detected by DA I, Detection algorithm II (DA II) will be run to distinguish between focused attention and attentional narrowing. Findings from the experiment described in Chapter 3 suggest that the average duration of fixations in the REMAN area is a promising metric for distinguishing between these two states. A significant increase in fixation duration was observed in the focused attention condition but not with attentional narrowing. DA II will thus use average fixation duration, as calculated over a window of time w, as input, and its output will be either (1) focused attention or (2) attentional narrowing, as illustrated in Figure 4.3.

Figure 4.3 - Detection Algorithm II structure diagram

An observation that was classified as “Attentional narrowing or focused attention” by DA I will be interpreted as “focused attention” if the average fixation duration of that observation is larger than a specific threshold. That threshold is defined in Equation 4.2:

$$\begin{aligned}&\text{Threshold DA II}\\&\qquad = \text{Average fixation duration during divided attention}\\&\qquad + \boldsymbol{\gamma}\,.\,\text{standard deviation}\end{aligned}$$

Equation 4.2 - Calculation of each individual’s threshold for DA II

The parameters (1) time window w and (2) sensitivities α, β and γ will be discussed in the following section of this chapter.

Adjusting the algorithm parameters

To determine the optimal values of the parameters w, α, β and γ, the above algorithm was run on the data from the experiment described in Chapter 3 and the effect of various values of the parameters on the detection rate were evaluated.

Window of time w

First, the parameter w (window of time) was estimated because its value should be optimized simultaneously for DA I and DA II. It needs to be small enough so that the various attentional states can be detected as quickly as possible, but large enough to ensure that the algorithm has enough data to make an accurate determination of the participants' attentional state. The optimal value for w was determined using data from the study described in Chapter 3. Specifically, the other parameters of the algorithm - α, β and γ – were fixed at an arbitrary value of 0.5, and the accuracy of the detection algorithm was then assessed for various values of w, using the data collected in the divided attention (baseline), attentional narrowing (novel problem) and focused attention conditions. For each scenario and each participant, the average values of each of the three metrics – percentage of fixations, dwell duration and fixation duration – were computed for all time windows contained in the scenario. For example, if w was set at 15 seconds, then the three metrics would be calculated for all twenty 15-second windows in the 5-minute divided attention scenario. These values were then compared against the thresholds defined earlier in this chapter. The thresholds were calculated for each participant using the data collected in the baseline condition (divided attention). A 'hit" was registered if the average value of the metric – as calculated over each window of time w - was larger than the threshold. For each participant, the hit rate for the entire scenario was calculated as the average number of hits for that scenario. Last, the detection rate was calculated for each window of time and each metric as the average of all participants' hit rates for each scenario. The "divided attention" condition is characterized by a low fixation percentage and short dwell durations in the REMAN task as well as short fixations, and should therefore lead to a low detection rate for all three metrics. In contrast, the “attentional narrowing” condition should lead to a high detection rate for the percentage of fixations and dwell duration, but low detection rate for the duration of fixations, while the “focused attention” condition should lead to a high detection rate for all three metrics.

The above parameter estimation technique indicated that the time window w should be at least 20 seconds to ensure that attentional narrowing and focused attention were classified as a state of reduced attention by DA I (using PoF and DD) in at least 60% and 80% of all cases, respectively (see Figures 4.4 and 4.5). Divided attention was correctly classified by DA I in at least 65% of all cases, irrespective of the value of w (see Figure 4.4 and Figure 4.5). Detection algorithm II (DA II) was not sensitive to the length of the time window (see Figure 4.6). It distinguished attentional narrowing from focused attention with about the same probability, regardless of the value of w.

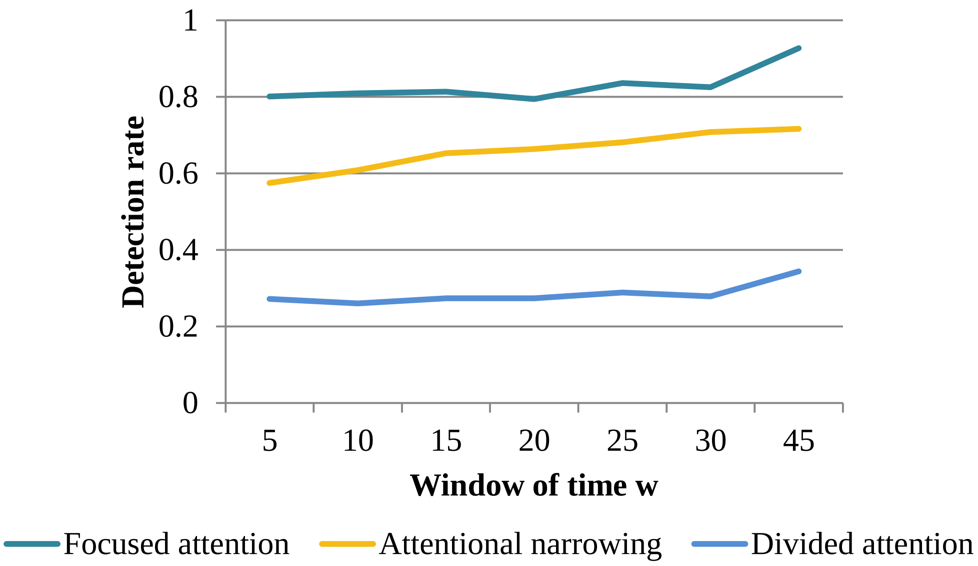

Figure 4.4 - Detection rate for the metric "Percentage of Fixations" ($\alpha = \beta = \gamma = 0.5$)

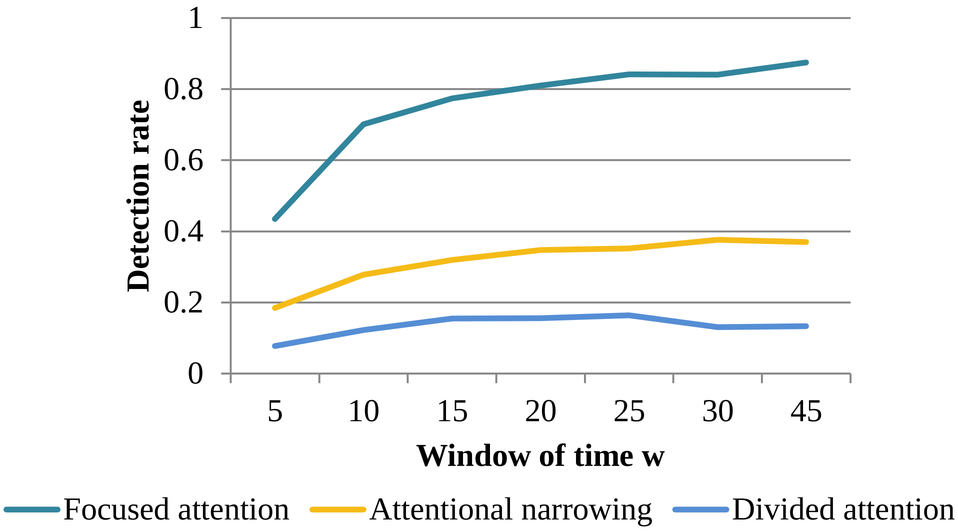

Figure 4.5 - Detection rate for the metric "Dwell duration" (α = β = γ = 0.5)

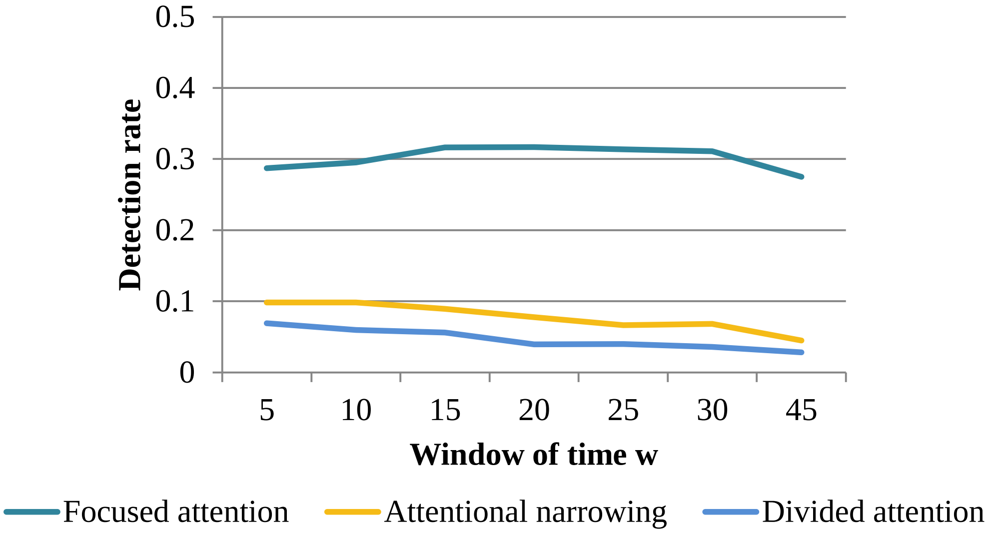

Figure 4.6 - Detection rate for the metric "Fixation duration" (α = β = γ = 0.5)

Sensitivity parameters α, β and γ

Having identified the optimal time window w, a similar approach was used to determine the optimal values of the parameters α, β and γ. The value of w was fixed at 20 seconds, and the accuracy of the detection algorithm was then tested for six values of α, β and γ (all between 0 and 1), using the data collected in the divided attention (baseline) condition, during attentional narrowing (novel problem) and in the focused attention condition.

The parameters α and β were used by DA I to distinguish the two states of reduced attentional field (i.e., attentional narrowing and focused attention) from divided attention. The tests showed that the classification of focused attention as a state of reduced attention was not affected by the value of α; it was accurate in more than 80% of the cases (see Figure 4.7). Higher values of α led to poorer detection of attentional narrowing by DA I but also to higher correct rejections rates for divided attention. Ultimately, a value of α = 0.4 was used because it appeared to be the optimal tradeoff, leading to a correct detection of attentional narrowing and a correct rejection of divided attention in 70% of the cases. Similarly, the value of β did not affect the classification of focused attention as a state of reduced attention, which would be correct in at least 75% in all cases (see Figure 4.8). β was assigned a value of 0.2, based on the tradeoff between the correct detection of attentional narrowing in 50% of the cases and the correct rejection of divided attention in 75% of the cases.

