Developing and Assessing Novel Paradigms for Computerized Measurements of Attention

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Hamburg, 18. März 2022

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Johann-Christoph Münscher

Schaff, das Tagwerk meiner Hände,
Hohes Glück, daß ich's vollende!
Laß, o laß mich nicht ermatten!
Nein, es sind nicht leere Träume:
Jetzt nur Stangen, diese Bäume
Geben einst noch Frucht und Schatten.

Abstract

Attention is a fundamentally important aspect of human consciousness and cognition that interfaces with all aspects of life. The concept can be viewed from a variety of perspectives, which has resulted in multiple definitions and approaches. A common view is that attention is a complex bundle of processes that filter and select information prior to reaching consciousness and higher mental processing. Essentially, attention is the lens through which we experience human existence. Obviously, this is a simplification, and the theories and models developed in the field describe quantities and qualities that vary situationally and individually. In the work context, where attention is routinely required, it is useful to assess not only an individual's ability but also situational demands. The present dissertation aims to contribute to the field of attentional assessment by designing and evaluating novel, computerized means of measurement. To this end, three distinct projects were carried out: The first strived to identify the relevance of attention as a job demand in the occupational landscape. Although this goal could not be achieved, the project, nevertheless, yielded an interesting perspective on occupations and their demands. The second project attempted to identify and operationalize which characteristics of jobs determine demands for attention. By integrating relevant theories of attention, a novel framework of parameters constituting demands for different manifestations of attention was created. A job analysis questionnaire (Parameters of Attention at Work – PAW36) based on the framework was constructed and positively evaluated in an empirical study. The third project consisted of designing innovative and computerized paradigms to measure attention. This design was strictly based on the theoretical landscape of attention and the framework of task parameters. A range of bespoke paradigms were created, one of which, the Continuous Matching Task (CMT) was evaluated in a second empirical study. This project brought several noteworthy innovations to attentional assessment, primarily by including adaptive testing and procedural stimulus generation; both of which proved to be useful additions. The paradigm was thoroughly evaluated using empirical data from performance tests, related personality assessments, as well as physiological measurements in the form of heartrate variability. The study also included a mobile application of the CMT in which participants completed the task using their own mobile devices. Further details, results, and interpretations of them are provided in this dissertation, as well as the four articles created within the scope of it.

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Introduction

Attention is a centrepiece of human cognition and consciousness. Moreover, it is a prerequisite for intelligence, perception, learning, and performance. Attention is by no means a monolithic entity or a single process but instead an overarching concept with many components. A speaker requests our attention, a situation comes to our attention, an event catches it, and a distraction diverts it. All of these scenarios describe different processes in which attention designates a range of cognitive and behavioural processes. We have an intuitive understanding of some of these processes, but academically describing them remains an ongoing challenge. In the field of psychology, attention describes a set of universally important mental faculties that are relevant to all branches of psychology and neighbouring disciplines such as education, medicine, economics, and political science. Its importance to the human condition cannot be overstated.

Psychological work, whether in research or practice, requires theories and constructs in order to be tangible, not merely philosophical. As a result, in addition to theoretical insights, modern psychology seeks to provide practical utility. This utility primarily aligns with the objectives of academic psychology. Namely, the ability to *describe*, *explain*, *change*, and *predict* human experiences. Measuring individual expressions of constructs like attention plays a vital role in this pursuit. The research performed in the scope of this dissertation aimed at conceptualizing, developing, and applying innovative approaches to measure attention. These efforts were mostly directed towards applications in the field of occupational psychology among adults.

This goal was initially motivated by the observation that the commonly used methods of measuring attention are relatively old-fashioned, particularly in light of the advent of digital and computerized testing. Many measurement paradigms for attention have not been updated for decades and their application frequently relies on paper-pencil formats, even in cases of performance measurements that would, clearly benefit from more precision and dynamic adaptation. The development of theories and paradigms for measuring attention will be discussed in detail at a later stage but the problem can efficiently be illustrated using a common test of attention: The Concentration Endurance Test (d2) (Brickenkamp, 1962) was initially developed in 1962 and has since been revised several times. While this is surely a testament to its utility, the field for which it was primarily developed – occupational psychology in adults – has seen drastic changes. A variety of factors, including globalisation and economic development, have transformed the world of work. At the same time, digitalization – and specifically computerized testing, adaptive testing, and digital media – have drastically changed the possibilities for testing and assessment. Sadly, these opportunities remain underutilized in a large portion of psychology.

Outline

In the following sections, I will first give a brief overview of how prominent theories and measurement paradigms for attention were developed, followed by a summary of contemporary multidimensional theories. As attentional assessment in occupational psychology is the primary subject in this dissertation, I will also outline the developments and challenges within this domain. These challenges were used to develop a set of research questions and goals. Three distinct research projects were undertaken, which resulted in four journal articles; two have been published, while two are under review at the time of writing. These projects concerned one or more of the following overarching topics: the measurement of attention, innovative measurement paradigms, the role and configuration of attention within occupational psychology, and changes within the world of work. The final section of this dissertation will discuss the findings from all three research projects and present future perspectives.

Defining Attention

Given the prominent position of attention within psychology, one would be safe to assume that the theoretical and practical aspects of attention are relatively well defined and understood by now. However, attention as a unique field of research is comparatively young, beginning only in the 1950s. Furthermore, the theoretical landscape is varied and even contradictory in places.

Important groundwork for the field was laid in 1860 by the *psychophysics* approaches developed by Gustav Fechner (Fechner, 1966). Fechner sought to measure mental processes by recording quantifiable physiological parameters in his so-called *black-box* approach. Roughly 30 years later, James (1890) advanced the field by describing the mental processes of attention and famously stated:

> *Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others.*

Primarily, he characterized attention as a mental process that facilitates focussing one's consciousness onto certain aspects of the internal or external world as well as its removal from others. In his seminal work, James described many aspects that would later be extended, discussed, and systemized by other researchers. In his view, these processes may either be active or passive, a distinction that is commonly described by the concepts of *bottom-up* or *top-down* information processing. He also identified multiple functions and effects of attention, namely perceiving of stimuli, conceptualizing content, distinguishing between elements, and memorizing information. Referencing research by Wilhelm Wundt (Wundt & Titchener, 1904), he also concluded that attention reduces reaction times, particularly when stimuli are actively anticipated. In contrast to the black-box approach of psychophysics, he did not restrict his perspective to quantifiable physiological responses that were assumed to be universal but described attention as an individual mental and psychological process. He actively rejected the then-common notion of experiences universally impacting the recipient by stating "Millions of items of the outward order are present to my senses which never properly enter into my experience. Why? Because they have no interest for me. My experience is what I agree to attend to.".

In the roughly 140 years since, a multitude of theories and approaches have been developed. The process is ongoing and the resulting theoretical landscape is the subject of controversial discussion – an overview of approaches relevant to the present research will be provided below. In contrast to James' assumption that everyone knows what attention is, Hommel et al. (2019) provocatively stated that "No one knows what attention is.", and criticized that attention as a singular explanation for many different neurological selection processes is a frequently used yet unfruitful concept. Subsuming different selection processes that occur within an organism, such as the human brain, under the broad term of attention dilutes the term. Therefore, Hommel et al. argue that the field cannot advance if it continues to take this approach. They maintain that a robust assessment of the nature of attentional phenomena should follow a synthetic approach that focuses on the key mechanisms that create, reinforce and shape selection processes.

The criticisms voiced by Hommel et al. appear justified, particularly in light of their primarily neurobiological and evolutionary perspective. The diluted terminology and overlapping concepts within the domain of attention was also a key issue in the present research. Heilman et al. (2003) echo this sentiment in their attempt to define attention, stating: "It has often been said that everyone knows what attention is, but no one can fully define it."

The different perspectives on attention stem from the various fields in which it is relevant. For instance, educational psychology, cognitive psychology, neuropsychology, developmental psychology, clinical psychology, and behavioural psychology are routinely concerned with attentional phenomena. While they often share definitions and perspectives, they also diverge in their accentuations. For instance, the neurological basis of selection processes may be critical when investigating disorders in children from a developmental psychological perspective. Here, the exchange of neurotransmitters (e.g., acetylcholine) and the development and activity of cortical areas – such as the (pre)frontal, and parietal regions – are of interest; for a review of the relationship between neurotransmitters, cortical areas and attention, see Klinkenberg et al. (2011). However, these aspects are likely not as pertinent in assessments of healthy employees for personnel selection in occupational psychology. In this case, the ability to allocate attention may be of interest from a broader behavioural perspective – this approach will be discussed in more detail later on. While the same underlying processes are obviously at play, the focus changes based on the specific application. Consequently, a wide range of conceptualizations of attention has emerged.

Development of theories

As referenced before, the theoretical landscape of attention is complex and has undergone developments in various directions. In the following summary, I will present the most prominent developments as well as the theoretical contributions that are most relevant for the projects in this dissertation.

Generally, theories of attention are concerned with information processing in human perception and cognition. Most of these approaches relate to the processing of sensory information, most prominently visual stimuli. In contrast, the inward-oriented aspects of attention described by James (1890) have received much less consideration. Modern concepts of attention capture such aspects in the form of internal attention (Chun et al., 2011; Verschooren et al., 2019).

Development of modern cognitive psychological approaches to attention started in the 1950s and initially sought to investigate attention as a singular process of filtering and selection. In the pursuit of thus, the boundaries of human information processing were explored. Early approaches measured various sensory perception thresholds by varying the intensity, also called *saliency,* of stimuli (e.g., size, loudness, duration, colour, frequency) and recorded subjects' reactions. The results showed that stimuli with an intensity below the sensory threshold initially enter sensory perception but seem to be rejected from further processing.

One such classical experimental setup is the change blindness paradigm. This phenomenon occurs when viewing images or video sequences in which elements – such as the colour of a piece of clothing – are changed after an interruption. Participants rarely notice changes in stimuli if their perception of these stimuli is briefly interrupted and they did not actively focus on them before the change. In an astonishing experiment by Simons and Levin (1998), participants did not realize that their conversation partner, who had asked them for directions just moments before, was exchanged mid-conversation when they were interrupted by construction workers carrying a door between them. This effect relies on an interruption to obfuscate the change; the door was used to briefly break the line of sight. Other experiments use neutral stimuli like noise patterns to achieve this effect. If the changes instead occur without an interruption, the difference is immediately recognized. These observations indicate at least two things. Firstly, attention and processing of stimuli appear to be continuous processes and interruptions to the continuity cause changes and errors to go unnoticed. Secondly, only a small range of stimuli are actively attended to. Other stimuli and changes to them seem to enter processing initially but are not processed further and thus do not enter consciousness.

The *dichotic listening* paradigm by Cherry (1953) is another classical paradigm in attention research. In this auditory attention task, participants had to listen to and recall a message they heard in one ear while a different message was presented to the other. The distractor message had to be actively ignored to hear the target message. Afterwards, participants could recall the target message but not the distractor message. The assumption was that it had not reached conscious processing and memory; therefore, it must have been discarded at a prior stage.

The presented observations led to the conceptualization of attention as an *early selection filter*. Broadbent (1958) formulated a corresponding theory that stimuli enter into sensory processing, where attentional processes select the relevant ones. Irrelevant stimuli are disregarded before they reach higher mental processing and memory. A prominent example for which this assumption does not hold, is the *cocktail party phenomenon* (Silsbee & Handel, 1993). It describes suddenly becoming aware that one's name has been uttered in a distant conversation. This awareness occurs even though no attention was directed towards the conversation; it may have even been actively ignored. This should not occur from an early selection point of view, and indicates that the unattended stimuli were processed and seemingly checked for relevance. Therefore, the unattended stimulus – the distant conversation – could not have been filtered out early.

From this and other observations, the *Attenuator Model* (Treisman, 1964) was developed. It states that the selection performed by attention is not a strictly binary process in which unattended stimuli are simply discarded. Instead, attention attenuates the unattended stimuli by assigning a degree of priority to them. Higher mental processing then continues based on this prioritization. In this perspective, unattended stimuli are not completely blocked but can be processed further, given sufficient priority.

The attenuator model is still an early selection model. Deutsch and Deutsch (1963) proposed a *late selection model* in which they assumed that all stimuli enter higher processing and the selection of relevant stimuli is performed at a later stage. This perspective was then expanded upon in *perceptual load theory* by Lavie and colleagues (1995; 2004). She combined the mechanisms of late, and early selection and proposed an approach in which both occur and are modulated by the current mental workload (MWL). MWL is a general concept that encompasses different types of mental effort that require cognitive resources. High MWL facilitates early selection while late selection occurs under low MWL. In situations with high mental demands, the effort of selecting stimuli is offloaded to mechanisms that occur before higher processing, thus freeing up resources for the current task. Under low MWL, stimulus information can flow more freely, and higher processing resources can be used for selection.

Viewing attention through the perspective of perceptual load theory also highlights the fact that cognitive resources are limited and need to be allocated based on the current situation. This perspective corresponds well with the *spotlight theory* of attention (Posner et al., 1980). Like the beam of a flashlight, attention can be focussed, defocussed, and directed to influence the flow of perceptual information to higher processing and memory. It can be seen as an allocation mechanism that serves several distinct functions and can take on different forms within this process. The following sections give an overview of these functions, as well as the different manifestations of attention.

Functions of Attention

In the spotlight metaphor, attention is neither just the flashlight nor the beam but the entire configuration of elements and processes. Attention is not one singular *thing* but the by-product of many processes interacting. Research into these processes has resulted in the identification of a set of types, and dimensions of attention. As previously mentioned, James

(1890) already assumed multiple functions of attention, namely perception, conception, distinction, memorization, and reaction. Petersen and colleagues (2012; 1971; 1990) provided a modern perspective on attentional functions. Their work in this crowded field is noteworthy because they worked from a strong neurological basis, integrating many specific research results into a single perspective. They determined three basic functions of attention: *alerting*, *orienting* and *executive control*. They presented these three functions as not only conceptually separate but also associated with distinct neural areas.

Petersen and Posner (2012) describe *alerting* as the organism's fundamental readiness for processing stimuli. An alert state is associated with activity in the right cerebral hemisphere and shorter reaction times to stimuli. Both hypo- and hyperarousal lead to reduced performance, resulting in a bell-shaped association between arousal and performance. Primarily, activity in the midfrontal cortex as well as activation of the locus coeruleus and the norepinephrine system appear to serve the function of preparing the processing systems for salient stimuli (Esterman & Rothlein, 2019; Petersen & Posner, 2012). This process is activated when a warning signal or cue is perceived, and other ongoing processes appear to be suppressed in anticipation of a stimulus. Besides activity in the neural areas that make attentional resources available, Esterman and Rothlein (2019) point out that alertness needs to be allocated towards a task and said allocation must be controlled to prevent unrelated wandering thoughts. Allocation and control of cognitive resources carry a cost that must be offset by the potential gains of performing the task. Ultimately, this highlights that alertness is not simply dependent on neural activation but also motivation and top-down processing.