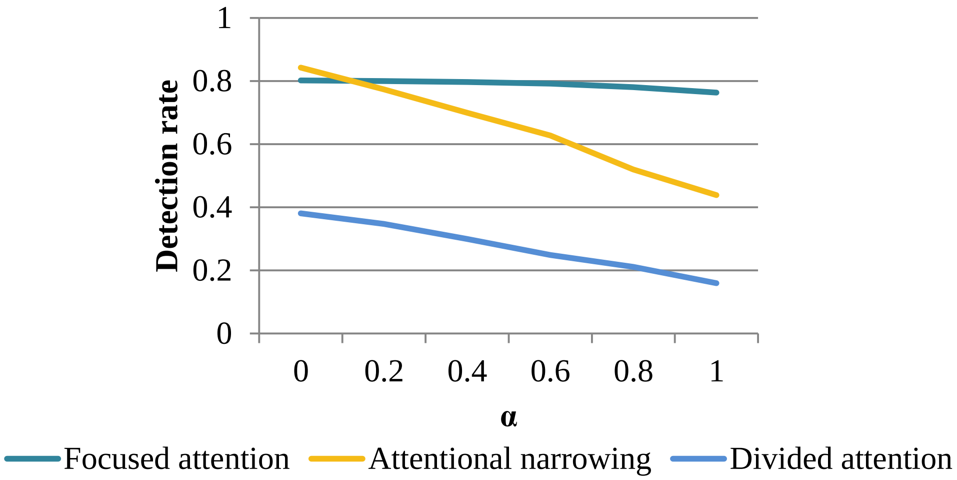

Figure 4.7 Detection rate for the metric "Percentage of fixations" (w = 20 seconds)

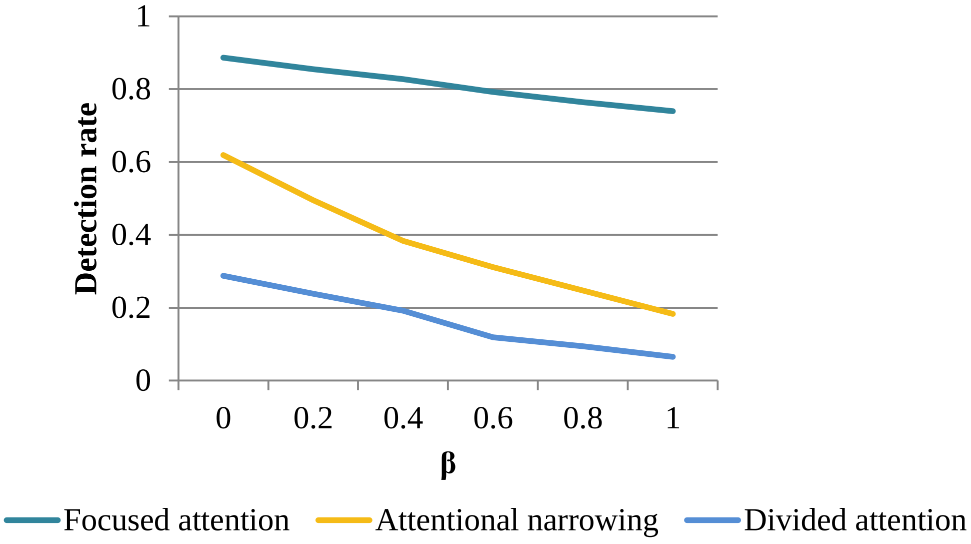

Figure 4.8 - Detection rate for the metric "Dwell duration" (w = 20 seconds)

γ was used by DA II to detect focused attention and distinguish it from attentional narrowing. The detection / rejection of the two attentional states was very sensitive to the value of this parameter (see Figure 4.9). Higher values of γ led to increased correct rejection of attentional narrowing, but also decreased correct detection of focused attention. A value of $\gamma = 0.1$ was found to lead to an optimal tradeoff between correctly detecting focused attention in 65% of the cases and correctly rejecting attentional narrowing in 70% of the cases.

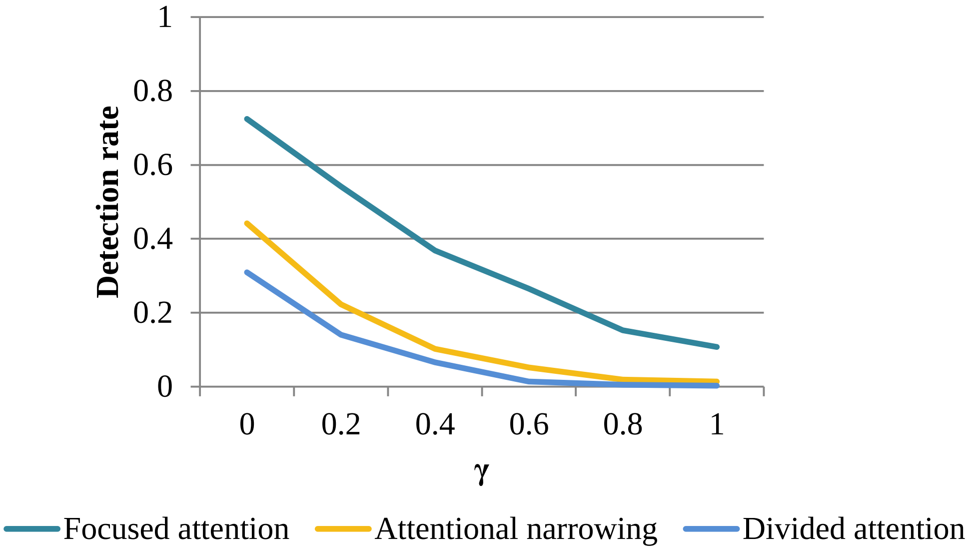

Figure 4.9 - Detection rate for the metric "Fixation duration" (w = 20 seconds)

In summary, the values of the parameters that led to the highest detection accuracy of the three attentional states were w = 20 seconds, $\alpha = 0.4$, $\beta = 0.2$ and $\gamma = 0.1$. Divided attention could be accurately detected in 70% of the cases, while attentional narrowing and focused attention were detected in 50% of the cases (see Table 4.1). These rates all exceeded chance performance, which would be 50% for detecting divided attention, and 25% for detecting attentional narrowing and focused attention.

Table 4.1- Probabilities of correct classifications of the three attentional states by the detection algorithm

Attentional state	**Probability of correctly classifying the attentional state**		
	DA I	**DA II**	**Overall algorithm**
Divided attention	0.7	N/A	**0.7**
Attentional narrowing	0.7	0.7	**0.49**
Focused attention	0.8	0.65	**0.52**

Discussion

This chapter described the development of an algorithm that can detect and distinguish, in real time, between three attentional states (1) divided attention, (2) attentional narrowing, and (3) focused attention. The algorithm is able to make this determination within a 20-second time window. Analyzing data over a longer period of time did not lead to a significant increase in accuracy but risks detecting attentional narrowing too late to prevent performance breakdowns. As a comparison, in a similar effort to use eye tracking to detect, in real time, drivers' distraction, Liang (2007) found that 40 seconds of data were needed to reach the highest detection accuracy given the model that was chosen (SVM).

The accuracy of the algorithm is above chance but could be further improved. One limitation of the approach that was used to develop the algorithm is that the parameters were evaluated one after the other because of programming limitations, and that it was assumed that there were no interactions between w on the one hand, and α, β and γ on the other hand. A more advanced optimization technique might have identified finer values for the 4 parameters and, as a result, led to higher detection accuracies. Also, the overall approach of comparing the metrics to set thresholds, which was used successfully by other researchers (Horng et al., 2004), was dictated, in part, by the limited processing power available to this research which made it impossible to use more elaborate methods such as supervised machine learning (Liang et al., 2005; Durkee et al., 2013), neural networks (Wilson & Russell, 2003), fuzzy classification (Bergasa et al., 2006) or Kalman filters (Ji, Zhu & Lan, 2004). Another limitation of this detection algorithm is that its training set was based on the experiment described in chapter 3 and that it was assumed that only one attentional state was experienced by participants during the entire duration of each scenario. It is possible that in some cases and besides the experimental manipulations (instructions to trigger divided attention and focused attention, and a novel and unsolvable problem to trigger attentional narrowing), participants engaged in other attentional states for brief periods of time. Such behaviors would not have been taken into consideration in the development of the detection algorithm and could have contributed to decreasing the accuracy of the algorithm.

The next and final step in this line of research is to test the detection algorithm in real time, confirm its overall accuracy, and examine its usefulness for triggering real-time countermeasures to attentional narrowing while avoiding undesirable disruptions of focused attention.

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Chapter 5

Development and evaluation of real-time countermeasures to attentional narrowing

The findings from the experiment reported in Chapter 3 show that, when presented with a novel and unsolvable problem, participants experienced attentional narrowing. The study also identified three eye tracking metrics – percentage of fixations, dwell duration and fixation duration in the resource management area - that responded in a unique way and can thus serve as indicators of the state of attentional narrowing. Building on these findings, Chapter 4 described an algorithm for detecting attentional narrowing and distinguishing it from focused attention in real time. The goals of the next step in this line of research are (1) to evaluate the accuracy of the detection algorithm developed in Chapter 4, and (2) to develop and assess the effectiveness of candidate interventions for supporting a broadening and reallocation of attention and, as a result, improve performance.

Several challenges need to be addressed in the design of countermeasures to attentional narrowing. First, the intervention needs to capture attention. One means of achieving this goal is to use salient cues that are presented in close proximity to the observed focus of attention (Pinet, 2015). At the same time, the salience of the cue must not be so high as to startle the operator and result in increased anxiety which would exacerbate the very problem it is meant to overcome. Second, attentional narrowing affects working memory and thus reduces the amount and complexity of information that can be processed by a person (Klein & Boals, 2001; Orasanu, 1997; Dismukes, Goldsmith & Kochan, 2015). A countermeasure to attentional narrowing should therefore be simple, unambiguous and easy to understand (Hancock & Szalma, 2003; Staal, 2004; Dehais et al., 2010).

A third important consideration is the type of information conveyed by the countermeasure. Does it inform the operator only of the problem itself (i.e., attentional narrowing), or does it suggest a course of action in response to the problem (i.e., broadening the attentional focus to include other tasks and pieces of information)? These two types of intervention are commonly referred to as a status display versus a command display. Status displays are preferable when the diagnosis of the problem is quite often inaccurate (Sarter & Schroeder, 2001) as they reduce the risk of operator overreliance. However, given a highly reliable decision aid, a command display should be employed as it offloads operators' working memory and allows them to skip the step of identifying and selecting a proper action (McGuirl & Sarter, 2006). This strategy has been shown to lead to faster responses (Prinet, Wan & Sarter, 2016) but incurs a high cost in case of a misdiagnosis of the problem. Preliminary studies have shown that both status and command displays are promising means of overcoming attentional narrowing (Dehais et al., 2010); however, to date, the effectiveness of the two approaches has not been compared systematically in a controlled experiment.