The allocation of cognitive and perceptual resources is also essential to the function of *orienting* laid out by Petersen, Posner, and colleagues (2012; 1990). They primarily define orienting as a process of visual-spatial attention that assigns processing priority to a location either overtly (i.e., by directing one's gaze toward them) or covertly (i.e., without head or eye movement). Petersen and Posner (2012) describe orienting attention as a process that is largely independent of alerting. Alertness is a prerequisite for orienting but an alert state does not require engagement with a stimulus.

Orienting takes place in three steps (Posner & Petersen, 1990): First, attention is disengaged from the present location of focus; this step is primarily performed by the parietal lobe. Second, attention is shifted towards the new target via activation in the midbrain. Third, the thalamic nucleus pulvinaris processes information from the new location. In their later work, Petersen and Posner (2012) conclude that this process is performed by two separate cortical systems, the dorsal and ventral attentional systems. The dorsal attentional system generates top-down strategic control impulses, like initiation and target selection. The ventral system generates bottom-up signals in response to stimuli and is active when following a target stimulus. When visual attention shifts, shifting back to the previous location is suppressed for a short duration. This *inhibition of return* is likely caused by the prefrontal cortex marking the coordinates of the last foveation (i.e., the object that was last looked at); refocusing on the same location is thus inhibited (Klein, 2000). Additionally, the processing of competing stimuli is reportedly suppressed (Petersen & Posner, 2012). In an alert but unengaged state, a stimulus can easily catch our attention, but when cognitive resources are already allocated, new stimuli are not engaged as readily. Attention can also be shifted between the internal and external domains (Chun et al., 2011; Verschooren et al., 2019) and between tasks (Gilbert & Shallice, 2002). Both are associated with characteristic switching costs that are attributed to increasing demands for executive control.

Executive control is the third function of attention identified by Petersen and Posner (2012). They assume that metacognitive and top-down activities that regulate the allocation of cognitive resources are performed by two separate systems. The frontoparietal system exerts immediate task-related control like initiating, adjusting, and switching tasks, while the cingulo-opercular system performs overarching background maintenance. The combined activity of these systems constitutes selective response control in the forms of intention, initiation, inhibition, switching, and supervision (Cohen, 2014). Fernandez-Duque et al. (2000) describe executive attention as a metacognitive system that engages in conflict resolution, error detection, planning, memory organisation, and emotional control. It is strongly associated with higher-order self-regulatory functions. In contrast to alerting and orienting, executive control actions occur in the later stages of processing and involve conscious control and memory. Specifically working memory stores and organises information in the short term and has been identified as a crucial component of executive control (Baddeley, 2010; Hedge et al., 2015; Werheid, 2002). An apt metaphor for this concept is the desk one works at to develop plans, process incoming information, and store past information. Organisation in working memory is performed continuously and primarily consists of retrieving data from memory and preparing relevant pieces of information, dealing with incoming information by either keeping or discarding it, and removing pieces of information that have become irrelevant. The number of elements that can be managed in this way is often called the capacity or span of executive control.

The metacognitive functions of executive attention are particularly relevant when switching tasks and resolving interference. Deliberately switching tasks and reorienting attention are distinct functions of executive control and differ from switching initiated bottom-up. Such interferences disrupt previous resource allocation and require additional executive control to inhibit unwanted processing and orient processing on the target. Engle (2018) describes this function of executive control as the "ability to maintain information in the maelstrom of divergent thought", which he attributes to working memory capacity. He also points out that these actions are highly correlated with fluid intelligence yet appear to constitute a separate action. Likewise, Schweizer et al. (2005) conclude that intelligence and attention, specifically working memory, are separate cognitive actions that share resources; likely those related to processing speed.

Reviewing the functions of attention – alerting, orienting, and executive control – it becomes apparent that they rely on separate yet dependent processes. The neurological evidence suggests that distinct cortical networks are at play in their functioning but the interplay is what ultimately creates the phenomenon of attention. Different manifestations or dimensions of attention can be distinguished depending on how these functions are engaged; one common classification scheme is presented in the following sections.

Dimensions of Attention

While the functional perspective on attention describes the underlying primary processes, viewing attention from a dimensional or multi-faceted perspective highlights how the functions interact and ultimately manifest in different behaviour. A common differentiation of types of attention was presented by Sturm (2009), comprising *alertness*, *sustained attention*, *vigilance*, *selective attention*, *spatial attention*, *divided attention*, and *focused attention*. He further specified that these different types are associated with the underlying dimensions of, *intensity*, *spatial orienting*, and *selectivity*. As a further type of attention, Schmidt-Atzert et al. (2008) isolated *concentrated attention*. Furthermore, Cohen (2014) described intentional/directed, effortful, controlled, automatic, and voluntary attention as manifestations. All of these types of attention capture ways of allocating and managing our attentional resources in various states. Ultimately, these selection processes result in the allocation of attentional focus and reactions to stimuli and tasks.

For example, during an exam, our level of activation is likely increased; we may feel excited or nervous. When we are ready, we read the first essay question carefully, word by word, until we grasp what being asked. After a period of concentrated reading, we might take a short break, look away from the text and think about what we have read and how we could answer the question. We decide to read the question again, yet just as we look down, another person loudly voices their frustration over the exam. For a moment, our focus is lost and we look at the other person and think about what they are doing. We might even get frustrated ourselves because we were distracted and lost our train of thoughts; perhaps we are now even more nervous than before. After a little while, we turn our attention back to the exam and read the question again.

This example illustrates various manifestations of attention. Primary to all of them are degrees and forms of arousal and alertness. *Alertness* as a type of attention is closely associated with alertness from the functional perspective (Petersen & Posner, 2012). It refers to a state of basic arousal that enables information processing. Sturm (2009) describes the states of *tonic*, *phasic*, and *intrinsic* alertness. Tonic alertness refers to the level of long-term arousal (e.g., the level of excitement and nervousness before and during the exam). It varies in intensity based on the current situation is required to initiate phasic and intrinsic alertness in anticipation of or in response to relevant stimuli. Phasic alertness is a short-term, bottom-up increase in arousal in response to external stimuli (e.g., the other person's outburst) that facilitates fast responses. Intrinsic alertness describes a similar activation that originates internally, i.e., top-down (e.g., carefully reading the question, and reading the question again after being interrupted). Both of these types depend on overlapping neural areas with intrinsic alertness exhibiting an activation delay compared to phasic alertness (Matthias et al., 2010).

Maintaining an alert state and producing appropriate reactions over a certain period of time, instead of just singular reactions, is called *sustained attention*. With more time-on-task, processing demands increase because recovery is hindered and demands for executive control rise (Holtzer et al., 2011). Thus, compared to short-term or singular attentional requirements, prolonged demands (e.g., reading and answering many questions on an exam) can lead to fatigue or, when motivation is low, boredom. Consequently, overall alertness and top-down regulation capacity decrease, leading to reduced performance. Working at a quality control desk where finished products must be continuously checked with the same rigour, demands mostly sustained attention, because each sample requires the same level of attention. Langner and Eickhoff (2013) point out that fatigue reduces overall performance but particularly affects executive control and intrinsic attention. On the other hand, automatic, and tasks that rely on learned behaviour and thus more reliant on bottom-up processes are subject to less of a performance decline in a fatigued state.

Vigilance is a closely related concept in this context. In some perspectives, vigilance is used interchangeably with alertness, specifically tonic alertness (Donald, 2008). However, most neuropsychological perspectives describe vigilance as a form of sustained attention (Cohen, 2014; Sturm, 2009). In this view, vigilance designates attentional performance over a period of time – minutes to hours – in which alertness must be maintained, while the performed task is simple and relevant stimuli are rare. Monitoring a class during an exam is primarily a vigilance task because students are usually calm and cheating rarely occurs. Langner and Eickhoff (2013) use the term *vigilant attention* for this kind of performance and conjecture that it is not the product of one attentional process but the combination of top-down and bottom-up processing. Essentially, phasic and intrinsic alertness need to be maintained simultaneously, with the latter requiring cyclical reactivation. Because activation through intrinsic alertness decays within seconds and competing thoughts and interferences divert resources, the required level of activation needs to be continuously provided anew through self-regulation (Esterman & Rothlein, 2019). Serving duty on a watchtower is a classic example of a vigilance task; a noteworthy event rarely occurs but a base-level of activation must be maintained, despite boredom or tiredness, to react in case it does.

Selective attention is among the most prominent dimensions of attention. Selection describes the process of assigning priority to an informational element and promoting its processing over competing elements (Cohen, 2014). Gilbert Keith Chesterton (1874-1936, English author) referenced this prioritization when he remarked, “I am not absentminded. It is the presence of mind that makes me unaware of everything else.” (n.d.). This direction of attention and higher processing can be top-down, initiated by executive control, such as when listening to a conversation. However, a new salient stimulus can also initiate a bottom-up reorientation of attention towards a previously unattended target, as demonstrated by the cocktail party phenomenon. Once a stimulus has been selected for processing, reorientation to other stimuli needs to be prevented. Here, the previously mentioned inhibition of return helps to promote a steady state of focus by preventing immediate orientation back to the last location. The ability to fixate attention on a task and maintain it is critical in many activities, including social interactions, studying, and reading. In a study involving primary school children, Commodari (2017) found that selective attention abilities are essential for the development of reading skills. According to the cognitive load theory presented by Lavie et al. (2004), maintaining focus and reducing interference are performed by two separate mechanisms: a *perceptual selection* mechanism that reduces the perception of competing stimuli and a *cognitive selection* mechanism that inhibits the processing of stimuli that have entered processing. The perceptual mechanism is engaged when cognitive load is high, to preserve higher processing resources for the current task. The cognitive mechanism, on the other hand, is active when cognitive resources are not otherwise engaged.

Spatial attention is primarily associated with the orienting function, specifically with directing visual attention in space. Its execution also overlaps with selective attention. Like the spotlight metaphor, this type of attentional performance can be conceptualized as a region of concentrated processing that is shifts between locations. The so-called attentional window is an area of at least 2° of the visual field that can be expanded or contracted based on the level of focus (Yeshurun, 2018). Interestingly, Chandrakumar et al. (2019) conclude that spatial shifting of this window is not only dependent on alertness in general, the level of arousal seems to influence the propensity for shifting in the left and right parts of the visual field. Low alertness seems to create a bias toward rightward shifts, while high arousal promotes leftward shifting. Hopf and Mangun (2000) reported evidence for a two-stage process that performs these shifts and comprises early parietal activity and late activity in the ventral extrastriate cortex. The underlying mechanisms for how shifts of the attentional window are guided through the visual field are not sufficiently clear. Hedge et al. (2015) conclude that a priority/saliency map is constructed and held in memory by preattentive processes. This map is assumed to contain information on the locations of past stimuli and anticipated locations of new stimuli. Areas of high priority guide the shifting of the perceptual window. Hamker (2004) suggest that this may happen in two steps. First, parallel processing of the map identifies any individual regions of priority, which are then focussed. If multiple locations of high priority are found, serial processing of these locations is performed to identify the next location of focus.

Divided attention is another famous type of attention. When Albert Einstein (1879-1955, German-born physicist) stated “Any man who can drive safely while kissing a pretty girl is simply not giving the kiss the attention it deserves.” (n.d.), he was referring to the fact that resources are limited and focusing on one action reduces attention to another. This reduced attention can either be the result of selection processes that inhibit the processing of a competing task to reduce interference or due to limited resources that must be split up between tasks. Under the assumption that our resources are limited, investing them in multiple activities requires dividing them up. This can either take place over time, by serially switching between tasks, or by processing multiple pieces of information in parallel. In contrast to selective attention, in which attention is focused on one thing and changes are suppressed, divided attention requires a degree of *flexibility* to allow for the distribution of focus (Sturm, 2009). Cohen (2014) summarized that simultaneous performance (dual-task) is possible when the performed tasks are highly automated. Complex tasks and those for which behaviour was not learned are instead subject to task switching, in which focus alternates between tasks. Research by Hahn et al. (2008) indicated that during selective attention tasks and dual-tasks, the same cortical areas are activated, with dual-tasks inducing stronger activity. Similarly, Hirsch et al. (2018) found that task-switching and dual-task performance relied on shared cognitive control processes. Consequently, divided attention can be conceptualized as a form of selective attention that heavily relies on executive control, resulting in either parallel or serial processing. In either case, performing two tasks, either serially or in parallel, requires additional cognitive effort, which is mostly associated with working memory management and therefore executive control (Hirsch et al., 2018).

Task switching is accompanied by certain switching costs that result in slower or less accurate reactions. Gilbert and Shallice (2002) describe these switching costs as the result of increased demands on executive control because carryover from one task to the next generates interference. Attention must be disengaged from one task, reoriented, and engaged to the other. During these switches, information on both tasks must be maintained in working memory and kept separate to minimize carryover. In parallel processing, similar memory management is necessary to isolate the simultaneously active information and prevent interference. Findings by Chipunza and Mandeya (2005) indicate that task similarity plays a prominent role in this regard. Simultaneously performing dissimilar tasks creates more interference and thus requires more processing. The research presented in this dissertation resulted in surprising findings with respect to this assumption.

The manifestations of attention described thus far relate to or result in the allocation of attention towards certain objects or pieces of information. The resulting state of focus is part of all manifestations of attention. Consequently, differentiating *focused attention* from the remaining types can be difficult, as it is characterized by integrating multiple types of attention to process a complex situation. Although the term “concentration” is sometimes used to describe attention in general, it is mostly used to refer to a state of focused attention. As Cohen (2014) describes, the concept of focus is routinely discussed as being object-related and the act of focusing typically refers to directing visual attention (Andersen, 1990; Neo & Chua, 2006). The demands and duration of a task modulate how intense the focus must be. For example, directing visual focus toward a salient stimulus can be relatively simple, whereas performing a complex task that involves planning requires more processing and focus. Similarly, the duration for which focus must be maintained impacts which type of attention is demanded; when focus is required for a long time, sustained attention overlaps with focused attention. Maintaining this focus also depends on selection processes that inhibit interruptions. Neo and Chua (2006) describe focused attention as a state of processing in which attended stimuli are processed with priority, and novel unattended stimuli are focused on less readily. This management of focus – suppressing distractions and maintaining focus – is performed by executive control. Although focus can also be engaged in response to bottom-up signals, maintaining it at the required intensity involves effort and self-regulation, especially when the task to be performed is demanding. Cohen (2014) points out that the need for focused attention is a direct consequence of limited processing capacity. Not all stimuli can be processed equally, meaning that focusing is required.

The ability to focus is limited in its capacity as well, which is assumed to be determined by two mechanisms. Firstly, structural restrictions limit how much information can be processed at one time; these are the result of neurological limits on memory capacity and processing speed. Secondly, psychological energetic factors like self-regulation and motivation additionally modulate the level of alertness and effort that is invested. Emphasizing the role of executive control in focusing, Sturm (2009) defines focused attention as the ability to isolate a section of reality and perform an in-depth analysis. This includes attending to and processing multiple stimuli, managing interferences, retrieving complex information from memory, and integrating these aspects into response selection. We employ focused attention in situations that require complex problem solving like programming, research, or debate. This definition of focused attention relies heavily on executive control to regulate how cognitive resources are allocated, a function identified by Petersen and Posner (2012). In summary, there are two perspectives on focused attention. Cohen (2014) describes it as a state in which attentional focus is directed onto an object with a variable level of intensity, while for Sturm (2009), it is primarily characterized by high-intensity focus and substantial demands for higher processing and executive control.