To fill this gap, an experiment was conducted using the same MATB II environment as in the study presented in Chapter 3. Three attentional states were triggered in participants: divided attention, attentional narrowing and focused attention. Building on the findings from

Chapter 3, attentional narrowing was induced by introducing a novel and unsolvable problem. The detection algorithm described in Chapter 4 was implemented and used to determine, in real time, participants' attentional state. Whenever attentional narrowing was sensed, one of two different display interventions – a status or a command display - was presented to make participants aware and/or help them break out of their narrowed state and redirect their attention towards the neglected tasks and screen areas.

The expectations were that (1) the detection algorithm would be able to detect participants' attentional state and trace potential fluctuations between divided attention, focused attention and attentional narrowing, (2) the algorithm would be better at distinguishing between focused attention and divided attention – two very dissimilar states – than between focused attention and attentional narrowing, both of which are characterized by a reduction of the visual attentional field and (3) that both the status and command display would help participants break out of attentional narrowing and, as a result, lead to overall improved performance.

Methods

Participants

41 graduate and undergraduate students at the University of Michigan volunteered to participate in this study. They had normal or corrected-to-normal vision (only contact lenses were allowed, due to the limitations of the eye tracker). 1 female and 3 males had to be excused from the study because the eye tracker could not be calibrated, or the percentage of samples with data point was less than 60%. The average age of the remaining 33 participants was 22.9 years (SD = 4.2 years; 14 females and 19 males). They were randomly assigned to one of two groups: 1) the status group (n=17; 6 females and 11 males; average age: 23.1 years (SD = 5.2 years)) and 2) the command group (n=16; 8 females and 8 males; average age: 22.7 years (SD = 3.0 years)). The two groups did not differ significantly with respect to age (t (31) = 0.247, p = 0.806) and trait anxiety (in the status group: trait anxiety = 14.5 (SD = 6.9); in the command group: trait anxiety = 18.8 (SD = 9.6); Mann-Whitney U = 93, p = 0.191). All participants gave informed consent and were compensated $30 for approximately 120 minutes of their time.

Apparatus and tasks

The experiment employed the similar setup as the study described in Chapter 3. An adaptation of the computer-based Multi-Attribute Task Battery II (see Figure 3.1 and Figure 3.2) was presented to participants who were asked to complete, simultaneously, five tasks (see Chapter 3 for a description of each task): (1) system monitoring, (2) tracking,

(3) scheduling, (4) resource management, and (5) peripheral light detection. These tasks were presented at the same frequency as in the study described in Chapter 3 (the system monitoring task and scheduling task had comparable frequencies of 4 events per minute, the tracking task required continuous inputs from participants, and the resource management (REMAN) task had on average one failure per minute). The task battery was displayed at the center of a 30-inch monitor with a resolution of 1280 x 1024 pixels. The MATB II interface was 16" wide and 12" high. It was placed at a distance of 24" from the participant, making for a visual angle of approximately 26 degrees in the horizontal direction, and 34 degrees in the vertical direction.

The eye tracker used in the experiment was the same as in the study described in Chapter 3 (desktop-mounted ASL Eye-Track D6, system sampling rate = 60 Hz, accuracy < 1 degree visual angle) and was placed below the monitor, at a distance of 24 inches from the participant.

Experimental Conditions

Scenarios

Scenario events and instructions were used to trigger the three attentional states of interest: (1) divided attention, (2) attentional narrowing, and (3) focused attention.

(1) Divided attention: participants were asked to complete all five tasks simultaneously.

(2) Attentional narrowing: participants were instructed to perform all five tasks, as in the divided attention condition, but they were presented with several

unexpected and unsolvable pump failures on the resource management task which made it impossible for participants to maintain the required fuel levels in tanks A and B.

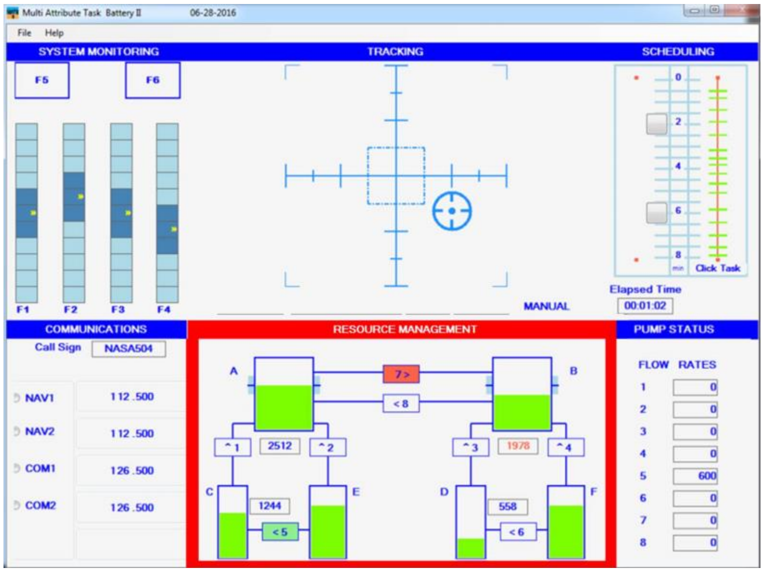
(3) Focused attention: participants were asked to perform only the resource management task. The other tasks and the peripheral lights were still presented but participants were told to actively suppress/ignore them.

Display interventions

When a state of attentional narrowing was detected by the algorithm in condition (2), one of three strategies was employed: no intervention (AN-None), status intervention (AN-St) or command (AN-Co) intervention.

(1) In the **no intervention** condition (**AN-None**), the MATB II display would remain the same, and no adaptation was triggered.

(2) The **status intervention** condition (**AN-St**) was designed to inform participants that they were allocating too much attention to the resource management task. A blinking outline box appeared around the resource management task area (where attention was focused due to the pump failures; see Figure 5.1). Studies have shown that the color red triggers avoidance behaviors (Goldstein, 1942; Elliot et al., 2007) and, as a result, it was expected that the use of this color would support a re-allocation of attention to the neglected tasks and display areas. The red box was presented three times, for 300 msecs each, with a 500 msec interval in between. The total duration of this status alert was 1.9 seconds (see Figure 5.2).



Call Sign NASA504

NAV1	112.500
NAV2	112.500
COM1	126.500
COM2	126.500

FLOW	RATES
1	0
2	0
3	0
4	0
5	600
6	0
7	0
8	0

Figure 5.1 - MATB-II display in the status intervention scenario

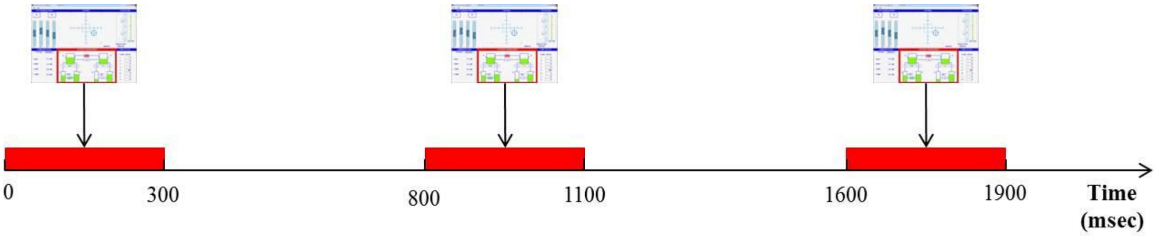


Figure 5.2 - Timing of the cues in the status intervention scenario

(3) In the **command intervention (AN-Co)** condition, the alert was designed to convey to participants the action they should take – i.e., broaden and re-allocate attention to the adjacent neglected tasks and display areas. The color green was used for the command display because it suggests something ‘good’ and ‘appropriate’ and has been shown to trigger a sense of comfort (Kaya & Epps, 2004) and is associated, in daily life, with indications that an instruction can safely be followed (e.g. traffic lights). A green outline box appeared around the resource management task area, followed by the presentation of a green outline

around the outer border of the entire MATB II display (see Figure 5.3). This sequence was repeated three times. Each outline box was presented for 100 msecs, and a 600 msec interval separated the two cues. The total duration of the command alert was 1.8 seconds (see Figure 5.4). The sequential appearance of the two contours was designed to convey the need for expansion of the attentional field.

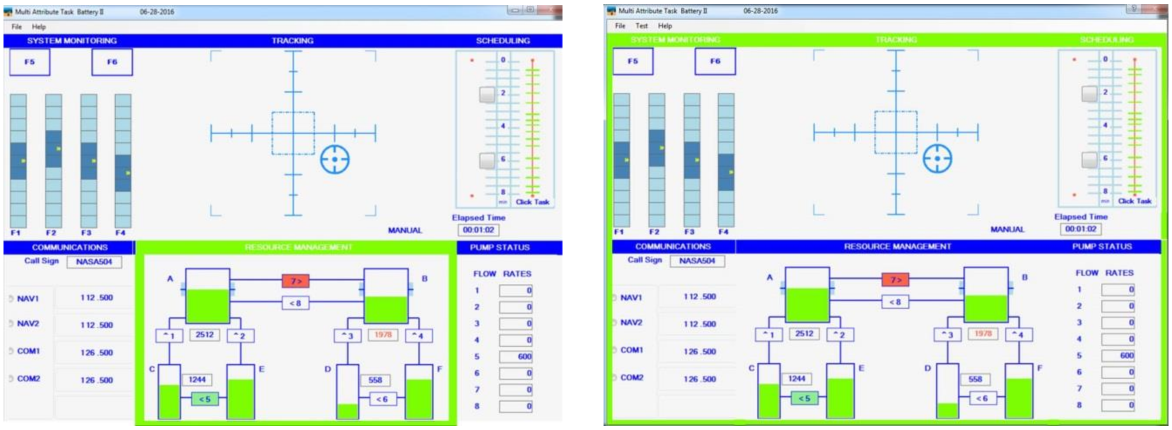


Figure 5.3 - MATB II display in the command intervention scenario. The first contour displayed is shown on the left, and the second contour is shown on the right.

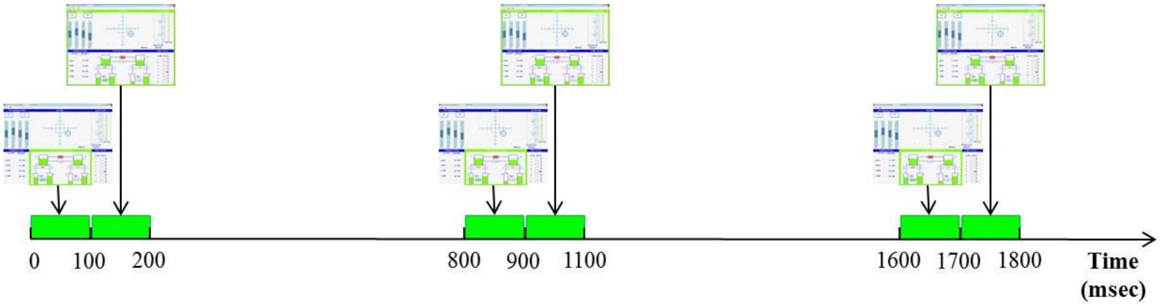


Figure 5.4 - Timing of the cues in the command intervention scenario

Earlier studies have shown that interrupting signals (such as the status and command alerts described above) lower performance if they are presented in very close temporal proximity (Speier, Valacich & Vessey, 1999). Therefore, a delay was introduced if the above alerts had to be repeated in case of prolonged or repeated attentional narrowing. The second alert would not be triggered until at least 30 seconds had passed. This time interval was chosen, in part, to allow sufficient time for the algorithm to assess attentional state (20 seconds).

Experiment design and procedure

The two independent variables in this study were attentional state and intervention strategy. The experiment employed a 3 x 3 fractional factorial design. Attentional state was a within-subject variable at three levels: (1) divided attention, (2) attentional narrowing (triggered by inducing a novel and unsolvable problem), and (3) focused attention. Intervention strategy was another within-subject variable at three levels: (1) no intervention (AN-None), (2) status intervention (AN-St) and (3) command intervention (AN-Co).

Upon arrival in the laboratory, participants were asked to complete the State Trait Anxiety Inventory questionnaire. They were then introduced to the MATB II simulation, the peripheral light detection task, and the arithmetic tasks. Participants were told that each of these tasks should be assigned the same priority and importance. Next, they completed a minimum of three 5-minute practice scenarios to ensure that they were proficient on all tasks. The eye tracker was calibrated, and participants were asked to complete the MATB II and peripheral light detection tasks for 5 minutes (as in the divided attention scenario) during which eye movement data was collected. Participants were then offered a short break, while the experimenter calculated and entered the participant's three baseline thresholds (fixation percentage, dwell duration and fixation duration), into the detection algorithm. Next, the experiment started, and participants were asked to perform all five tasks (MATB II and peripheral light detection). They were told that the system might present cues to remind them to divide their attention if it detected that they were focusing in on one task. No further explanation or demonstration of the status and command interventions were provided, for two reasons. First, it was important to avoid that participants anticipated problems in the resource management task area which might have defeated the goal of inducing narrowing. Second, one of the interests of the study was to evaluate how participants would interpret the alerts on their own – the intuitiveness of the cues. In total, each participant was asked to complete four different 5-minute scenarios: 1) divided attention, 2) attentional narrowing (triggered by a novel problem on the resource management task) with no intervention (AN-None), 3) attentional narrowing with intervention (AN-St or AN-Co), and 4) focused attention. Following each scenario, they were asked to fill out the part of the STAI questionnaire that relates to state anxiety. The order in which participants were presented with the 4 experimental conditions was counterbalanced. After completion of all experimental conditions, participants were asked to complete a debriefing questionnaire. The total duration of the experiment was approximately 2 hours, and participants were compensated $30 for their time.

Dependent measures

Detection algorithm outputs, performance measures, and subjective ratings were collected to evaluate the accuracy of the algorithm and assess how the two intervention strategies – status (AN-St) and command (AN-Co) - affected participants' multitasking performance, attention allocation and level of anxiety.

Detection algorithm outputs

Raw gaze data were used to compute, in real time and over a time window of 20 seconds, the three eye tracking metrics used by the detection algorithm: fixation percentage, dwell duration and fixation duration. As described in Chapter 4, these metrics formed the basis for the algorithm's assessment of the participant's attentional state every 5 seconds. The algorithm output was recorded for each scenario.

Performance

For the MATB II, peripheral light detection and arithmetic tasks, accuracy, detection rate and/or response time were measured. In order to evaluate the effects of the two intervention strategies, these measures were used to compute an overall performance score. Performance on the resource management task was not included in this overall performance score for two reasons. First, the pump problems that participants experienced on this task were impossible to solve, and performance on this task was therefore expected to be poor for all participants. Second, the intervention strategies were meant to help participants break out of a state of attentional narrowing on the resource management task with the goal to improve performance on all other tasks.

To calculate the overall score, performance on each of the four tasks - system monitoring, tracking, scheduling and peripheral light detection – was expressed as a value comprised between 0 and 1. The lowest performance recorded for each task was assigned a value of 0, while the highest performance was given a value of 1. A linear regression was used to calculate the value for the other levels of performance. Finally, the overall performance score was computed as the average of all four values.

Finally, in order to compare participants between the two groups – status and command intervention - an additional score was computed to reflect performance on all five tasks in the divided attention condition. For this score, performance on the resource management task was included in the above calculation.

Subjective ratings

The State and Trait Anxiety Inventory (STAI) was used to assess participants' general (trait) and temporary (state) anxiety levels. Participants also completed a questionnaire at the end of all experimental sessions to record their preferences and strategies in each experimental condition.

Results

Detection of attentional states

Dependent t-tests were used to compare the accuracy of the detection algorithm for the three attentional states – divided attention, attentional narrowing and focused attention – in each experimental condition. The error bars on the graphs represent the standard error.

Divided attention scenario

In the divided attention scenario, the algorithm categorized participants' attentional state as divided attention" in 63% (SD = 18%), "attentional narrowing" in 19% (SD = 12%), and “focused attention” in 18% (SD = 13%) of all cases. Divided attention was labeled significantly more often than attentional narrowing and focused attention (t (32) = 8.79, p = 0.000, and t (32) = 8.40, p = 0.000, respectively; see Figure 5.5).

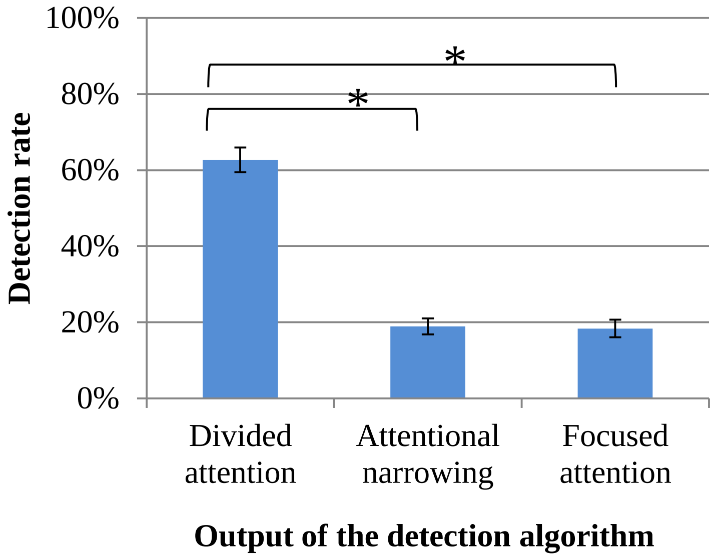


Figure 5.5 - Detection rates of the three attentional states in the divided attention scenario

Attentional narrowing scenario

When participants experienced the attentional narrowing scenario without intervention (AN-None), the algorithm interpreted their state as “attentional narrowing” 50% (SD = 22%), “divided attention” in 28% (SD = 22%), and “focused attention” in 22% (SD = 23%) of all instances (see Figure 5.6). Attentional narrowing was categorized significantly more often than divided attention and focused attention (t (32) = 3.476, p = 0.001, and t (32) = 4.151, p = 0.000, respectively).

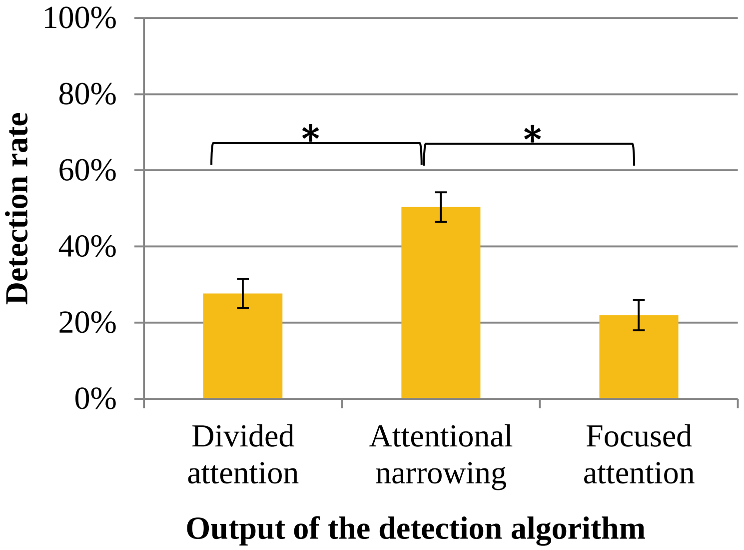


Figure 5.6 - Detection rates of the three attentional states in the attentional narrowing scenario

Focused attention scenario

Finally, in the focused attention scenario, 71% of all cases were categorized by the algorithm as "focused attention" (SD = 0.20), "divided attention" was sensed in 3% of the cases (SD = 7%), and participants' attentional state was categorized as "attentional narrowing" in 27% of all instances (SD = 19%) (see Figure 5.7). Focused attention was labeled significantly more often than divided attention and attentional narrowing (t (32) = 16.65, p = 0.000, and t (32) = 6.50, p = 0.000, respectively).

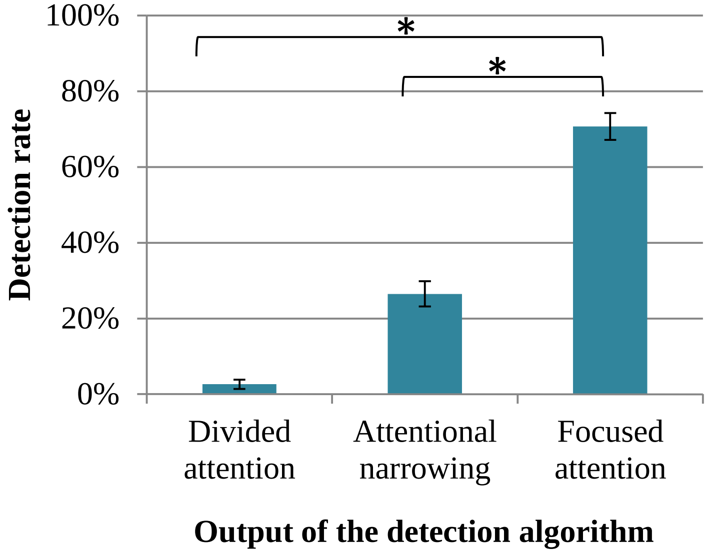


Figure 5.7 - Detection rates of the three attentional states in the focused attention scenario

A summary of the detection rates of the algorithm in each three experimental condition is provided in Table 5.1.