Intense attentional focus can also be regarded as a separate manifestation of attention often called *executive attention.* This describes a state of increased focus in response to high demands on executive control. Multiple works have identified this construct; however, it is not commonly regarded as a separate dimension of attention. Moosbrugger et al. (2006) identified the two latent factors, perceptual and executive attention that determine attentional performance. Perceptual attention describes manifestations of attention that are associated with sensory processing, whereas executive attention relates to later stages of mental processing. A similar distinction was presented by Schweizer et al. (2005), who distinguished between the two dimensions of perceptual processing and executive attention. Schmidt-Atzert et al. (2008) extracted a similar construct they call *concentrated attention*. From their perspective, concentration lies at the intersection of attentional processing and higher cognition. They separate concentration into the components of concentrated attention and concentrated processing. Concentrated attention relates to executive control and higher processing that is part of attentional processing, while concentrated processing is not part of attention, but rather higher cognition. However, this perspective was criticised by Sturm (2008), who believed that it had an insufficient neuropsychological basis. Consequently, viewing executive attention as a manifestation of attention that is separate from focused attention is not justified. It can be better understood as a type of focused attention in which executive control demands are particularly pronounced.

A concept that is predominantly relevant to executive control is the degree of *effort* one exerts when performing a task. Varying degrees of effort are required for different tasks and Cohen (2014) describes *effortful attention* as a type of attention that requires increased executive control and conscious processing, multitasking, and even physical exertion. The amount of effort exerted depends on the individual’s motivation and ability. An unmotivated person can perform a task without mobilizing much effort and will likely underperform relative to their ability. A highly competent person can perform well while also exerting relatively little effort. The amount of effort required thus arises from the interplay of task characteristics and individual ability. Schmeichel and Baumeister (2010) define the concept of effort in attention somewhat differently. They present two perspectives: On the one hand, it describes the amount of effort required by a stimulus to catch someone’s attention (bottom-up). Novel and evolutionarily relevant stimuli can draw our attention without much effort. On the other hand, it can designate the conscious effort exerted to attend to a stimulus or task (top-down). This is the case when internal (e.g., motivational) or external forces (e.g., distractions) need to be resisted to maintain focus; mirroring the perspective by Cohen (2014). However, Schmeichel and Baumeister (2010) also describe *effortless attention* as a state in which the characteristics of the stimulus promote intense focusing without requiring much effort. This may be the case when listening to music, watching a movie, or, under the right circumstances, in a state of flow (Ullén et al., 2010).

Automaticity is a related concept that encompasses the two aspects of automatic task performance and automatic processing. The effort required by a task is modulated by the degree to which it has been learned, because performing learned behaviour places a reduced load on executive control. As previously mentioned, the effect of fatigue on task performance was found to be lower for learned tasks compared to novel tasks (Langner & Eickhoff, 2013). This mechanism also impacts dual-task performance when one of the tasks is highly learned. Driving a car while having a conversation is a classic example of this. The second aspect is the automatic processing of information as part of attention. Cohen (2014) summarizes that orienting, selection, focusing, and switching can occur automatically regardless of the current state of focus. If this automatic processing conflicts with the intended processing (e.g., the current task), it is considered interference. Such interruptions require executive resources to be resolved, either by refocusing on the previously attended information if the distraction is irrelevant, or by engaging with the new information if it is important. In the latter instance, involuntary processing can transition into voluntary attention. Controlled voluntary attention describes the scenario in which conscious control results in deliberately orienting attention.

Reviewing the theoretical landscape of attention indicates that two broad perspectives are commonly taken when describing its role in information processing. From the first, the functional perspective, attention serves the distinct purposes of alerting, orienting, and selection. The second describes a range of manifestations, which are highlighted in the multidimensional perspective. These two approaches not only describe information processing on a theoretical level but are also relevant to practical applications. The degree to which the attentional system can perform the relevant functions and produce manifestations is of particular interest for psychological assessment.

Measuring attention

Measuring attention is a typical component of the analysis of neurological functions in clinical assessments. Other fields such as developmental, occupational, and forensic psychology incorporate attentional assessment as well. Usually, the goal in these applications is to identify potential performance deficiencies (Ward, 2004). From a neuropsychological perspective, assessing attention can give insights into how diseases and disorders affect processing. Individual-level performance is relevant for assessing individuals' abilities. Over time, a range of measures and tests have been either developed or adapted to assess attention. The following section will give a brief overview of a selection of common and historically significant tests and paradigms.

Common Tests and Paradigms

Tasks that aim to measure attention are usually designed to rely on reaction time and perception rather that higher mental processing, like reasoning or long-term memory. Therefore, they are often regarded and designed as so-called speed tests. While higher cognitive abilities are not independent of attention, they are typically assessed with so-called *power tests* that are based on higher mental processing. In theory, this differentiation should allow a given performance to be measured unidimensional, and tasks should exclusively rely on either the speed or the power components. Most attention tasks thus involve simple materials and are designed to measure limits in processing speed and capacity by employing a time limit or measuring reaction times. However, as previously described, later parts of attentional processing also involve conscious and executive functioning; hence it is not always possible to clearly distinguish between pure speed and pure power tests.

As Ward (2004) points out, the *Wechsler Scales*, although not specifically designed to measure attention, have been used by clinicians to assess attentional performance. This collection of tasks was first published in 1955 and designed to measure general cognitive ability. Since then, the scales have been updated several times and have also been adapted to measure intelligence in children (Wechsler, 1955, 2008, 2014). Specifically, the Digit Symbol and Block Design tasks can be used to assess attention. Both tasks are assumed to require aspects of attention, but low performance cannot exclusively be attributed to a lack of attention (Ward, 2004). Inferring attentional performance based on the Wechsler Scales thus requires case-specific observations. Besides interpreting subscales separately, fatigue after a long testing session involving different task can also indicate difficulties in sustaining attention and alertness. Moreover, the difficulty differentiating speed from power components of tasks becomes apparent here. The Wechsler Scales were designed to measure general cognitive abilities and therefore are primarily power tasks.

Since the construction of the Wechsler Scales, a range of dedicated measures specific to neurological conditions have been developed. The *Wisconsin Card Sorting Task* (Milner, 1963; Nelson, 1976) is a popular example in which the challenge lies in recognising the rule by which cards are sorted. The rules change at some point during the trials, and the participant must recognise this change. Performance in this task is particularly sensitive to frontal lobe lesions, which cause patients to fail to recognize the new rule. Similarly, the Trail-Making Test (Reitan, 1958) is also reported to be sensitive to frontal lesions. In Form A of this classic task, participants must connect numbered circles by drawing lines between them. In the more complex B variant, letters must also be connected in alphabetic order, in a sequence alternating between numbers and letters (e.g., 1, A, 2, B, 3, C, …). The two sequences need to be maintained, the current position must be tracked, and the impulse to continue directly with the next letter or number must be inhibited; therefore, the task requires increased executive control. Other prominent examples of tasks include the Paced Auditory Serial Addition Task (Gronwall, 1977) and the Rey–Osterrieth Complex Figure Test (Osterrieth, 1944).

Another classic task that is used in attentional assessment was developed by Stroop (1935), and plays an important role in the research presented later on. This classic paradigm is usually deployed in word-reading and colour-naming conditions. The colour words “red”, “blue”, “green”, and “yellow” are presented either in print or on-screen, and participants must read the word (word-reading condition) or identify the colour in which the word is presented (colour-naming condition). The words are presented in the colours red, green, yellow, and blue. In the congruent condition, the colour the word is presented in matches its contents, while in the incongruent condition it does not. Accurately naming the colour the word is presented in – either by speaking it out loud (vocal condition) or pressing a corresponding button (manual condition) – is more demanding in the incongruent condition. The challenge of this task lies in managing the impulses generated by involuntarily reading, which must be suppressed to respond based on the colour of the text. This so-called Stroop interference induces load on executive control, and the number of correct and incorrect answers as well as the response times are used to determine an interference score that expresses the individual’s ability to manage these impulses. In general, Stroop tasks are used in a wide range of research and practical applications including neuropsychology (Canabarro et al., 2017), developmental psychology (Wright, 2017), and general/cognitive psychology; they have even been adapted to personality psychology in the form of the emotional Stroop test (Wingenfeld et al., 2006).

The tasks presented thus far were primarily conceived as measures of neurological functioning and were later adapted to assess of attention. Dedicated tests of attention and batteries of such tests were developed at a later stage. For example, the previously mentioned Concentration Endurance Test (d2) (Brickenkamp, 1962), is a task specifically designed to measure attentional performance in healthy individuals; for a review of this task see Daseking and Putz (2015). Similar tasks were eventually combined into assessment batteries like the Test of Everyday Attention (TEA) (Robertson et al., 1994), which is a collection of eight subtests that aim to measure attention based on the model by Petersen and Posner (2012).

Development of dedicated measures of attention has continued, and a wide range of tasks and batteries – which cannot be further elaborated here – are available. Schmidt-Atzert et al. (2008) reviewed a range of commercially available German scales for attention and provided an overarching perspective. Most of these measures rely on measuring reaction times in either paper-pencil or computerized form. A particularly noteworthy instrument is the Test Battery for Assessing Attentional Disorders (TAP) (Zimmermann & Fimm, 1993). It employs 12 subtests that measure attention according to the multidimensional perspective presented by Sturm (2009).

A family of tasks that are particularly relevant to the present research are continuous performance tasks (CPT). They make it possible to measure performance for a prolonged period and thus allow for the measurement of sustained attention and vigilance. Until dedicated attention tests and batteries had been developed, these types of attention were mostly assessed indirectly by observing performance and behaviour after a series of other tasks, such as the Wechsler Scales (Ward, 2004). Instead of presenting participants with self-paced items (i.e., task progress is based on the participant's performance), CPTs usually employ a forced-pace format, in which progress is automated and independent of performance. The Stoop task can be viewed as related to this kind of task, although it is usually not regarded as a CPT. The prototypical example of a CPT is the Conners Continuous Performance Task (Conners & Sitarenios, 2011). In this computerized task, a series of letters are presented for a brief duration, with a short inter-stimulus interval. Participants must push a button for every letter that appears, except for the relatively rare instances of the target "X" (ignore X condition). When the target stimulus is shown, it must be recognised and the automatic response to press the button must be inhibited. This task is regularly used in neuropsychological applications and has a tradition as a predictor of attention-deficit-hyperactivity disorder (ADHD), especially in children (Epstein et al., 2003). However, contradictory results and recommendations against using the CCPT to assess ADHD have also been published (Baggio et al., 2020; Huang-Pollock et al., 2012).

There are different forms and adaptations of the CCPT, and the test specifications can be altered to emphasize different dimensions of attention by manipulating the design, rules, and stimuli (Roebuck et al., 2016). Some examples include the CPT-Degraded Stimuli (Nuechterlein & Dawson, 1984), in which blurred (degraded) stimuli increase demands on visual perception, the immediate/delayed memory task (Dougherty et al., 2002), which increases demands on working memory and requires a number to be kept in memory for a short duration; or the Conjunctive-CPT, which employs not only visual (symbols) but also auditory stimuli (syllables) and thus incorporates two different sensory modes.

When reviewing methods of assessing attention, the complications of the concept become apparent. No task can be performed without attending to it in some way, and directing one's consciousness is part of every waking moment. The further the domain of interest moves from the specific to the general (i.e., from fields that operate close to the theoretical basis, like clinical and neuropsychology, to more applied branches of psychology), the harder it becomes to differentiate attention. This is especially evident in practical fields like occupational psychology.

Attention in the Work Context

Attention is a complex configuration of processes that manage focus and guide consciousness. It undoubtedly plays a vital in everyday life and is therefore an essential part of work and individual performance. Industrial and organizational (I/O) psychology is a field that incorporates a multitude of perspectives. Characteristic for assessment in I/O psychology are a variety of variables and factors that are organized into complex relationships. Campbell (2013) describes assessment in this domain as concerned with predicting dependent from independent variables. From this perspective, attention is considered an independent variable. Specifically, it is regarded as a cognitive ability, with reference to the classification of abilities and job task requirements presented by Fleishman (2001). This system provides a nuanced perspective on 52 human abilities. It is commonly used in occupational psychology and was also adopted into the Occupational Resource Network (O*Net). O*Net is a database of occupational information that is maintained by the US Department of Labor's Employment and Training Administration and can be accessed online (http://www.onetcenter.org). The aggregated data finds use in many research and practical applications; further details are provided in the first article (Münscher et al., 2022).

Fleischman's (2001) categorization of abilities has been used to systematically describe tasks within jobs and create requirements profiles. Attention, as defined in the previous sections, is represented in several of Fleischman's ability categories. Because this collection of human abilities was created to describe abilities rather holistically, attention is not represented in its theoretical entirety. Some abilities reference aspects directly, while others include it in combination with other actions. The abilities “selective attention”, “reaction time”, “perceptual speed”, “time-sharing”, and “response orientation” can clearly be associated with components of attention. In contrast, the abilities “rate control”, “speed of closure”, and “information gathering” are combinations of elements of attention and other aspects of work performance. Table 1 gives a summary of these abilities and the corresponding dimensions of attention.

Table 1. Overview of abilities in the Fleishman taxonomy that correspond to dimensions of attention.

Fleishman Ability	Content	Corresponding dimensions of attention
Selective attention	Concentrate on a boring task and ignore distraction.	Sustained and selective attention.
Reaction time	React to stimuli as fast as possible.	Alertness
Perceptual speed	Compare stimuli with other stimuli and information in memory.	Selective attention and alertness.
Time-sharing	Shift between multiple pieces of information.	Divided Attention.
Response orientation	Direct a response to multiple sensory inputs in the correct direction.	Selective and spatial attention.
Rate control	Continuously respond to and in anticipation of stimuli.	Alertness and sustained attention.
Speed of closure	Process incoming information to categorize and order it.	Focused and executive attention.
Information gathering	Order pieces of information according to a set of rules.	Focused and executive attention.

The way attention is represented in the Fleishman taxonomy of abilities illustrates how it is conceptualized as an individual cognitive ability in occupational psychology. The neurological basis and corresponding dimensions of attention are not of primary interest; instead, the perspective is task-oriented.

Viewing abilities and task characteristics in this way is often used to determine person-environment fit (PE-fit) (Walsh et al., 2000). PE-fit is an overarching concept that describes the congruence between an individual and the environment. Su et al. (2015) describe it as a multilevel construct that can reference congruence in regards to a group, organization, superior, or one’s job. The degree of fit can then be assessed and categorized as either supplementary (i.e., the individual and environment are similar) or complementary (i.e., the individual meets the environment’s requirements) (Muchinsky & Monahan, 1987). Attention as a cognitive ability is most relevant when analysing person-job fit (PJ-fit) with regard to complementary fit. In this application, work analysis is employed to decompose the requirements of a job or task and compare them to the individual’s characteristics, ultimately enabling inferences about dependent variables like performance or stress (Sanchez & Levine, 2013). This kind of PE-fit is often of interest in selection or placement processes, in which the goal is to find an employee or applicant well-suited for a position or vice versa. A related application is work design, in which tasks and jobs are modified or optimized.

Work analysis tools are often designed as questionnaires and have included attention in the past. The Fleishman Job Analysis Survey (F-JAS) (Caughron et al., 2012) is a commonly used tool based on the taxonomy of abilities by Fleishman (2001). Examples of similar tools include the Multiple Resources Questionnaire (MRQ) (Boles & Adair, 2001), the Short Questionnaire for Job Analysis (KFZA) (Prümper et al., 1995), and the Copenhagen Psychosocial Questionnaire (COPSOQ) (Nübling et al., 2006). A detailed overview and discussion of these and other instruments can be found in Article 2 (Münscher et al., 2021b). They all share incorporation of attention in a similar way to or based on the Fleishman taxonomy. They thus capture only parts of the concept of attention and do not allow for a comprehensive assessment of attentional demands, a shortcoming that is addressed in the work presented in Article 2. The only exception to this observation is Masoudian and Razavi (2018), who created a dedicated tool to assess vigilance demands in nurses.

Research on Attention in the Work Context

Beyond the practical application of assessing attention to determine PE-fit, attention in the work context has also been the subject of academic research. As the volume of this research is too large to be efficiently presented here, the following section will present selected notable examples to illustrate common approaches and issues.

A common perspective on attention is its role in high-demand occupations like nursing and air traffic control (Averty et al., 2004; Mohammadi et al., 2015; Santos & Brito Guirardello, 2007). In these inquiries, attention is primarily viewed as a component of MWL. The need for focused and executive attention is often seen as contributing towards workload, while distractions, interruptions, and simultaneous demands are viewed as sources of stress and causes of burnout. With regard to interruptions, Jett and George (2003) describe intrusions, breaks, distractions, and discrepancies as the four types of interruptions during work activities. These types can be associated with negative or positive effects on the person being interrupted, depending on the specific nature of the interruption. For example, a distraction during focused work can contribute to stress and decreased performance, but if relevant information is communicated during the distraction, it can also alleviate stress and workload. Similarly, a break can take the form of procrastination and be detrimental to performance, while a period of uninterrupted rest after an intense workload is necessary to prevent stress and burnout.

Presenting a general perspective on the function of attention in the work context, Gardner et al. (1989) developed a general model of focus of attention at work. They point out that during the workday, employees focus their attention on either the organization, their co-workers, the job itself, daydreaming, off-job topics, or their supervisor. They conclude that job complexity, interdependence, and participation in decision-making facilitate directing one's attention towards the job, while low job complexity and not being involved in decision-making promote a focus on off-job topics.

In addition to attempts to integrate attention into the broader concept of workload, specific dimensions of attention have also been investigated. For instance, the relation between stress and sustained attention was investigated by Hancock and Warm (1989), who formulated the Model of Stress and Sustained Attention. They describe the bell-shaped relation between attentional performance and stress along a continuum from hypo- to hyperstress. In their perspective, this association is modulated by the degree of meaningful information that is processed during task performance. Physiological and behavioural adaptability (i.e., the ability to deliver performance) is highest in an individual's comfort zone, at a moderate stress level. Unstructured or meaningless information contributes to reduced performance even when the stress level is optimal, while meaningful information can keep one in one's comfort zone despite high stress levels. They also point out that external factors like noise and temperature cause decreases in performance in the case of prolonged exposure.

A large body of work on attention in the work context addresses its relation to stress and burnout. The association is by no means one-sided. Work stress can result in burnout, which leads to increased cognitive failures and reduced performance. van der Linden et al. (2005) found that individuals with burnout symptoms were impaired in allocating attention and resorted to automatic processing. This led to higher distractibility and reduced inhibition. Reaction times were largely unaffected, but burnout participants exhibited reduced overall executive control. These findings were corroborated by Tams et al. (2015), who also found a link between stress, attentional inhibition, and interruptions.

Horrey and Wickens (2005) investigated multiple-task settings and divided attention during synthetic driving tasks. They specifically focused on hazard awareness during driving and concluded that simple driving activities (i.e., staying in one's lane) are barely affected by performing a secondary task. However, they found that reaction times and hazard responses were subject to substantial performance decreases. Ho et al. (2014) reviewed the literature on spatial attention in the context of driving a vehicle. They approached the topic from a methodological perspective and concluded that laboratory tests of spatial attention lack validity with respect to real-world settings. They criticized the theoretical approach that is often adopted in research and argue for more ecologically valid measurements.

Offering a general viewpoint, MacDonald (2003) argues in her review of the association between demands, workload, and stress that the concept of workload is often viewed too broadly. She emphasized the role of attentional demands for workload and stress and pointed out that the matter is not treated in a sufficiently differentiated manner. The result is that stressors are rarely distinguished from demands, making successful interventions impossible. Instead, she argues that the specific origins of attentional demands and their contribution to workload need to be distinguished in order to improve their management in the workplace. A similar conclusion was reached by Morgeson et al. (2016), who argued for a decompositional perspective in job analysis rather than holistic judgements.

In summary, the literature illustrates both the importance of attention in the work context and the challenges inherent in specifying the concept. Attention plays a crucial role in work-related stress and is itself influenced by stress and burnout. At the same time, it constitutes an essential part of general workload. The result is that attention is not only a normal demand, but can also be a stressor, as well as be impaired itself as a result of stress. Consequently, distinguishing the role and position of attention in the work context is difficult. The fact that it is often either integrated within the general concept of workload or a few isolated aspects are highlighted further complicates this challenge.

Research Questions and Goals

In the sections presented thus far, a range of challenges associated with attention in general and its position in the work context have been laid out. It has become apparent that attention is neither an easily defined construct, nor one that can be applied in an isolated way. These challenges of definition are also present in assessment, especially in the work context.

The present research aimed to investigate, develop, and apply novel paradigms of assessing attention in the work context. Before work on this project could begin, attention's position as a form of cognitive performance had to be determined. Consequently, the main contribution of the project is presented in Article 3, while Articles 1 and 2 represent preliminary, foundational investigations. Based on the positions presented by MacDonald (2003) and Morgeson et al. (2016), the first step in the presented research endeavour was to define attention's position in the context of work demands. This was performed in two separate research inquiries.

The first project aimed to highlight attentional performance at work from a broad point of view using aggregated job analysis data. However, while working towards this goal, an opportunity to expand the scope of the project arose. An international cooperation provided interesting insights on the demands of apprenticeship occupations, which are presented in Article 1 (Münscher et al., 2022).

The second project then focused on attentional demands from a job analysis perspective. Surprisingly, there was no existing instrument to comprehensively assess how demands on attention are configured in an occupation. A scale construction process based on contemporary theories of attention resulted in a self-report questionnaire that can be used for job analysis. The landscape of attention theories is complex, and presented challenges when constructing the scale. To resolve these difficulties, a theoretical framework of task parameters was developed, which is also presented in Article 2 (Münscher et al., 2021b).

Finally, the third project represents the core of this dissertation and incorporates insights from the prior projects. The goal was to create innovative measurement paradigms for attention that leverage computerized testing to address some of the shortcomings of existing assessments. For this project, hardware and software solutions were developed that can employ a variety of paradigms. Based on the insights gained in Project 2, a range of tasks were conceptualized and prototypes were constructed. Ultimately, one of these prototypes was further developed for deployment and tested in an empirical study, the results of which are presented in Article 3 (Münscher et al., 2021a). An implementation of this paradigm on mobile devices was also developed and tested and a comparison of how laboratory and mobile measurements relate is presented in Article 4 (Münscher, 2022).

Occupational Demands – Article 1

Münscher, J.-C., Greiff, S., Sander, N., Bliem, W., & Herzberg, P. Y. (2022). *A European Perspective on Apprenticeship Occupations and Their Psychological Demands* [manuscript submitted for publication].

General Objective and Summary

What is the position of attention in the work context? What groups of occupations exist that require attention to a certain degree, or in a unique configuration? These questions were the broad point of entry for the research presented in this dissertation. Although manifestations of attention were included in the Fleishman taxonomy, they were not represented in their theoretical entirety. The first project thus sought to approach the topic in an exploratory manner, through the analysis of occupational databases. Work on this part of the project began with the analysis of the Austrian occupational database BIC.at (IBW - Institute for Research on Qualification and Training of the Austrian Economy, 2018). The database was openly accessible and provided an entry point into the domain of occupational demands. For each occupation, a requirements profile made up of a set of demands was present. This data seemed like a good source of general information on how attentional demands are positioned within the work context. Preliminary analyses had indicated that attention was of the top three most commonly listed job demands. My original plan was to explore the structure of occupational demands and define the position of attention within it via cluster analysis. However, during the course of the project, it became apparent that this path would not yield the anticipated insights. Although BIC.at and databases like it are the product of extensive professional job analyses, the information was too general and not sufficiently connected to established theories of attention.

During this project, the German Federal Employment Agency became aware of the work and offered access to their data, that were similarly structured to that by IBW. The BERUFENET database (Bundesagentur für Arbeit, 2011) contains aggregated occupational information as well as requirements profiles for different occupations. Examining both sources of data presented an opportunity for international collaboration. After conferring with both institutions, the project continued with a different goal: To explore the structure of demands in apprenticeship occupations. Both Germany and Austria have government-regulated apprenticeship programs; these programs regulate entry to and training in apprenticeship occupations. Considerable effort is expended on coaching and guiding potential apprentices in their career choice.

Vocational guidance and coaching naturally employ theories and models from occupational psychology. The most prominent model used in this context is the RIASEC interest model (Holland, 1970, 1997). Using occupational information from the O*Net database, Prediger and Swaney (2004) developed the World of Work Map (WWM), another practically useful map-based model that describes the association between interest types and job groups.

Given that these and similar models are often based on the United States labour market, the question of their applicability to European labour markets arose. It was particularly unclear how well perspectives like the WWM would transfer to apprenticeship occupations, which are organized very differently in the US. Analyzing the German and Austrian datasets provided an opportunity to compare the configuration of demands between these two contexts, primarily through the use of co-clustering. This method of cluster analysis was used to simultaneously construct groups of occupational demands and groups of occupations, effectively producing a perspective similar to the WWM. Merging the solutions from Austria and Germany provided a joint perspective based on two similar yet independent labour markets and aggregated job descriptions from them. The resulting solution was then compared to the WWM. In summary, Article 1 did not highlight attention in the work context, but rather presented data on apprenticeship occupations in Austria and Germany in comparison to models derived from the United States labour market.

Results and Interpretation

The co-clustering of the two datasets resulted in 7 groups of demands and 21 clusters of occupations in BERUFENET, while for the BIC.at data, 5 groups of demands and 13 occupational clusters were found. The demands groups were similar between the two solutions, and overall, the groups *universal*, *personal, cognitive, practical, social, creative,* and *miscellaneous* demands were identified. Detailed information on these groups, their names and content are provided in Article 1. The universal category is especially noteworthy, as these demands are not characteristically associated with specific groups of occupations. They can be assumed to be relevant to all fields; unsurprisingly, attention is in this group, alongside related demands like flexibility, planning, and observation. The other demands groups showed more differentiation across occupational groups. The two solutions could be merged and evaluated using correspondence analysis (Greenacre, 1989). This method employs principal component analysis to display multidimensional relations within a contingency table in a two-dimensional space. The result is displayed in Figure 1 and was compared to the WWM.

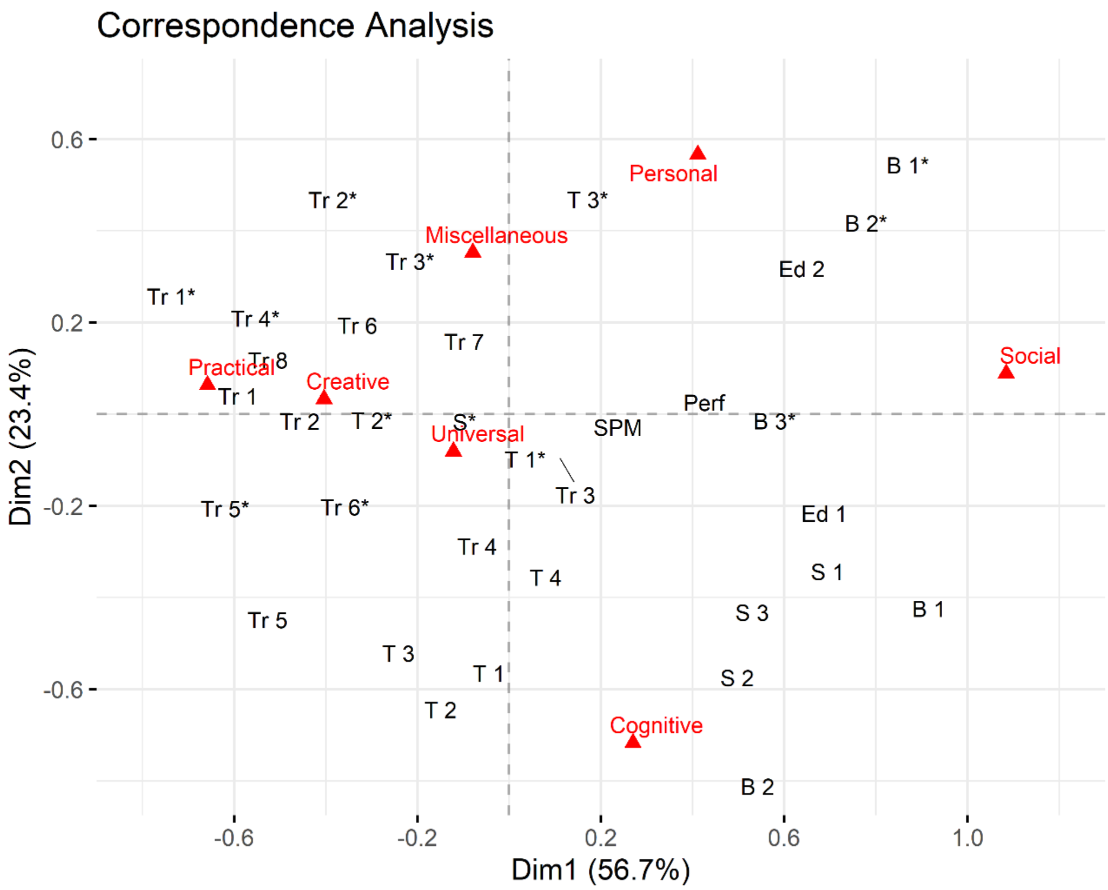

Figure 1. Correspondence analysis plot for demands groups and occupational clusters.