Table 5.1 - Summary of the algorithm detection rates in the three different experimental conditions (divided attention, attentional narrowing and focused attention). The standard deviation is indicated in parentheses.

		Output of the detection algorithm		
		Divided attention	Attentional narrowing (AN-None)	Focused attention
Scenario	Divided attention	**0.63 (0.18)**	0.19 (0.12)	0.18 (0.13)
	Attentional narrowing	0.28 (0.22)	**0.50 (0.22)**	0.22 (0.23)
	Focused attention	0.026 (0.07)	0.27 (0.19)	**0.71 (0.2)**

Performance

Baseline performance of the two groups – as measured in the divided attention scenario - was similar. The average performance ratio on all five tasks was 0.79 (SD = 0.1) for participants in the status group, and 0.76 (SD = 0.1) in the command group, and there was no significant difference between the two groups (t (31) = 0.815, p = 0.421)

The performance effects of the various experimental factors were analyzed in three steps. First, dependent t-tests were used to compare performance between the divided attention scenario and the attentional narrowing scenario without intervention (AN-None). Next, dependent t-tests were conducted to compare the performance of participants within the two intervention groups (status and command) when they experienced the novel problem scenario in the absence (AN-None) or presence of the respective intervention. Last, independent t-tests were employed to compare performance between the status and the command intervention (respectively, AN-St and AN-Co). The error bars on the graphs represent the standard error of the mean. The following sections present the findings for (1) each of the four MATB II tasks, (2) the peripheral light detection task, and finally (3) the overall performance score calculated on all the tasks, except for resource management.

In addition, to evaluate the accuracy of the detection algorithm during the attentional narrowing scenario, the algorithm's detection rate of "attentional narrowing" was correlated with the percentage change in performance between the attentional narrowing and divided attention scenarios on the system monitoring, tracking, scheduling and light detection tasks, as well as the overall performance score.

System monitoring (SYSMON)

The detection rate for the system monitoring task was significantly smaller in the attentional narrowing without intervention (AN-None) condition (DR = 0.64, SD = 0.25), compared to the divided attention condition (DR = 0.75, SD = 0.19; t (32) = 3.14, p = 0.004). Neither intervention (status or command) led to a significant difference in performance from the no intervention condition (within the status group: AN-None: DR = 0.66, SD = 0.27; AN-St: DR = 0.64, SD = 0.26; t (16) = 0.40, p = 0.70; within the command group, AN-None: DR = 0.63, SD = 0.23; AN-Co: DR = 0.68, SD = 0.21; t (15) = 1.50, p = 0.15; see Figure 5.8). Performance on the system monitoring task did not differ between the status and the command group (t (31) = -0.462, p = 0.65).

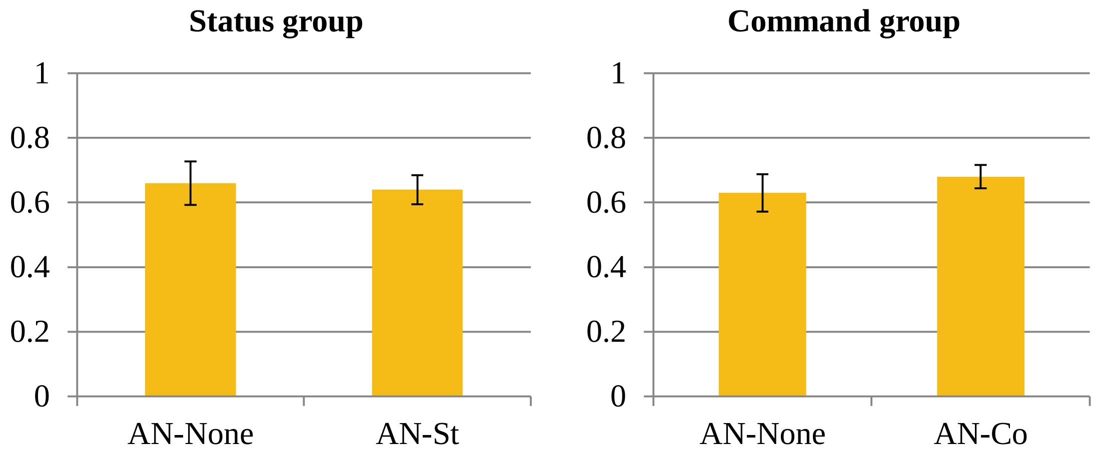


Figure 5.8 - Detection rate of the system monitoring task in the intervention and no intervention conditions
(left: the status group; right: command group)

Tracking (TRCK)

The attentional narrowing without intervention condition (AN-None) led to a significant increase in the root mean square deviation (RMSD) of the target from the center of the axis (RMSD = 62, SD = 22), compared to the divided attention condition

(RMSD = 54, SD = 21; t (32) = -5.24, p = 0.000). Neither intervention led to a significant difference in performance from the no intervention condition (within the status group: AN-None: RMSD = 57, SD = 17; AN-St: RMSD = 55, SD = 18; t (16) = 1.4, p = 0.180 - within the command group: AN-None: RMSD = 67, SD = 26; AN-Co: RMSD = 63, SD = 19; t (15) = -1.1, p = 0.703; see Figure 5.9). Performance on the tracking task did not differ significantly between the status and command groups (t (31) = -1.18, p = 0.247).

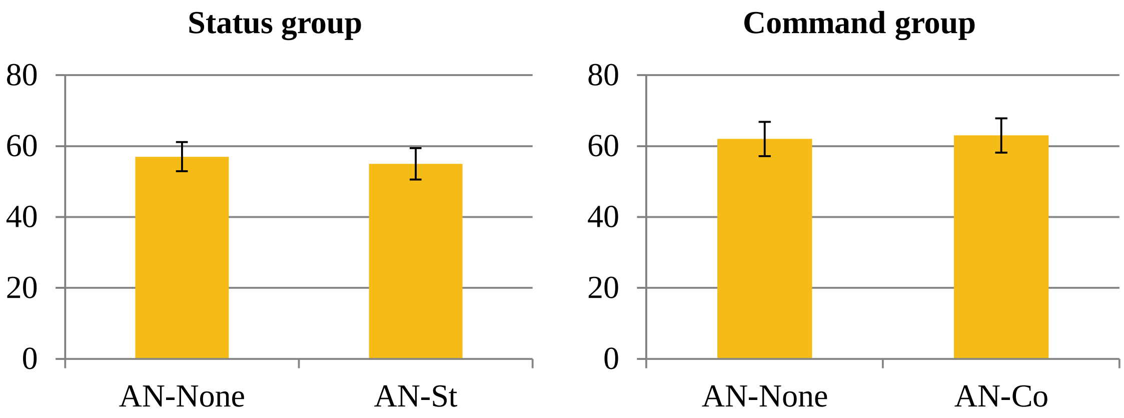


Figure 5.9 – Average deviation of the tracking task in the intervention and no intervention conditions
(left: the status group; right: command group)

Scheduling (SCHED)

The detection rate for the scheduling task was significantly lower in the AN-None condition (DR = 0.46, SD = 0.26), compared to the divided attention condition (DR = 0.63, SD = 0.22; t (32) = 4.78, p = 0.000). The status intervention resulted in a significant decrease in the detection rate (DR = 0.46, SD = 0.27), compared to the no intervention scenario (DR = 0.52, SD = 0.26; t (16) = -1.14, p = 0.048). In contrast, the command intervention led to a significant increase in the detection rate (DR = 0.52, SD = 0.24), compared to the no intervention scenario (DR = 0.40, SD = 0.25; t (15) = 2.99, p = 0.039; see Figure 5.10).

There was no significant difference between the performance on the scheduling task between the status and command groups (t (31) = -0.58, p = 0.56).

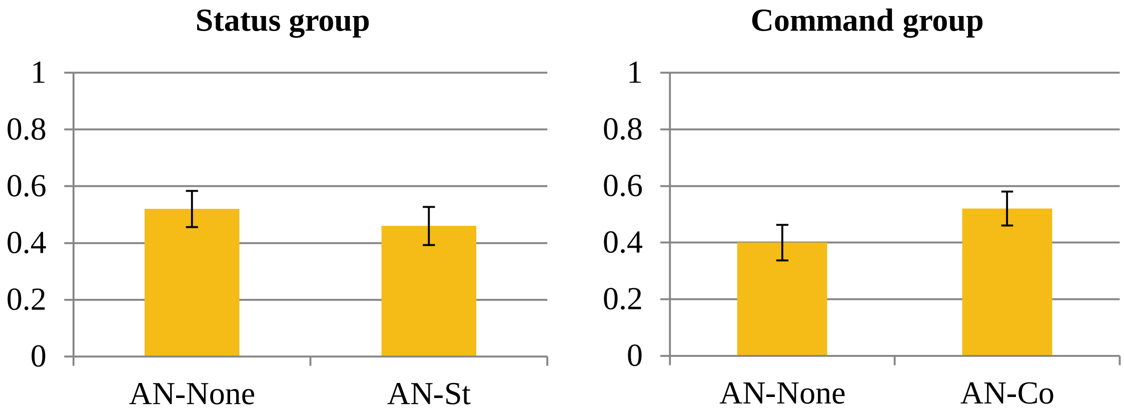


Figure 5.10 - Average detection rate of the scheduling task in the intervention and no intervention conditions
(left: the status group; right: command group)

Resource Management (REMAN)

The average deviation of the tank levels from their target value of 2,500 units was significantly higher in the AN-None scenario (328 units, SD = 81 units), compared to the divided attention condition (23 units, SD = 16 units). Both status and command interventions led to a significant reduction of the deviation, compared to the AN-None condition (within the status group: AN-None: 332 units (SD = 91 units), AN-St: 160 units (SD = 139 units), t (16) = -6.2, p = 0.000; within the command group: AN-None: 323 units (SD = 72 units), AN-Co: 170 units (SD = 91 units), t (15) = -4.58, p = 0.000; see Figure 5.11). There was no significant difference between the status and command groups (t (31) = -0.25, p = 0.8).