Note: Abbreviations: Tr: Trades, T: Technical, S: Services, B: Business, Perf: Performances. Presentation and Training, SPM: Supervision, Protection and Monitoring.
Complete names for occupational clusters can be found in Article 1; asterisks mark classes derived from the BIC.at dataset. The emergent structure seems to capture the People-Things aspect on the x-axis and the Data-Ideas aspect on the y-axis.

The structure that emerged superficially resembled the People-Things-Data-Ideas model (Prediger, 1982). Personal demands are situated opposite of cognitive demands, which matches the data-ideas axis of the PTDI model. Social and practical demands seem to form the poles of an orthogonal axis, which corresponds to the people-things axis. However, these similarities are somewhat superficial. The axis spanning practical and social demands matches the PTDI model well, whereas the cognitive-personal axis does not. Detailed comparisons in Article 1 show that the demand structure found in Germany and Austria diverges from the structure of the PTDI model. This discrepancy could lead to suboptimal recommendations in coaching or misjudgements of fit in research and practice.

The group of creative demands illustrates this possibility: In the WWM, occupations requiring creativity are situated between social and artistic interests and thus would be associated with the people and ideas aspects of the PTDI model. The results of Article 1, however, indicate that creativity in apprenticeship occupations is associated with practical demands, or the things aspect. Simply applying the WWM and RIASEC models in this context, for example when counselling an aspiring apprentice with creative interests and abilities, could result in suboptimal recommendations.

The results do provide some insights regarding attention, although this was no longer the main objective of the study. As mentioned before, attention, flexibility, planning, and observation are among the group of universal demands. Furthermore, aspects of attention were identifiable in the cognitive and practical demands groups. It can therefore be assumed that, in addition to its universal importance, attention is particularly relevant in occupations involving practical and cognitive work. Admittedly, this revelation is not novel or surprising, but it nevertheless provided a directional impulse for the overarching project.

Attentional Requirements at Work – Article 2

Münscher, J.-C., Bürger, M., & Herzberg, P. Y. (2021b). Parameters of Attention at Work (PAW36)—Construction of a Questionnaire. *Trends in Psychology.* Advance online publication. https://doi.org/10.1007/s43076-021-00086-y

General Objective and Summary

Hommel et al. (2019) argued for a synthetic view on attentional phenomena, Morgeson et al. (2016) advocated for a decomposed and theory-driven approach to job analysis, and MacDonald (2003) likewise demanded a more differentiated view on workload. Evidently, there is a need for a differentiated view of attention in the work context. As discussed previously and in Article 2, job analysis tools for the comprehensive assessment of attentional demands were not available; most measures are limited in their coverage of the phenomenon. Consequently, the theoretical framework for how attentional demands are configured in the work context was incomplete as well.

Keeping in mind the primary goal of this dissertation – designing and applying innovative measurement paradigms for attention – such a framework could be used to guide test construction. Thus, designing and conceptualizing a work analysis tool to comprehensively assess attentional demands presented an opportunity to solve two problems at once. First, by employing established theories of attention, a framework could be constructed to inform later test construction. Second, the resulting work analysis tool could be used in combination with the subsequently constructed paradigms to determine which test or set of tests from a battery should be used in practice. The steps involved in constructing such a work analysis tool and its underlying framework are described in Article 2.

Initially, the questionnaire items were to be designed based on the multidimensional perspective on attention outlined in previous sections. However, the overlap between the dimensions made it difficult to create items. Capturing the dimension of interest without confounding the measurement with ambiguous or complicated wording was a particular challenge. At this juncture, key difficulties within the broader field of attention research came to a head. Attention is a pervasive aspect of everyday life and is, as discussed previously, difficult to define. However, applications of theories, such as work analysis, require and benefit from clear definitions. The dimensions of attention undoubtedly have utility, but did not lend themselves to questionnaire construction in this project. In essence, they describe prototypes, whereas the present endeavour requires the underlying variables.

Ultimately, the decision was made to pursue a different approach. Instead of trying to measure how the dimensions of attention are in demand at work, the characteristics (parameters) that make up these demands would be measured. To this end, the theories of attention presented before were reviewed and the specific task parameters that evoke a specific type of attention were extracted. Masoudian and Razavi (2018) provided an important starting point by describing task parameters related to vigilance demands. Their framework was substantially extended and generalized to encompass demands on multiple dimensions of attention. In total, a model of 22 parameters for attention at work (PAW) organized in a semi-hierarchical structure was established; see Figure 2 for a summary. The rationale behind these parameters is discussed in Article 2.

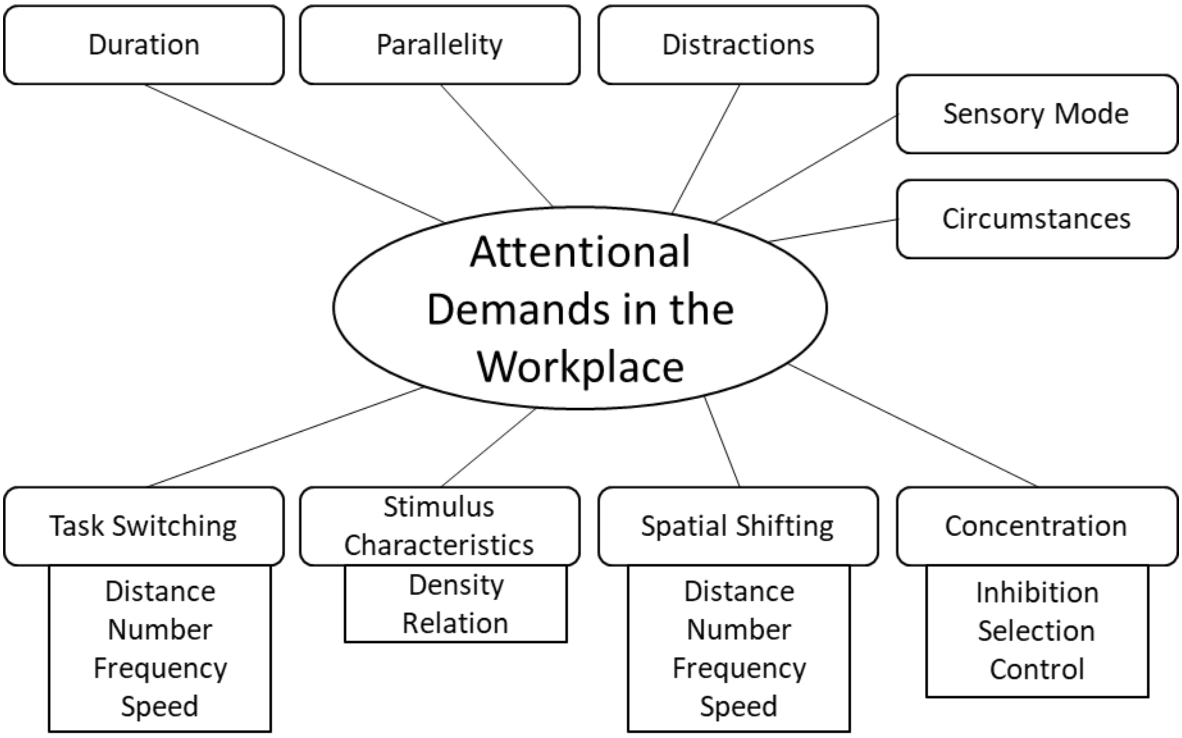

Figure 2. Parameters of Attention at Work (PAW).

Note. The components of the PAW framework model were extracted from common multidimensional perspectives on attention. The parameters were then used to construct the PAW36 questionnaire.

How these parameters are configured in a job provides information on which dimensions of attention are required during tasks. For example, high expression of the duration parameter indicates a need for sustained attention, while pronounced time pressure when switching between tasks indicates a need for selective or divided attention. Each common manifestation of attention can be described by a unique combination of parameter expressions. The associations between the parameters and dimensions of attention are presented in Article 2 and summarized in *Table 2*. The resulting framework of parameters was then used to create questionnaire items. These were subsequently optimized and evaluated in an empirical study.

This process of scale construction and validation was performed according to recommendations by Boateng et al. (2018). In the resulting questionnaire, items are grouped based on the underlying task parameter and preceded by a short explanation. Responses are given with a seven-point Likert scale; see Figure 3 for an excerpt from the paper-pencil version. The full scale as well as a scoring template were published in the supplementary material of Article 2.

PAW36

Parameters of Attention at Work

Münscher, J.-C., Bürger, M., Herzberg, P.Y. (2021) Parameters of Attention at Work (PAW36)—Construction of a Questionnaire. *Trends in Psychology.* https://doi.org/10.1007/s43076-021-00086-y
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The following questionnaire aims to identify the types of focus and attention that are important in your job. It is about a typical working day of your main occupation and the activities that you carry out.
Use the scale from **1 (does not apply)** to **7 (absolutely applies)** to express how much a statement applies to your job.
There are no right or wrong answers, please answer honestly and spontaneously.
If you are not currently working or retired, please refer to the occupation that you have mainly carried out in the past.

Assess how many things and events occur in everyday work and how many of them are particularly important to your job.
In work activities ...

1.	...many things need attention.	①--○--○--④--○--○--⑦
2.	...a lot of information has to be processed.	①--○--○--④--○--○--⑦
3.	...many hints and cues must be considered.	①--○--○--④--○--○--⑦
4.	...many things have to be followed carefully.	①--○--○--④--○--○--⑦
5.	...almost all details are important.	①--○--○--④--○--○--⑦
6.	...all information that is available, is important and must be used.	①--○--○--④--○--○--⑦
7.	...you have to be able to concentrate on many things.	①--○--○--④--○--○--⑦
8.	...many little things have to be considered.	①--○--○--④--○--○--⑦

For some activities, the head has to be moved more or less frequently. Evaluate, how often the field of view has to be shifted.
In work activities ...

9.	...the head does not have to be moved often in order to view relevant information.	①--○--○--④--○--○--⑦
10.	...relevant information is recognizable without much movement of the eyes / head.	①--○--○--④--○--○--⑦
11.	...the head has to be moved to see important information.	①--○--○--④--○--○--⑦
12.	...you have to move around to keep an eye on important things.	①--○--○--④--○--○--⑦
13.	...eyes and head have to be moved frequently to keep an eye on important things.	①--○--○--④--○--○--⑦

Figure 3. Excerpt from the paper-pencil version of the PAW36 questionnaire.

Note. In the final version, the items forming a subscale are grouped and are preceded by a short introduction. The full instrument can be found in the supplementary material of Article 2.

Results and Interpretation

The initial item pool was applied and optimized in a preselection study. The pool was further refined in the main study, comprising a sample of $N = 800$ adult German individuals. A holdout cross-validation design (Koul et al., 2018) was employed to finalize item selection and test the model fit of the finished questionnaire. Two random subsamples $n_1 = 300$, and $n_2 = 500$ were drawn and used for exploratory and confirmatory factor analysis. The scale construction process resulted in a questionnaire comprising 36 items, forming the following seven subscales:

information, view shift, concentration, task variety, parallelity, relocation, and duration. The factor structure was evaluated and resulted in good model fit (SRMR = 0.054, RMSEA = 0.051, CFI = 0.921, TLI = 0.913).

The 18 original theoretical parameters were not reflected in the model as individual subscales. However, the high-level theoretical structure was preserved within the subscales; the hierarchy of parameters was collapsed in the questionnaire, resulting in a subscale for each of the categories task switching, stimulus, spatial shifting, and control. Spatial shifting was unique in this regard, as its hierarchy of four parameters resulted in two subscales. The association between theoretical task parameters, dimensions of attention and PAW36 subscales are summarized in Table 2.

In addition to these indications of factorial validity, construct validity was assessed by correlating the PAW36 with commonly used work analysis questionnaires that incorporate attention in some capacity. Overall, expected levels of convergence between the PAW36 and the respective subscales of these instruments was observed, indicating construct validity. Internal consistency was very good for all subscales. In addition, measurement invariance across groups based on age, gender, and occupational field was assessed and confirmed. All values and a detailed account of the evaluation of the quality of the PAW36 can be found in Article 2.

Table 2. Overview of the association between task parameters in the PAW framework, the dimensions of attention and the final subscales of the PAW36 questionnaire.

	Dimensions of Attention[a]							PAW36
Parameters	SA	V	SpA	SelA	FA	DA	EA	Subscales
Task Switching								
Distance				+		+		
(Number)				+		+		Task Variety
Frequency				+		+		
Speed				+		+		
Stimulus								
Density	+	-		+		+		Information
Relation	+	-		+				
Spatial-Shifting								
Distance			+					Relocation
(Number)			+					+
Frequency			+					View Shift
Speed			+					
Control								
Inhibition					+		+	
Selection				+	+		+	Control
Control				+	+		+	
Duration	+	+						Duration
Parallelity				+	+	+		Parallelity
Distraction					+	+		
(Sensory mode)						+		
Circumstances								

Note.
[a] Abbreviated types of attention: (SA) Sustained Attention, (V) Vigilance, (SpA) Spatial Attention, (SelA) Selective Attention, (FA) Focused Attention, (DA) Divided Attention, (EA) Executive Attention.
Elements in brackets were omitted in initial item construction.

Applying the PAW36 in a job analysis results in a differentiated profile of attentional job characteristics. Figure 4 shows four profiles from the sample: a nurse, a salesperson, a translator, and an individual working in manufacturing. Characteristic differences between the four can be identified and interpreted. The salesperson reported drastically lower demands on the information dimension compared to the others. Parallelity was reported to be less pronounced for the salesperson and the translator. The nurse indicated strong demands on parallelity, relatively high task variety, and duration, a pattern that likely represents an occupation with high demands and stress levels. In practical applications, such differentiated profiles can be useful to not only describe a job but also determine an individual's perception of a job. When interpreting individual results, age, personality, and work experience should be considered.