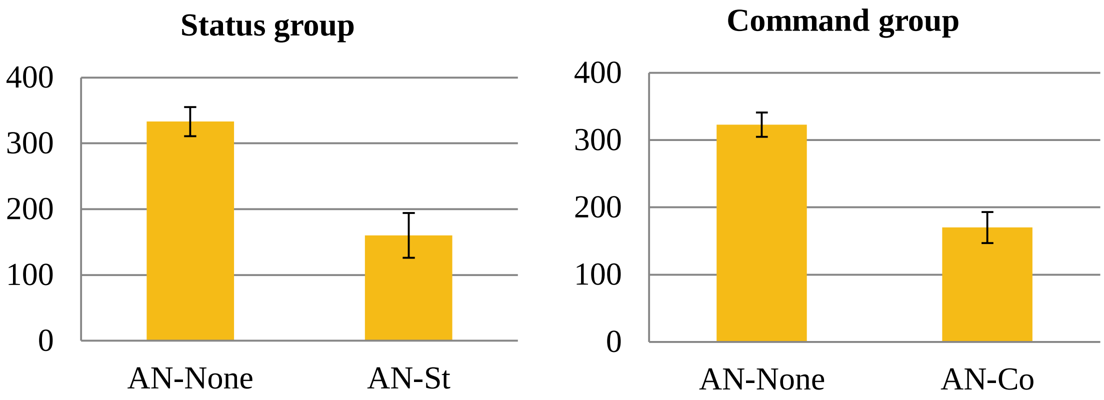


Figure 5.11 - Average deviations of the tanks in the resource management task in the intervention and no intervention conditions
(left: the status group; right: command group)

Peripheral Light Detection Task

Hit rate (HR)

Significantly fewer peripheral lights were detected in the AN-None scenario (HR = 0.47, SD = 0.24), compared to the divided attention condition (HR = 0.69, SD = 0.24; t (32) = 6.2, p = 0.000). No significant differences were observed for detection rates with and without intervention (within the status group: AN-None: HR = 0.48, SD = 0.26, AN-St: HR = 0.46, SD = 0.24; t (16) = -0.59; within the command group: AN-None: HR = 0.47, SD = 0.21; AN-Co: HR = 0.5, SD = 0.24; t (15) = 0.56, p = 0.58; see Figure 5.12). There was no significant difference in detection rate between the status and command intervention groups (t (31) = -0.532, p = 0.599).

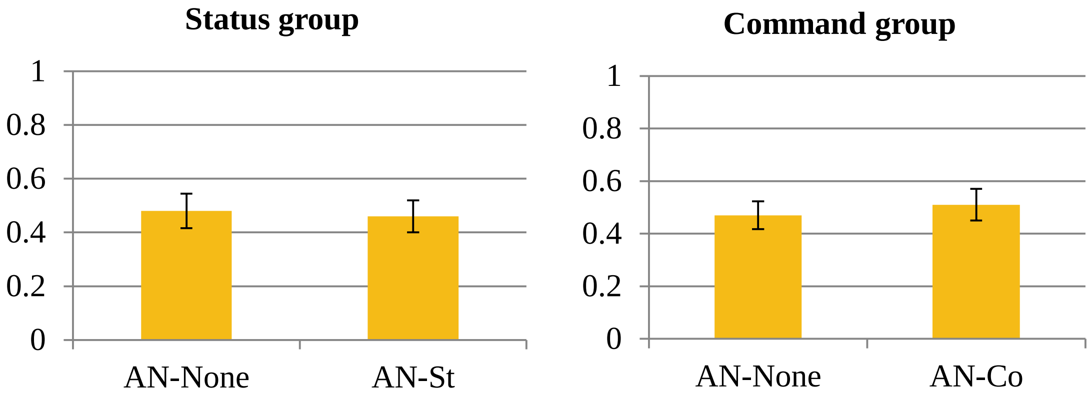


Figure 5.12 - Average hit rate of the peripheral light detection task in the intervention and no intervention conditions
(left: the status group; right: command group)

<u>Response Time (RT)</u>

Attentional narrowing without intervention scenarios (RT = 1.4 sec, SD = 0.60) led to significantly faster response times to peripheral lights, compared to the divided attention condition (RT = 1.2 sec, SD = 0.28 sec; t (31) = -2.5, p = 0.019). Neither intervention had a significant effect on response times (status group: AN-None: RT = 1.6 sec, SD = 0.7 sec, AN-St: RT = 1.5 sec, SD = 0.5 sec; t (16) = -0.63, p = 0.539; command group: AN-None: RT = 1.3 sec, SD = 0.3 sec, command intervention: RT = 1.4 sec, SD = 0.4 sec; t (15) = 0.77, p = 0.455). There was no significant difference in response times between the status and command groups (t (31) = -0.12, p = 0.903).

Overall performance score

The overall score was calculated based on participants' performance on the system monitoring, tracking and peripheral light detection tasks. In the divided attention condition, the average performance on all four tasks was 0.79 (SD = 0.1) for participants in the status group, and 0.76 (SD = 0.1) in the command group. There was no significant difference between the two groups (t (31) = 0.815, p = 0.421). AN-None led to overall poorer performance (S = 0.59, SD = 0.14) than the divided attention condition (S = 0.73, SD = 0.12; t (32) = 7.7, p = 0.000). There was no significant performance effect of the status intervention, compared to no intervention (AN-None: S = 0.62, SD = 0.14, AN-St: S = 0.60, SD = 0.16; t (16) = -0.89, p = 0.383). However, the command intervention resulted in a significant increase in overall performance, compared to no intervention (within the command group: AN-None: S = 0.56, SD = 0.14, AN-Co: S = 0.61, SD = 0.15; t (15) = 2.41, p = 0.029; see Figure 5.13). There was no significant difference between the status and command intervention conditions (t (31) = -0.16, p = 0.873).

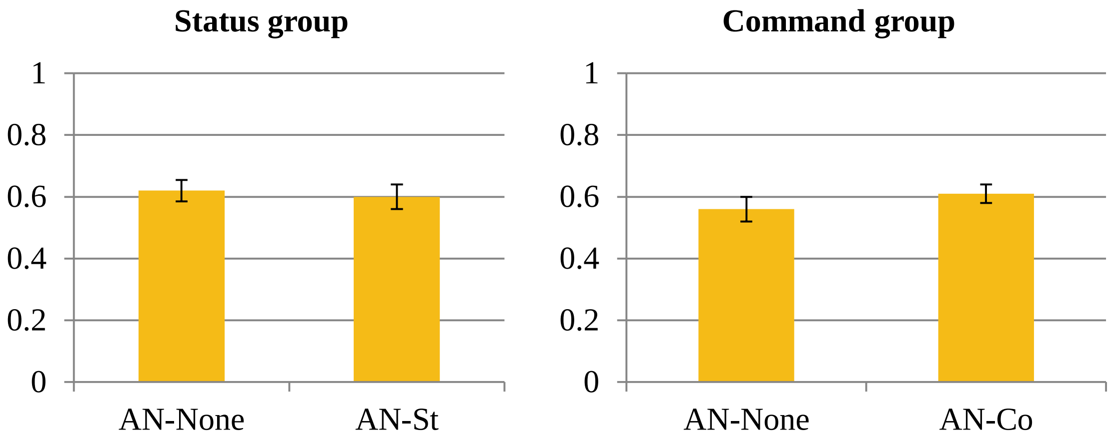


Figure 5.13 - Combined performance (based on the system monitoring, tracking, scheduling and light detection tasks) in the intervention and no intervention conditions (left: the status group; right: command group)

Correlation between the overall score and the algorithm detection rate

There was no significant correlation between (1) the change in participants' performance on individual tasks and their overall performance score in the attentional narrowing scenario as compared to the divided attention scenario and (2) the algorithm's detection of a state of "attentional narrowing" (system monitoring: Pearson correlation coefficient r = 0.083, p = 0.644; tracking: Pearson correlation coefficient r = 0.014, p = 0.937; scheduling: Pearson correlation coefficient r = 0.065, p = 0.717; light detection task: Pearson correlation coefficient r = -0.288, p = 0.105; overall score: Pearson correlation coefficient r = -0.11, p = 0.952).

Summary of the performance results

The novel unsolvable problem that was presented in the context of the REMAN task to induce attentional narrowing led to a significant drop in overall performance on all tasks, compared to the divided attention scenario. Both intervention strategies – status and command – led to an increase in performance on the resource management task, compared to the 'no intervention' condition. The scheduling task was also affected by both interventions: in this case, the status display led to a drop in performance while the command intervention led to an increase in performance, compared to 'no intervention'. Finally, there was no main effect of intervention on the performance of the system monitoring, tracking and light detection tasks (see Table 5.2).

Table 5.2 - Comparison of the performance effects of the two interventions. The performance in each intervention scenario is compared to the AN-None scenario.

		AN-St	**AN-Co**
MATB II	System monitoring	No difference	No difference
	Tracking	No difference	No difference
	Scheduling	↓ **Decrease**	↑ **Increase**
	Resource management	↑ **Increase**	↑ **Increase**
Peripheral light detection		No difference	No difference
Overall score		No difference	↑ **Increase**

Subjective ratings

STAI anxiety

Non-parametric tests were used to analyze the subjective data from the STAI. First, Wilcoxon signed-rank tests were conducted to evaluate the levels of anxiety experienced (1) in the AN-None scenario, compared to divided attention, and (2) in the AN-St and AN-Co scenarios, compared to AN-None. U-Mann Whitney tests were employed to compare the state anxiety experienced in the two AN scenarios with intervention: status and command.

The average trait anxiety of participants was 38.9 (SD = 8.3). Participants reported a significantly higher level of state anxiety in the AN-None condition (40, SD = 12), compared to the divided attention condition (36, SD = 10; Z = -3.184, p = 0.001). The status intervention resulted in a significant increase in state anxiety (41, SD = 13), compared to the attentional narrowing without intervention (38, SD = 11; Z = -2.179, p = 0.029; see Figure 5.14). The command intervention did not affect state anxiety levels (42, SD = 13 with and without intervention, respectively; Z = -0.346, p = 0.729; see Figure 5.14). Also, reported state anxiety levels did not differ significantly between the status and command intervention cases (Mann-Whitney U = 124, p = 0.895).