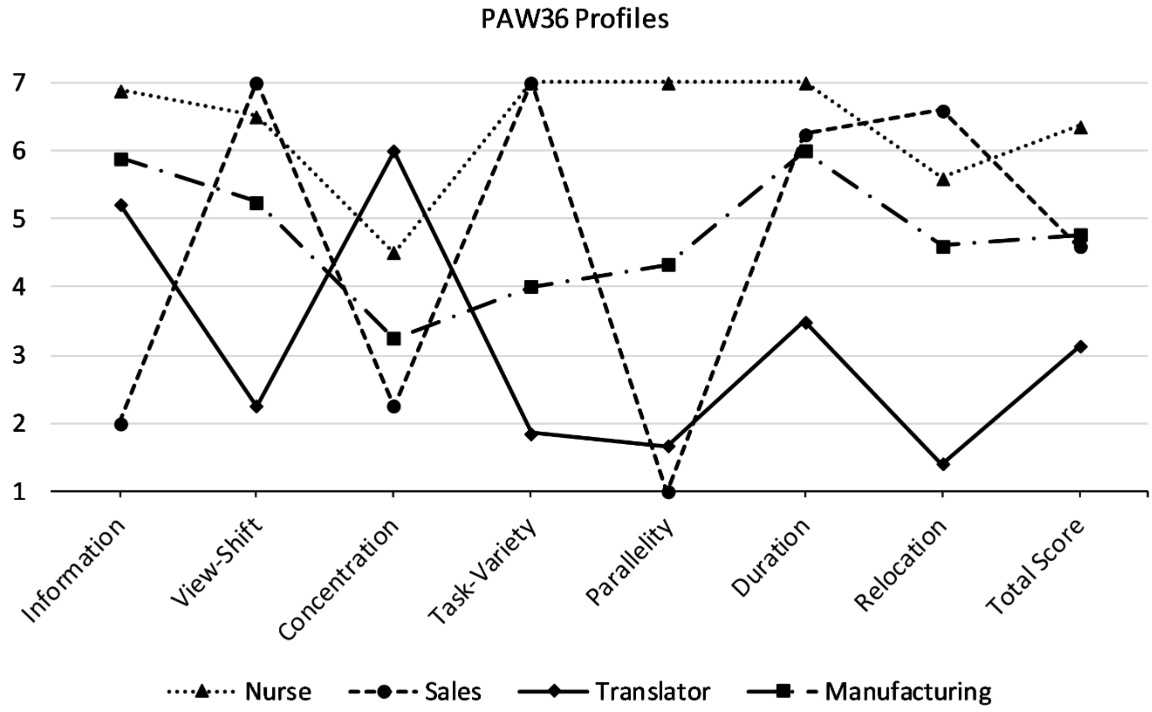

Figure 4. Illustrative results from the PAW36 questionnaire for four individuals.

Note. These four examples were manually selected for illustrative purposes. Interpreting these profiles provides detailed information on characteristic demands and patterns of demands. The total score is reported only for illustration. A higher-order model was tested and resulted in reduced model fit, indicating that interpreting total scores was not appropriate.

Overall, the development of the PAW36, reported in Article 2, was successful. It resulted not only in a capable and novel work analysis tool but also an underlying framework of task parameters, which provides a decomposed perspective on attention in the workplace, answering the calls for such a perspective voiced in the literature (Hommel et al., 2019; MacDonald, 2003; Morgeson et al., 2016).

Development and Testing of Novel Measurement Paradigms

Articles 3 and 4 addressed the main goal of this dissertation, creating and testing novel paradigms for measuring attention. A range of paradigms were conceptualized, some of which were further developed into testable prototypes, and one of which was advanced further and applied in a laboratory study. In the following sections, I will outline the paradigms that were developed before highlighting the results of Articles 3 and 4.

The analysis of job demands in Article 1 reinforced the general importance of attention in the work context, particularly in occupations with practical and cognitive demands. Article 2 provided a framework of task parameters that determine attentional demands in this context. Both of these insights greatly influenced the subsequent process of test construction, which now aimed at translating the task parameters into a standardized test to assess attention on a detailed, individual level; not just attention as a monolithic ability, or limited to one or a few manifestations, but in a dynamic and specific fashion. To this end, the paradigms presented in the following sections were designed to incorporate the parameters of the PAW framework. Furthermore, the goal was to integrate them in a dynamic way, allowing the assessment to be tailored to the application. This would effectively enable the assessment to recreate the configuration of demands found in an occupation.

Thus, rather than simply measuring attention holistically, the assessment was designed to be tuned to create standardized demands based on the desired task parameters. Looking at the profiles in Figure 4, for example, the demand characteristics reported by the nurse are drastically different from those of the translator. Both occupations require attention, but using the same assessment measures to determine PJ-fit in both cases would ignore these differences. For the translator, demands are characterized by relatively high amounts of information processing and concentration, while the nurse must perform various tasks, switch between them, and do so for prolonged periods. Ideally, the newly developed assessment paradigms would be able to specifically manipulate these parameters to reflect the occupation in question. This could be achieved by either selecting a different test within the assessment or changing the test parameters to reflect the demands.

Target Characteristics of Paradigms

One of the core goals during test design was to create the paradigms in a way that allows for individual parameters to be changed. A set of target characteristics that new paradigms should possess in order to ensure this adaptability were identified. These were based on the

PAW parameters and comprised variable amounts of stimuli, spatial flexibility, complexity of content, dynamic switching between tasks, and inclusion of dual-task paradigms.

- The number of stimuli and the ratio of relevant to irrelevant stimuli should be variable. The amount of information to process is related to selective attention and could be regulated via the number and type of stimuli present at one time. A high ratio of irrelevant to relevant stimuli would offer the opportunity to configure the task to measure vigilance over the course of a longer testing period.
- To operationalize the spatial orientation of attention and integrate the corresponding parameter spatial shifting, the location of the task material should be variable. In a computerized task, this could be realized by relocating the relevant stimuli on the screen or switching them to a different screen. Furthermore, including practical material that must be interacted with outside the computer could force test-takers to disengage their attention from the screen. The effects of such interferences on other tasks could then be measured. For example, an ongoing task could be interrupted by instructions to look up information in external material, like a book. The time needed to disengage from the current task to perform this action and performance progress after reengagement would then indicate the costs of spatial reorientation. Turning to the sub-parameters of spatial shift, the frequency, number, distance, and time constraints could also be varied.
- Executive attention and the corresponding parameter of control could be operationalized through variable demands on working memory. Here, the previously discussed distinction between speed and power tests is relevant. Demands on executive control could be realised by including sets of rules. These rules could be varied in complexity, as could the number of rules to be followed at one time.
- Rather than presenting tasks in a strict sequence, the paradigms should allow for changing tasks quickly and dynamically. Just as with the changing locations of stimuli, the performance impacts of switching tasks can be measured by modifying the switching frequency, time constraints (speed), similarity (distance), and variability (number). A possible implementation could be to introduce a range of tasks and then have test-takers abruptly switch between them. Comparing baseline performance to that after a switch could yield information on individuals' ability to manage switching costs.
- To integrate the aspect of parallelity, it should be possible to easily create dual-task configurations. This could either be achieved by creating tasks that integrate multiple subtasks into a single activity, or by presenting two tasks at once. Again, baseline

performance could be measured and compared to performance under dual-task conditions.

- The stimulus material should include practical or real-world elements. This improves ecological validity and mirrors the importance of attention for occupations with practical demands. Such elements could include realistic stimulus material like videos. Additionally, materials outside of the computer could be included, like books for lookup tasks or items that need to be interacted with. Furthermore, the mode of interacting with the tasks should go beyond simple keyboard and mouse interactions. Analog input methods like sliders, knobs, and touchscreens could be used.
- It became apparent that within the planned scope of assessment, implementing the relocation aspect from the PAW would not be feasible. This aspect describes an individual's physical relocation while working on a task. The task must be disengaged with, held in memory for a while, and then reengaged with at the destination. While such a process can be implemented in an academic study, it is not viable in an assessment session.

Computerized Implementation

By implementing these characteristics into a range of measurement paradigms, it becomes possible to manipulate the relevant task parameters in a controlled manner. Efficiently incorporating these alternative specifications and keeping testing dynamic to the described degree is really only possible with computerized paradigms. Computerized tests ensure high temporal precision while enabling the complex configurations of materials, response methods, and sequences outlined above.

Computerized testing also creates opportunities for adaptive testing (computerized adaptive testing, CAT) (Masoner & ElBassiouny, 2020; Weiss, 1982). This assessment method adapts the difficulty of the task to a given individual's ability. Besides being a novelty in the assessment of attention, adaptive testing is associated with increased reliability due to the reduced number of items that must be presented to each test-taker. Alternatively, these improvements can be leveraged to reduce test duration. In the context of attention, adaptive testing presents a novel possibility. Just as in the experiments in psychophysics conducted to identify the sensory threshold for a stimulus, adaptive testing could be used to measure the individual threshold for information processing with respect to task parameters. For example, adapting the number of stimuli or changing the ratio of relevant to irrelevant stimuli could be used to identify an individual's threshold for optimal performance. Here, another advantage of computerized testing becomes apparent. Carrying out such adaptive measurements over time and continuously recording performance makes it possible to analyse developments in performance over time and in response to events. For example, a task could be performed adaptively until a stable estimation of performance is achieved, at which point the stimulus material could change its location, forcing a reorientation of attention. The performance reduction following this switch would then indicate the individual's ability to spatially reorient their attention. The time required to return to the original performance level would likely indicate the individual's ability to switch quickly.

Another example application could be to perform a task for a long time and evaluate developments in performance as an indicator of sustained attention or vigilance, depending on the stimuli. A battery of controllable and adaptive tasks that correspond to the PAW parameters would enable a differentiated analysis of attentional performance. Within the current dissertation, only one novel paradigm could be developed and evaluated to a sufficient degree. Constructing an entire test battery of adaptive and fully parametrised tasks exceeded the scope of this dissertation but is nevertheless desirable.

Software and Hardware Environment

In order to implement the described specifications, custom hardware and software were developed. After some proof-of-concept work and initial prototyping, the decision was made to create a tailor-made software solution. Although software for psychological measurement like E-Prime® could have been used to develop initial prototypes, the limitations of this software likely would have caused issues in later stages of development. Based on the target characteristics outlined above, it became clear that real-time interactivity and continuous processing were required. Additionally, the ability to dynamically move elements between screens and incorporate real-time audio and video was a requirement. Software designed for psychological experiments usually does not provide all of these functions.

For the present dissertation project, custom software was designed to facilitate implementation of the required features. The software environment "Psychological Objective Reaction and Testing Environment" (PORT) was constructed. It is programmed in Python3 and uses portions of the PsychoPy (Peirce et al., 2019) library to provide the desired functionality. Substantial effort was put into developing this software to ensure accurate timekeeping, recording of responses, and fluent real-time presentation. In short, the software allows for dynamic presentation of stimuli on multiple screens and includes real-time video as well as a broad range of standard stimuli (e.g., shapes, text, images, sounds). All of these stimuli are displayed and updated in real-time, allowing for a highly dynamic and responsive presentation. Instead of running through static, sequential steps of stimulus presentation and response recording – as is typical for experiment software – PORT uses a real-time loop incorporating both stimulus display and response recording. On a modern PC running the Windows® operating system and a dedicated graphics card, experiments can run with refresh rates beyond 300hz; on less powerful machines like the laptops used for the laboratory study in Article 3, a rate of 30hz was achieved. A 30hz refresh rate means that the content on the screen can be dynamically updated 30 times a second. Therefore, the display of moving objects is perceived to be smooth, immediate, and continuous when changing in size, colour, or position. Touchscreen inputs, responses collected via a response box, and keyboard inputs are recorded with millisecond accuracy, irrespective of the refresh rate. Analog input devices like sliders and knobs are continuously monitored. This results in a very high temporal resolution for the recorded analogue inputs. At each iteration of the cycle, complete information on the current test and the inputs are recorded and saved.

A custom response box was developed to accompany the software. It was designed to provide the necessary inputs and functionality for the testing paradigms to be implemented in the desired way. A low-latency USB controller was used to connect the inputs to the host PC. Figures 5 and 6 display the development stages for this input device. After an initial proof of concept, a prototype was constructed and tested in use. The final iteration was then developed and constructed in collaboration with Helmut Schmidt University's Central Workshop and their product design and CAD specialists.

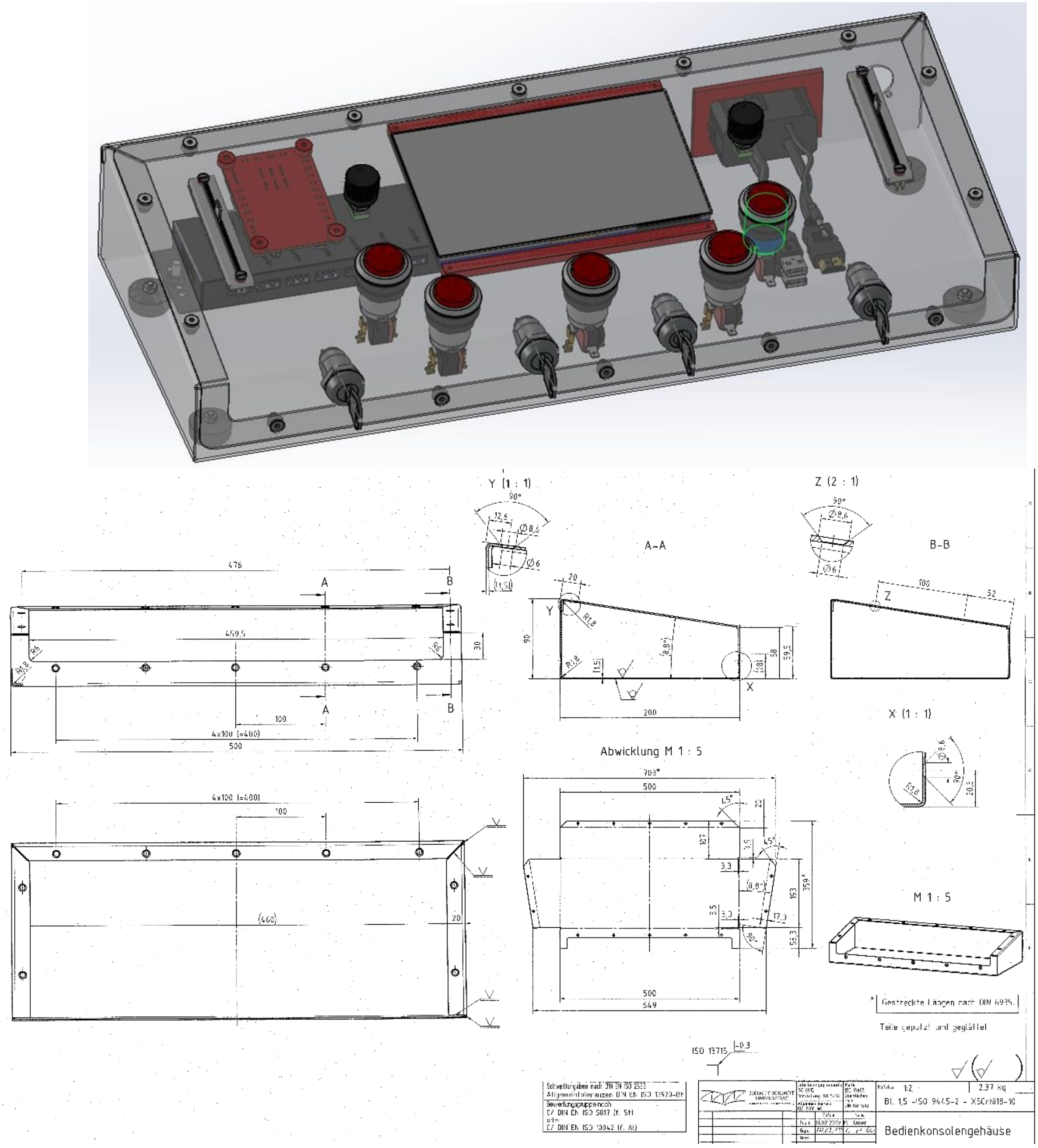

Figure 5. The design stages conducted in collaboration with Helmut Schmidt University's Central Workshop.

Note. Top: The final response box and its components were first designed and modelled using CAD software. Bottom: The design was then converted into blueprints, which the Central Workshop used to manufacture five boxes.

The response box features five brightly lit response buttons in red, green, blue, white, and yellow. They were ergonomically positioned on the device so that two hands can be used to comfortably trigger the two buttons on the left and right sides. Above the buttons, a seven-inch touchscreen with a resolution of 1024 by 600 pixels was mounted. On both the left and right sides of the screen, a twisting knob with 270 degrees of rotation and an input slider were placed. The front of the casing holds four momentary key switches.

Figure 6. Different stages of hardware development for the response box.

Top left: An initial prototype constructed from simple components was used to ensure basic functioning and test the integration with the software solution at an early stage. Top right: A more advanced prototype was used in initial field testing to gather first insights and data. Bottom centre: In the final stage, the response box was solidly constructed based on the blueprints displayed in Figure 5 and wired to be used in the laboratory study.

The flexible design of the PORT software and the response box also allows for the implementation of existing paradigms and other methods. Simple reaction time tasks are easy to deploy, and the Stroop task (Stroop, 1935) and the Conners Continuous Performance Test (Conners & Sitarenios, 2011) were implemented in the study reported on in Article 3. In addition to providing an environment for performance measurement, this setup also enables questionnaire data to be collected. The questions are displayed on the main screen and response categories are presented on the secondary touchscreen in front of the participant. The touchscreen can also be used for a visual analogue scale on which respondents draw using their fingers.

Paradigms

The following section will outline the paradigms that were developed based on the set of desired characteristics described before. To save time and concentrate initial efforts on the most promising aspects, not all paradigms were advanced into functional prototypes. Specifically, two paradigms involving practical interactions were conceptualized but not developed further.

- For the key turning task, instructions would appear on the screen prompting the use of a colour-coded key from the keychain. The keychain would have to be handled to find the correct key; the key would then have to be inserted and turned to complete this task.
- In the book lookup task, verbal or written instructions would require the participant to look up some information – e.g., a certain number – in a booklet next to the response box. After finding the desired entry, a response would be given, for instance with a number pad that is displayed on the touchscreen.

Both tasks would serve to reorient attention to tangible materials and potentially interfere with an ongoing task. However, these tasks were not developed further, as they would have primarily served as distractions and interruptions rather than contributing measurements themselves. In the context of an assessment battery, they would likely serve as important modifiers, but their contribution to the current endeavour was not sufficient to warrant further development. Five other paradigms were developed beyond the concept stage and tested on a small sample of participants for prototyping.

Map Task

In the map task, a map must be observed and responses given as aeroplanes move across it. Each plane is labelled with its origin and destination, and zones are defined with coloured indicators. The participant is tasked with pressing the coloured button corresponding to the zone colour when a target plane crosses the boundaries of that zone. A set of rules defining the target conditions for reactions are displayed and participants are instructed to respond accordingly. In the prototype displayed in Figure 7, the displayed map is based on a full-motion video of real flight movements that have been sped up. In the prototype, the playback speed of the video could be increased to increase stimulus density. The ratio of relevant to irrelevant stimuli can be modified by changing the number of zones and corresponding rules. The rules also add executive control demands to the task because the rules, zones, and abbreviations of origins and destinations need to be kept in memory.

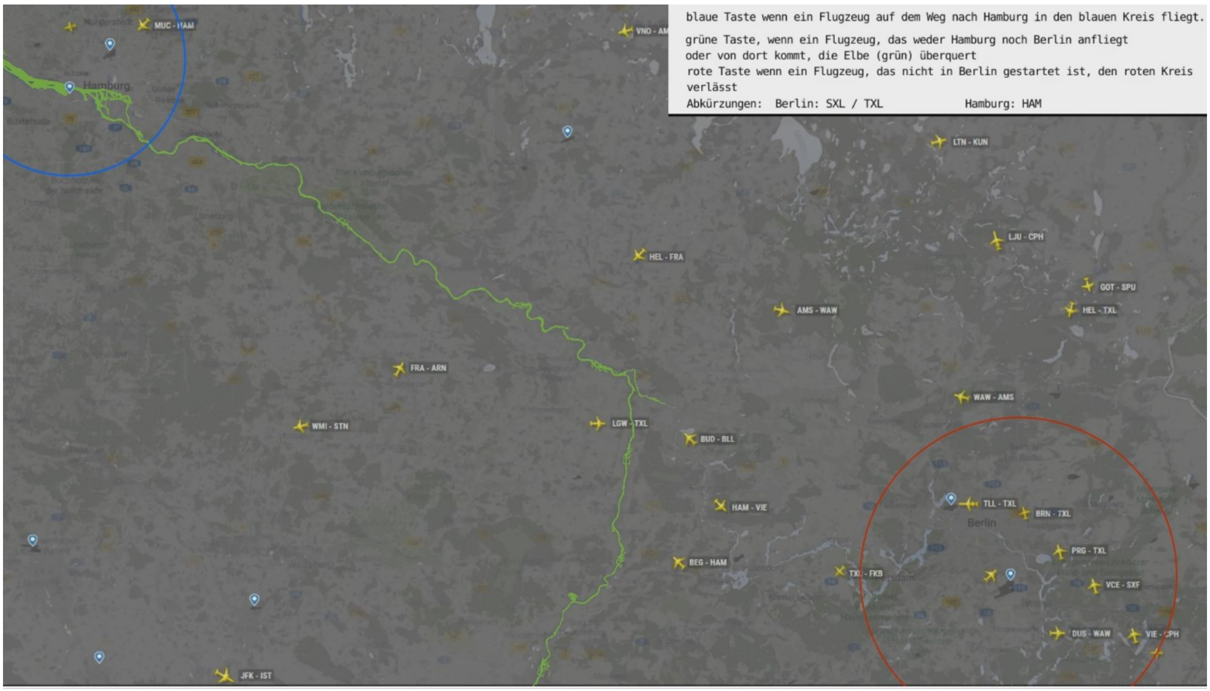

Figure 7. Example material from the maps task.

Note. Each yellow plane moves slowly across the screen and has its origin and destination displayed next to it. The blue and red circles, as well as the green river, are target zones that the respondent must monitor. When a target plane crosses the boundaries of these zones, the button with the corresponding colour must be pressed.

An advanced implementation for use in a study or assessment battery would be a programmed solution that generates plane stimuli based on controllable parameters, rather than video recordings. In such a solution, variable numbers of target and distractor planes could be generated and modified adaptively. Despite its promise, this paradigm was not developed beyond the prototype stage. The similarity to the Map Mission task from the TEA battery was too substantial. Furthermore, while surely informative, the number of simultaneously relevant parameters in this task was deemed too large to be efficiently assessed in the scope of this dissertation.

Dots Task

While the map task uses material from realistic scenarios, the dots task requires a similar type of performance but uses abstract material. The screen is filled with yellow dots that move unpredictably. If two dots collide, one or both change colour; the respondent is instructed to press a button when only one dot changes colour (target collision). No response should be given if both change colour (distractor collision). Figure 8 shows an example for an instant shortly after four distractor collisions. The dots that were part of the target collision disappear shortly after colliding, and correct responses are those that happen within this timeframe.

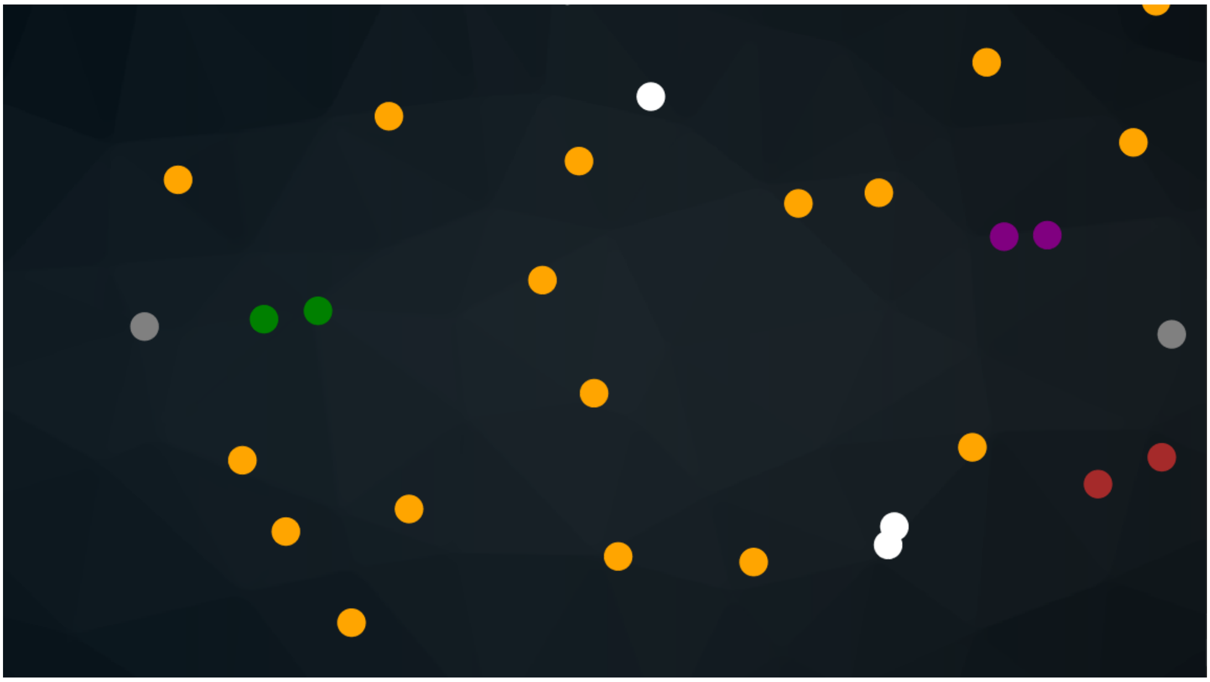

Figure 8. Example material from the dots task.

Note. The yellow dots randomly move across the screen. When two dots collide, a target (one dot changes colour) or distractor (both dots change colour) collision can occur. The number and speed of the dots can be modified as an operationalization of stimulus density. The ratio of target to distractor collisions operationalizes the stimulus relation parameter.

The rules for this task are much simpler compared to the map task. Thus, demands on executive control via working memory are reduced. However, reacting to target collisions only incorporates a go/no-go paradigm, creating a demand for executive control through inhibition. The number of dots, their speed of motion, the frequency of collisions, and the ratio of target to distractor collisions can be modified adaptively. Thus, the PAW parameters of stimulus density and relation are controllable.

Highway Task

The highway task was among the furthest developed paradigms in this research. Using real-world full-motion video of cars on a motorway was intended to increase the ecological validity. At its core, the task is designed as a simple reaction-based paradigm. The video of two multilane roadways is played on the screen. One roadway is approaching and one is departing from the participants' point of view. Two target zones are defined through coloured overlays; see Figure 9. The participant is tasked with pressing one of two response buttons when a car enters a target zone. Again, a set of rules must be followed and several rule variations were implemented. In the simplest form, a response is required for every car. A more complex setup would include conditions for the car colour and direction of travel; this could result in different rules for each side of the motorway.

Figure 9. Example material from the highway task.

Note. In this configuration, both roadways are used and the respondent must press the response buttons when a target vehicle enters the target zones (blue). Other configurations with vehicles on only one side of the roadway or mirrored displays were also developed and tested.

Due to the task design and the video stimulus, a range of interesting variations that highlight different parameters of demands are possible. The simplest variation is to mirror the image vertically to compensate for lateral differences. Because traffic is approaching on one roadway and departing on the other, the required reaction times differ between the two. In Figure 9, there is much less preparation time for responses on the right side of the roadway, while cars on the left side can be anticipated; the two subtasks therefore require different approaches to solve them. Effectively performing this task also requires a degree of planning and therefore executive control. However, this requirement can be removed by manipulating the video such that traffic is visible on only one side of the roadway. Accordingly, the approaching and departing traffic can be presented separately or in combination. The latter variant is also an example of an inherent dual-task paradigm. Another exciting possibility for this task was the option to dynamically change the playback speed of the video. Faster playback would increase the frequency of stimuli and could be controlled by an adaptation algorithm.

Railway Task

Like the highway task, the railway task makes use of real stimulus material, albeit with a simplified construction. The video shows the perspective of a railroad car on a journey. The participant is tasked with reacting to signs that are placed next to the tacks. Five symbols are presented at the top of the screen and the corresponding button must be pressed when a sign is visible. Figure 10 shows this configuration with a sign currently in view (marked by an arrow).

Figure 10. Example material from the railway task.

This paradigm does not strongly rely on rules and conditions for responses. It was designed to be executed with a long task duration. The task thus demands vigilance and sustained attention. Controlling the playback speed also allows for some alteration of the density of stimuli; adaptive adjustment does not seem beneficial in this context. The type of task and material lend themselves to inclusion in dual-task paradigms. Other reaction-based tasks or more complex paradigms could be deployed at the same time.

The Continuous Matching Task – Article 3

Münscher, J.-C., Bürger, M., & Herzberg, P. Y. (2021a). The Continuous Matching Task (CMT) - real-time procedural stimulus generation for adaptive testing of attention. *Applied Neuropsychology. Adult*, 1–14. https://doi.org/10.1080/23279095.2021.1969399

Most of the paradigms presented thus far were tested and developed into usable prototypes. They showed promise, particularly the highway task, but were ultimately not deployed or explored further. Detailed analyses and applications of multiple paradigms were not feasible within the scope of this dissertation. A single paradigm had to be selected, resulting in the deployment of the Continuous Matching Task (CMT). Thus, the following analysis is the central contribution of this dissertation.

General Objective and Summary

The CMT is a very simple paradigm that simultaneously showed the most promise with respect to the goals of this dissertation. The task involves a continuously moving target stimulus and an input indicator, which is controlled by the respondent using an analogue slider. The slider must be moved so that the motion of the input indicator matches the movement of the target indicator. Figure 11 illustrates the two indicators and the implementation of the CMT in combination with the response box.