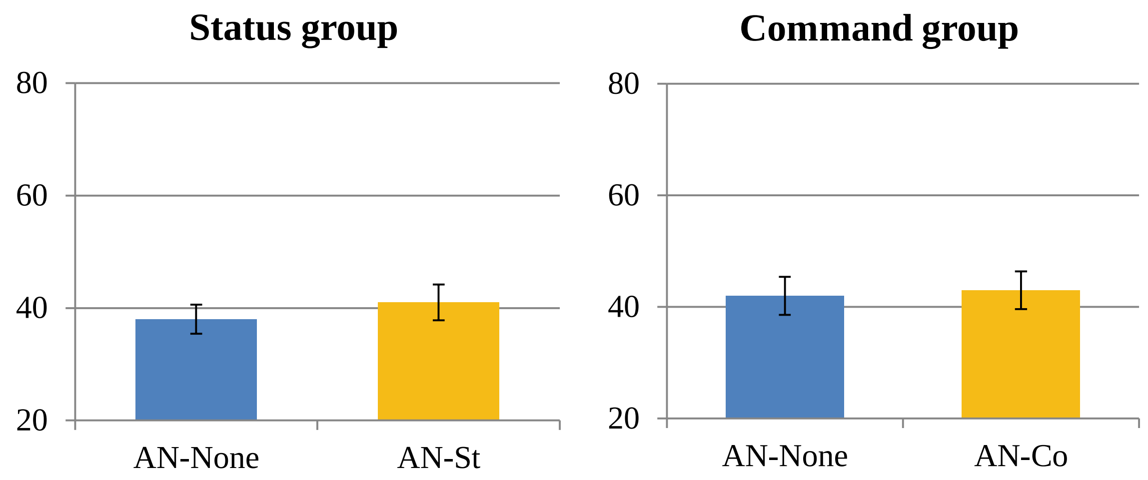


Figure 5.14 – State anxiety in the two groups

Debrief questionnaire

When asked whether the meaning of the display intervention was immediately clear to them, 73% of participants responded ‘yes’. However, within the status group, 18% of participants indicated that they did not understand the cue right away. And all but one of the participants who indicated that the meaning of the status intervention was clear actually misinterpreted the cue, thinking that they should pay more attention to the resource management task (see Figure 0.11). Within the command group, 37.5% of participants experienced difficulties understanding the cue. Among those that indicated that they understood the meaning of the cue, only 60% correctly interpreted it. The other 40% thought they should increase their attention on the resource management task (see Figure 5.15).

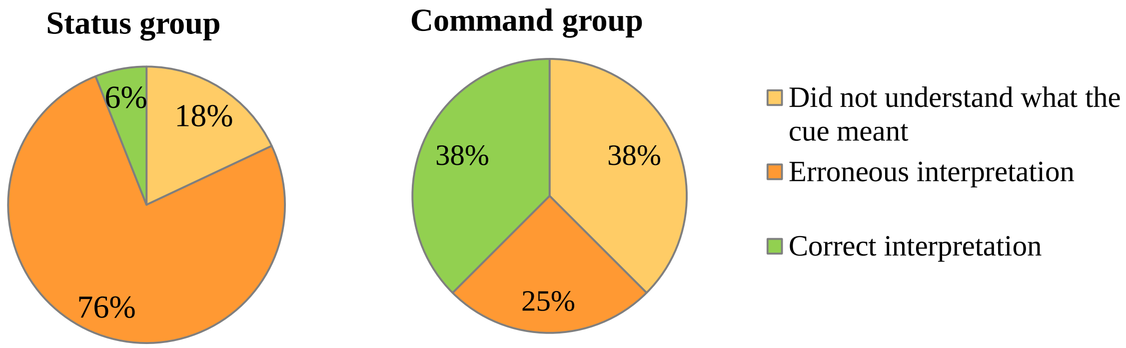


Figure 5.15 – Participants' interpretation of the status and command display interventions

Discussion

This study was the final experiment in a line of research aimed at examining and overcoming the problem of attentional narrowing. Chapters 2 and 3 identified promising means of inducing this potentially dangerous attentional state in participants. Chapter 3 also highlighted effective eye tracking-based markers of attentional narrowing. Next, chapter 4 described how these eye tracking metrics were used to develop an algorithm capable of assessing, in real time, an individual's attentional state, and the algorithm was used to distinguish between divided attention, attentional narrowing and focused attention. The goals of this last experiment were (1) to evaluate the accuracy of the detection algorithm developed in Chapter 4, and (2) to assess and compare the effectiveness of two different display adaptations for supporting the re-allocation and broadening of attention, and multitasking performance when individuals experience attentional narrowing. The findings from this study are discussed in the following sections.

Detection algorithm diagnosticity

The algorithm classified the participants' attentional state as divided attention, attentional narrowing and focused attention in 63%, 50% and 71% of all cases, respectively – all values exceeding chance, which was of 50% for divided attention and 25% for attentional narrowing and focused attention in this case. These values may indicate that either (1) the algorithm accurately captured fluctuations in participants' attentional state, or that (2) it was not perfectly reliable. These two possibilities will be discussed in more detail below.

While an attempt was made to trigger divided and focused attention by means of instructions, and attentional narrowing by introducing a novel unsolvable problem, it is not possible to know for sure whether participants were engaged in, or experienced these states throughout the entire respective scenario. It is possible that transitions between states occurred and were accurately captured by the algorithm, leading to detection percentages below 100%. In the past, some researchers simply assumed that participants complied with instructions (Liang, Reyes & Lee, 2007), asked them to simulate attentional states (Bergasa et al., 2006), or they judged the accuracy of their detection algorithms by comparing their assessments against the experimenter's subjective impressions of participants' attentional states (e.g., Pizziol, Dehais, Tessier, 2011; Horng et al., 2004). Adopting the latter approach, it was sometimes observed in this study that, despite the instruction to divide attention equally among all tasks, participants neglected the resource management task for extended periods of time. This may be explained by the nature of the task: once the tanks were in a stable condition, at the level of 2,500 units, no additional actions were required from participants for some time. They knew they could attend to other tasks until a pump failure would require their attention. In some cases, participants falsely assumed that the tanks were in a stable condition, and they allowed the tanks to deviate far from the target value. When they noticed the problem, participants may have struggled to return the tanks to 2,500 units and experienced anxiety and attentional narrowing for a short period of time, even though no novel unsolvable problem had been introduced by the experimenter. In other cases they may have decided to temporarily engage in focused attention to solve the resource management problem.

During the attentional narrowing scenarios, the algorithm categorized participants' attentional state as being narrowed only 50% of the time. Again, this may not reflect a shortcoming of the algorithm but rather show that participants, at times, broke out of this attentional state. This explanation is supported by the fact that performance on the various tasks did not drop to 0% during the novel problem scenarios, suggesting that participants attended to them occasionally and experienced divided attention. In addition, few participants reported that, after they had tried for a few minutes to solve the novel problem, they assumed that it was due to a flaw in the system and consciously adopted a new strategy of focusing on the resource management task for limited periods of time, and divided their attention across the other tasks the rest of the time.

Finally, the algorithm classified participants' attentional state as focused attention 71% of the time in the respective scenarios. This high percentage may be explained, in part, by the fact that participants were explicitly instructed to perform only the resource management task while ignoring all other tasks and stimuli. This reduced their task load and may have resulted in a more uniform behavior. It led to considerably larger fixation percentages and longer dwell durations in the resource management area. Because these two metrics were used by the algorithm to distinguish divided attention from a state of reduced attention (attentional narrowing or focused attention), it was therefore easy for the algorithm to rule out a state of divided attention when participants were engaged in focused attention.

While the above observations explain, in part, why the algorithm did not classify participants' attentional state to be the same in all cases and throughout entire scenarios, it is also possible that the algorithm was imperfect. In particular, the lack of correlation between (1) the detection of "attentional narrowing" by the algorithm and (2) performance drop in the attentional narrowing scenario indicates that the algorithm may not have consistently detected a narrowing of attention. Several actions could be taken to further improve its accuracy. First, using a computer with a higher processing power would allow inclusion of a larger number of eye tracking metrics in the algorithm. Earlier studies have found that using additional metrics can lead to improved detection accuracy (Bergasa et al., 2006). In addition, increasing the number of metrics that can be computed simultaneously and in real time would also allow the use of more advanced categorization tools, such as learning machines or logistic regression, instead of a simple comparison of metrics values to pre-determined thresholds. Performance metrics could also be included in the algorithm calculation to help trace attentional breakdowns. Finally, it has been shown that the inter-individual variability of eye movements is very large (Andrews & Coppola, 1999; Castelhano, Mack & Henderson, 2009). Improvements could thus be made to the detection tool by taking into considerations these differences and designing a more flexible algorithm.

Effectiveness of the two interventions – status and command

For most tasks, the performance effects of the status and command displays were the same. Neither intervention affected performance on the system monitoring, tracking and peripheral light detection tasks. However, both displays led to improved performance on the resource management task – the one that presented the novel problem. The performance effects of the two strategies differed with respect to the scheduling task, where the status display led to performance degradation but the command strategy resulted in improved performance. Thus, overall, the status display did not achieve its goal of broadening participants' attentional field as it did not improve performance on any of the non-REMAN tasks. The command display, on the other hand, was partially successful. It resulted in participants attending to the scheduling task, in addition to the REMAN task. These results will be further discussed in the following sections.

The failure of the status display to help participants notice and overcome their narrowed state may be explained by several factors. First, the status information was co-located with the task that participants had narrowed in on. As a result, it may have exacerbated the problem and focused their attention in that area even more in a bottom-up fashion. During the debriefing, all but one participant explained that they had misinterpreted the cue as ordering them to look more carefully at the resource management task. For some of the participants, this was reinforced by the fact that the status information was presented in red, the same color pumps turned to when they failed. Finally, some of the participants' belief that the adaptation represented a system failure (rather than an aid) may have led to mistrust (Muir, 1994), disuse of the display (Lee & Moray, 1992; Parasuraman & Riley, 1997; Wickens & Hollans, 2000) and a significant increase in anxiety, thus reinforcing attentional narrowing.

The command display was more successful at improving attention management and multitasking performance, possibly because it indicated more clearly a course of action for operators to follow – the expansion of their attentional field. It is interesting to note that the positive performance effect of the command display was most pronounced for the scheduling task (where participants had to detect when slowly moving green marks aligned with two blue lines). This suggests that the entire MATB II task set may have overwhelmed participants who felt that they could at best attend to one additional task. The choice of the scheduling task can be explained by participants' comments during the debriefing session. Several of them reported that they broadened their attention and attended to this task because, in contrast to the system monitoring, tracking and light detection tasks, it allowed them to anticipate when an action would be needed (based on how far the green marks had to travel before aligning). This helped with scheduling the two tasks they performed. Studies have shown that having a better awareness of the situation can help reduce workload, and as a result, increase performance (Billings, 1991). In addition, some participants mentioned that the green color of the alert matched the color of the scheduling task which made them think that this task was the one requiring their attention the most. On the other hand, the color coding misled some other participants who wrongly assumed that the command alert was telling them to increase the attention given to the resource management task because the color of the alert (green) matched the color of the fluid in the different tanks. The command adaptation could therefore be improved by carefully selecting a unique color.

The subjective data offer further suggestions for how the design and implementation of the two interventions could be improved. Several participants mentioned that they found the status and command alerts "annoying", in part because they did not remember their purpose, which had been explained to them during training. Participants did not experience the actual intervention in advance of the experiment to avoid that they would anticipate problems in the resource management task area which, in turn, might have defeated the goal of inducing narrowing. This may be the reason for some of the reported confusion. One way to overcome this dilemma could be to induce novel problems and associated interventions on the other tasks during training – such as system monitoring, tracking or scheduling. An additional means to improve the design of the command intervention could be to use written instructions in addition to or in place of the colored cues. To help support pilots' attention allocation and decision making when experiencing attentional narrowing due to difficult weather conditions, Dehais et al. (2010) evaluated the effectiveness of displaying a clear message on top of the task towards which pilots had narrowed their attention. In this experiment, a command intervention was used and the message would provide instructions on what was the right action that pilots should take – in this case, they were asked to fly back to the airport and the message displayed "Go back to Blagnac". It was found that 9 out of 12 pilots effectively broke out of attentional narrowing and correctly interpreted the instruction.

Another promising, more indirect countermeasure to attentional narrowing may be to try to reduce participants' anxiety levels by means of soothing colors or calming auditory messages. This reduction in anxiety may, in turn, result in a broadening of attention, without using a command display to explicitly encourage this change in behavior.

In conclusion, the results of this study confirm that it is possible to detect attentional narrowing in real time, and distinguish it from the overlapping attentional state of focused attention. Furthermore, this experiment showed that the use of adaptive displays – more precisely, a command intervention - is a promising means of counteracting this dangerous attentional state. Future work should further address the limitations of this study and explore how improved training on the status and command display, more appropriate color coding and an enhanced detection algorithm could better support detecting and overcoming attentional narrowing.

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Chapter 6

Summary and Conclusion

Attentional narrowing is characterized by an involuntary reduction in the range of cues that can be utilized by an individual (Mueller, 1976). When experiencing this attentional state, individuals falsely assume they have a complete picture of the situation, when, in reality, they only perceive parts of it, and their decision-making and problem-solving abilities are seriously affected. This potentially dangerous state tends to be triggered by high levels of anxiety which are experienced when facing novel challenges or life threatening situations – the exact times when it is most essential that operators gather all relevant information and make decisions in a timely fashion. Attentional narrowing has therefore been identified as a major threat to safety in domains like aviation (Shappell & Wiegmann, 2003), sports (Janelle & Hatfield, 2008; Wilson, Wood & Vine, 2009), medicine (Arias-Hernandez & Fisher, 2013), driving (Crundall, Underwood & Chapman, 2002) and police work (Price, Lee & Read, 2009).

Despite these concerns, attentional narrowing remains poorly understood. One of the main reasons for the lack of understanding of its triggers and possible countermeasures has been the difficulty to reliably reproduce the phenomenon in controlled laboratory settings.

Another difficulty is the partial overlap between attentional narrowing and focused attention. Both states are characterized by a reduced attentional field. However, when engaged in focused attention, a person deliberately, in a top-down fashion, concentrates on one task or source of information and to the exclusion of any other. It is thus a desired state that should be supported. In contrast, attentional narrowing is involuntary and needs to be avoided at all times. The challenge is to develop a tool that can reliably detect and distinguish between the two attentional states.

The objective of the work presented in this dissertation was to fill these gaps in the literature on attentional narrowing. More specifically, the goals of this research were to:

(1) identify reliable triggers of attentional narrowing for use in controlled laboratory settings

(2) identify markers of focused attention and attentional narrowing that help detect and distinguish between the two attentional states in real time

(3) develop adaptive display designs that help overcome the undesirable state of attentional narrowing.

In order to achieve these goals, a review of the literature on attentional narrowing and related concepts was conducted first. Chapter 1 identified the various proposed triggers of attentional narrowing and organized them into two main categories: (1) arousal and (2) high motivational intensity. Chapter 2 described two preliminary studies that were performed to explore the effectiveness of two triggers of arousal – noise and high attentional load – and one trigger of high motivational intensity – ego-threat – in the context of a visual search task.

High levels of attentional load and ego-threat were identified as the most promising means of reliably inducing attentional narrowing in this context.

Building on these findings, an experiment was then conducted to confirm the efficacy of these two factors in the context of timesharing multiple and more challenging tasks – a situation that is representative of domains where attentional narrowing represents a major concern. Also, in this study, eye tracking data were collected with the goal to identify eye tracking metrics that can be used to reliably detect and trace attentional narrowing. Chapter 3 highlighted that ego-threat – caused by a novel and unsolvable problem - was the most effective means of triggering attentional narrowing. It resulted in participants spending significantly more time looking at the affected task, with their performance on all other tasks dropping. Three eye tracking metrics emerged as promising markers of attentional narrowing: (1) the percentage of fixations, (2) dwell duration and (3) fixation duration in the display area where the novel problem was presented.

Chapter 4 described an eye tracking algorithm that was developed to detect and distinguish, in real time, between divided attention, attentional narrowing and focused attention. Because of observed high inter-individual variability for various eye tracking metrics, the values of each of the parameters used by the algorithm were designed to be specific to each participant. In addition, in order for the algorithm to perform well in complex real-world environments where there is no a-priori knowledge about operators' eye movements during the rarely experienced state of attentional narrowing, the algorithm assumed that baseline data (to be used as a training set) would be available only for eye movements when engaged in divided attention. The algorithm detects attentional narrowing based on a two-stage process: first, fixation percentage and dwell duration are used to distinguish divided attention from both attentional narrowing and focused attention. Next, if the algorithm determines that the participant is engaged in one of the two latter states, then a third metric, fixation duration is used to distinguish between attentional narrowing and focused attention. Based on extensive testing, the shortest time interval for making these determinations was determined to be 20 seconds.

Finally, an experiment was conducted to assess the feasibility and accuracy of the algorithm and test its use for triggering two types of countermeasures to narrowing. A status and a command display were designed and implemented, and their effectiveness for supporting a broadening of the attentional field and resulting performance benefits was assessed. Divided attention, attentional narrowing and focused attention were detected by the algorithm 63%, 50% and 71% of the time, in the respective experimental conditions. Based on observed participant behavior and subjective data, this suggests a high level of accuracy, reflecting that the actual attentional state of participants varied, to some extent, throughout each scenario. The command display helped broaden participants' attentional focus and led to improved overall performance whereas the status display was ineffective, primarily due to the fact that several participants misunderstand the meaning of this intervention.

Intellectual Merit and Broad Impact

The findings from this research contribute to a better understanding of attentional narrowing - a growing concern in high-risk complex domains. More broadly, they add to the knowledge base in attention – its various forms and factors affecting the allocation of attentional resources and attention management. It also illustrates how display design can be employed to foster proper attention allocation in a bottom-up fashion.

Specifically, this line of research identified a reliable method for triggering attentional narrowing that can be used by future studies. An eye tracking-based algorithm was developed for the real-time detection of this dangerous attentional state which represents a major step towards counteracting the phenomenon. It supports early detection of attentional narrowing and thus helps anticipate and prevent resulting performance breakdowns. Using an eye tracking-based algorithm is beneficial as it represents a display-independent – and thus domain-independent – detection tool. Finally, this research also demonstrated one promising countermeasure to attentional narrowing in the form of a command display to support broadening of the attention – a significant contribution to the field of augmented cognition which aims at evaluating the cognitive states of users to trigger real-time changes in task allocation and information presentation.

By doing so, this research makes a significant contribution to safety and efficiency in a wide range of complex data-rich application domains, including aviation, nuclear power plant operations, and medicine, as well as environments involving high levels of anxiety, such as police work, sports or driving.

Future Work

Research on attentional narrowing has long been hampered by the inability to reproduce this dangerous phenomenon reliably in controlled laboratory settings. The work presented in this dissertation helps overcome this challenge and, as a result, opens the door to future studies, some of which are outlined in the following paragraphs.

First, it will be important to examine inter-individual differences in attentional narrowing. Recent studies highlighted the need for considering inter-individual differences when conducting research in cognition (Kanai & Rees, 2011). It is still unclear how other factors - such as genetic, age or environmental – could modulate the narrowing of attention. Specifically, some experiments have suggested that highly anxious individuals are more likely to experience the phenomenon (Derryberry and Reed, 1998; Koster et al., 2005). In addition, it was found that differences in electrical activity in the vision system (vision evoked potential, VEP) between individuals can lead to variations in how attention is affected by stimuli (Proverbio, Del Zotto & Zani, 2007). Also, older people tend to experience more difficulties with attention management and are known to have a reduced visual field, compared to younger individuals (Sekuler, Bennett & Mamelak, 2000). The time of day has also been suggested as a factor that can influence attention and arousal (Anderson & Revelle, 1994). Better understanding the role of inter-individual differences is important, for example, for personnel selection and training.

Another important question is the extent to which modalities other than vision may be affected by attentional narrowing. To date, there is only very limited and controversial evidence of the existence of the phenomenon in hearing (Dehais et al., 2014) and touch (Hess, 2006). If other sensory channels are less affected, it may be possible to prevent problems by transferring information to these modalities in highly demanding stressful situations.

Improved means of assessing and improving the accuracy, validity and speed of the algorithm should be explored. To this end, the inclusion of additional eye tracking and possibly performance metrics should be explored. Also, neuro-imaging could serve as a complementary method to detect and/or anticipate attentional narrowing. Techniques such as functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) or electroencephalography (EEG) have allowed researchers to identify regions of the brain that activate when individuals experience high levels of anxiety (Bishop et al., 2004; Heeren et al., 2013), and they could help trace attentional states (for a review, see Brouwer, Zander & van Erp, 2015).

Finally, a broader range of countermeasures to attentional narrowing needs to be developed. The findings from the last experiment described in chapter 5 suggest that the command display was an effective means of broadening attention. It is not clear, however, whether even simpler more generic interventions (such as a brief aural or text alert) may be sufficient, provided that operators are trained on its meaning and proper response. Identifying the simplest and lowest salience intervention is critical to minimize disruptions caused in cases where the algorithm may fail and trigger an intervention when the operator is actually engaging in focused attention. On a related note, it is important also to determine the effect of imperfect reliability of the algorithm on operators’ acceptance of, and compliance with interventions (McGuirl & Sarter, 2006).

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