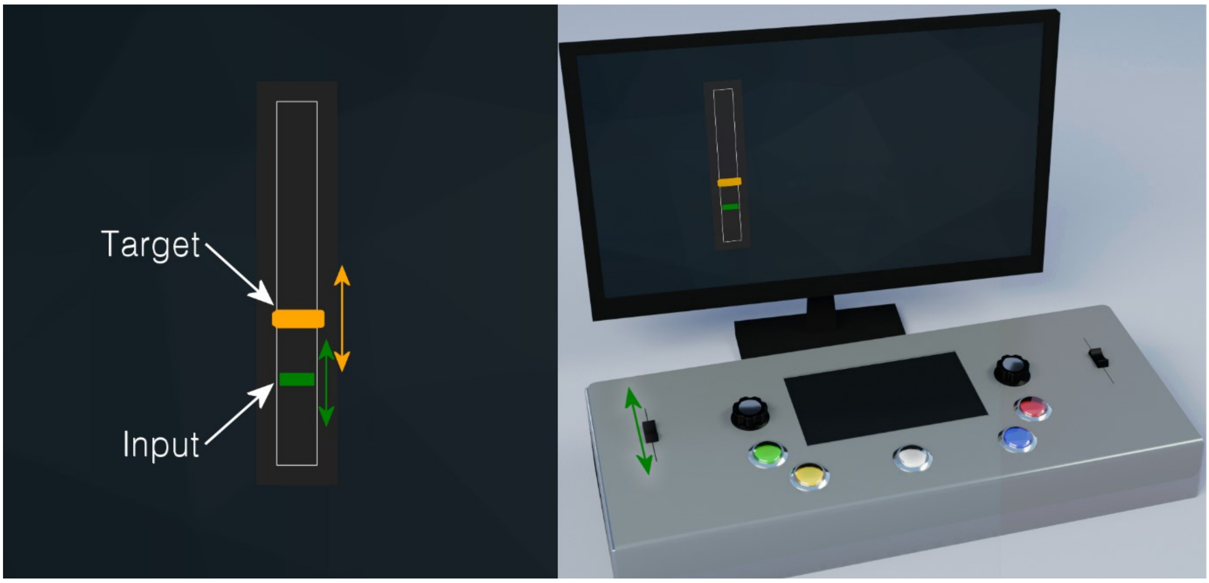

Figure 11. Example content from the CMT, and an overview of the testing apparatus.

Note. Left: The CMT stimulus. The orange bar (target indicator) moves up and down slowly in the white frame. The green indicator (input) is controlled by the respondent by moving the analogue slider. Right: An artistic rendering of the response box and the CMT. The participant must use their left hand to manipulate the left analogue slider (green arrow) to move the green indicator on the left side of the screen. In a dual-task application, the right slider would also be used to respond to a second target on the right side of the screen.

Initially, the task was designed to utilize the rotating knobs as inputs and the stimulus material consisted of a circular gauge, similar to that of a car's speedometer. The target and input indicators would move in a circular fashion and respondents were instructed to rotate the knob in order to match the input to the target. However, feedback from the respondents who tried this prototype indicated that the twisting motion required substantial finger dexterity and was even reported to be physically exhausting. Furthermore, this input method seemed to require an increased amount of spatial awareness, as the indicators on the screen changed their direction of motion when moving from one side of the circular trajectory to the other. Switching to linear motion and using the input sliders instead resolved these issues entirely, while leaving the task itself unchanged.

Over the testing period, the target indicator moves up and down continually, meaning that the input slider must also be moved constantly. The motion of the target stimulus is generated algorithmically at the time of testing. A random walk algorithm continuously and smoothly changes the position of the target. Compared to pre-recorded motions, this algorithmic implementation enables not only an arbitrary test length without repeating stimuli, but also real-time difficulty adjustments. The difficulty is controlled by a central parameter b that modifies the speed of motion and frequency of direction changes. Both of these aspects need to be adjusted in combination and have a range in which they generate informative behaviour. Movements below the sensible range are too slow to produce challenging motions of the target indicator, while too fast motions could exceed the respondent's motor abilities. Similarly, infrequent direction changes would not generate informative material, while too frequent changes would result in a flickering motion that could not be followed. Thus, the algorithm was tuned to produce reasonable output in the range $b = [0; 1]$ with an approximately medium level of challenge at $b = 0.5$. The paradigm, its characteristics, and details on the stimulus generation algorithm are described in Article 3. Noteworthy aspects are the continuous nature of the stimulus and the possibilities for adaptive testing.

Previous research, for example by Frank and Macnamara (2021), indicated that tasks utilizing continuous stimuli are more demanding than those using discrete items. As previously pointed out, attention is a continuous process, and the design of the CMT reflects this characteristic. Consequently, a testing session consists of one uninterrupted performance rather than a sequence of distinct items. Compared to classically constructed tests, this provides a moment-to-moment record of performance over a period of time.

Figure 12 illustrates this with data recorded over 30 seconds of testing. The detailed recording of all stimulus and response information allows for a complete record of performance. In the example, adaptive testing was carried out, and the difficulty was continuously adjusted upward.

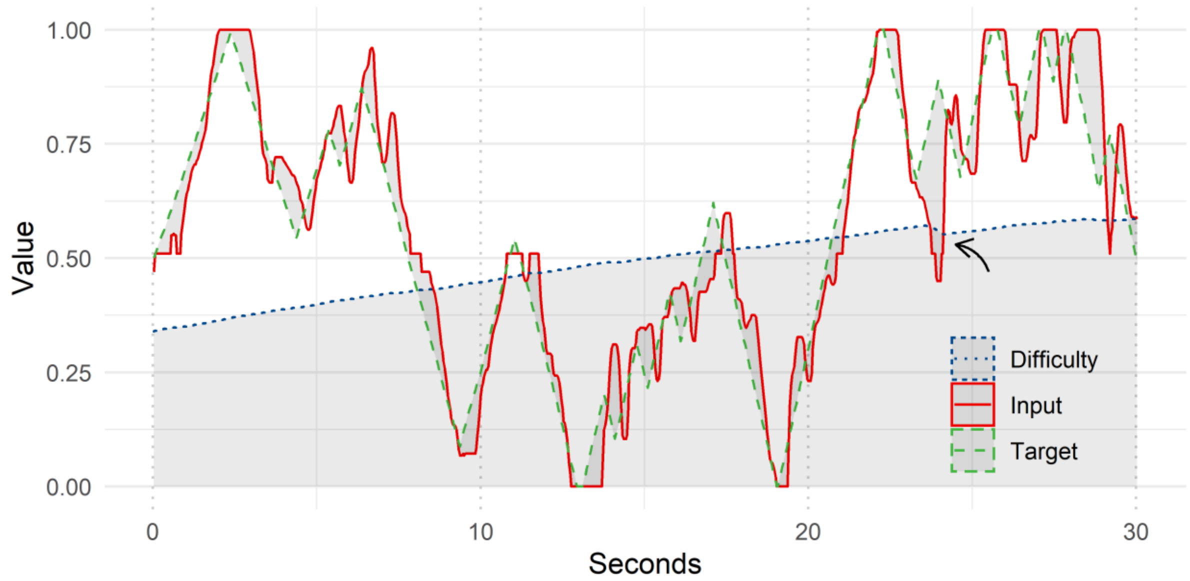

Figure 12. A plot of recorded data from 30 seconds of adaptive CMT testing.

Note. At the marked location, the participant incorrectly overshot the motion, which resulted in an immediate reduction in difficulty.

Due to its very easy design, the task requires almost no executive control. It was primarily designed to test sustained attention and be able to dynamically modify the demands placed on the respondent. It was applied in a laboratory study with $N = 122$ participants. The goal of this study was initial application and evaluation of the task. To this end, two common attention tasks (i.e., CCPT and the Stroop task) were administered alongside it. Additionally, MWL throughout the testing session was measured using self-reports and physiological measurements. The NASA Load Index (TLX) questionnaire (Hart, 2006) was administered after most tasks, while heart rate variability was measured via ECG measurements throughout the entire testing session (Kim et al., 2018; Shaffer & Ginsberg, 2017). Furthermore, the CMT was applied in various conditions, in a single-task application using both hands separately, a dual-task application using both hands simultaneously, and in a task-mixing configuration in which the CMT and CCPT were performed at the same time. In the dual-task application, the CMT was performed independently with each hand and adapted independently, resulting in equally independent performance estimates for both hands. Based on the previously presented results and concepts regarding dual-task performance and task mixing, the expectations were that single tasks are less demanding than dual-tasks, resulting performance to be decreased in the latter, especially when different tasks are performed with each hand. To further assess validity in regards to attention in everyday contexts, the Conners Adult ADHD scale (Christiansen et al., 2013) was also deployed in this study.

In this first full application of the CMT, possibilities for adaptive testing were also evaluated. In line with the benefits usually associated with adaptive testing, the expectation was that it would yield higher reliability and the possibility for reduced test durations. However, due to the nature of the CMT as a test of sustained attention, the latter aspect was not expected to be relevant. Further information on the study and procedures is provided in Article 3; all relevant Python code and explanations are published in the article's supplementary material.

Results and Interpretation

The results of the laboratory study revealed some insights into the CMT and the other performance tasks. Neither CCPT nor Stroop task performance was meaningfully associated with ADHD symptoms reported in the CAARS questionnaire. This observation mirrors previous findings in this area of research. Although the CCPT is regularly used in ADHD assessment (Epstein et al., 2003), other researchers caution against its use in this context (Huang-Pollock et al., 2012). The lack of association observed in this study supports the latter notion.

However, CMT performance showed some association with ADHD symptoms, especially for adaptive single tasks, and no associations with Stroop task or CCPT performance. As the Stroop task is assumed to be a selection task, the lack of convergence was in line with the expectations, whereas convergence with CCPT performance was expected. Interestingly, while no convergence between Stroop, CCPT and CMT was observed, an association between CMT performance and reaction times in the other tasks was present. These findings indicate that the CMT is likely not a task of sustained attention, but primarily a reaction task and thus a task of sustained alertness. This suspicion was corroborated by the results of the analysis of MWL across the trials. Figure 13 displays the progression of MWL as indicated by TLX scores and HRV measurements across the trials in the study. HRV was determined through ECG measurements, for which the correlation dimension D2 was calculated in each trial; D2 is an indicator of MWL and lower when MWL is higher (Delliaux et al., 2019). Self-reports and D2 measurements both indicate a higher mental workload in the CMT trials compared to the other tasks, which is in line with previous research and corresponding expectations (Frank & Macnamara, 2021).

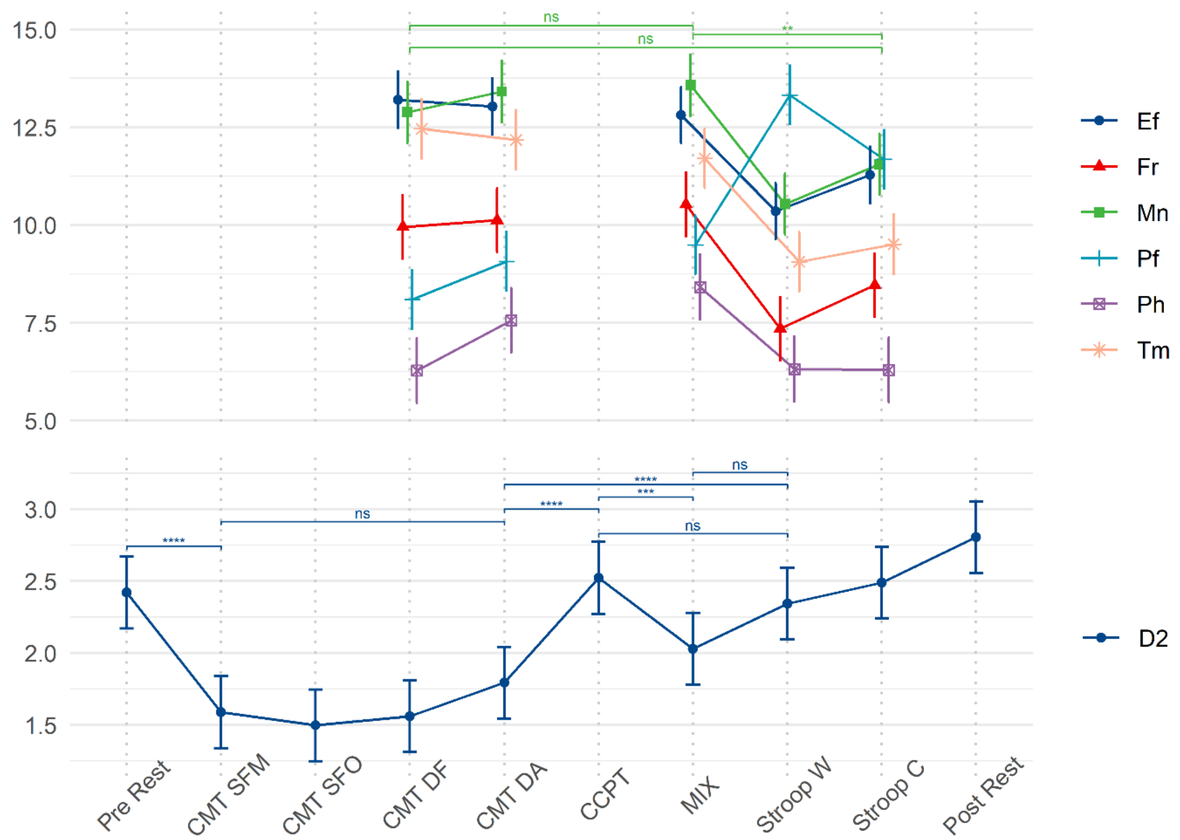

Figure 13. Dynamics of estimated marginal means of TLX and D2 ratings during the trials.

Note. Top: TLX scores. Bottom: HRV parameter D2. Error bars indicate 95% confidence intervals. Lower values in correlation dimension D2 indicate greater workload, while higher values in TLX scores correspond to higher self-reported load in the six dimensions; Mn: mental demands; Ph: physical demands; Tm: temporal demands; Pf: performance; Ef: effort; Fr: frustration. For TLX-Mn and D2, the significance of selected mean comparisons is annotated **p<.01; ***p<.001.

Detailed results and further interpretations can be found in Article 3. Overall, the results indicate that the CMT induces substantial MWL, and participants reported that they perceived these tasks to be particularly demanding. An interesting finding was the difference in MWL and performance during the task-mixing trials. Contrary to prior expectations, CCPT performance increased during the mixed trial compared to the single trial. In light of the mixing costs usually associated with performing two dissimilar tasks, a decrease in performance and an increase in MWL were expected. However, an increase in CCPT performance was observed, accompanied by an increase in MWL. A possible explanation for these results is that performing the CMT increased the level of intrinsic alertness, which led to a performance increase in the CCPT. This observation reinforces the notion that the CMT is primarily an alertness task.

The results also indicate the utility of the adaptive testing technique. Split-half reliability was drastically improved in the adaptive testing condition. Thus, the CMT benefits from CAT, and provides a novel approach to assessing the threshold of information processing in an alert state.

Another noteworthy innovation is the dynamic generation of stimulus material at the time of testing. Automatic item generation is typically employed to generate items before testing, usually in educational applications (Lai et al., 2016). Generating stimuli dynamically is usually not pursued because issues with standardization and validity arise; the generated items thus need to be checked manually. However, this approach can be used for the CMT. The simple nature of the task allows for automatic stimulus generation, given that the algorithm produces consistent outputs at all levels of difficulty. This assumption was tested in a preliminary analysis, which is reported in the supplementary materials of Article 3.

Overall, the CMT appears to be a viable instrument to assess an individual's ability to maintain alertness. Out of all the tests deployed in the study, the adaptive single-task CMT was the only task that showed a link to ADHD symptoms. Thus, it fulfils many of the previously defined goals for the paradigms developed in this dissertation. It allows for specific and adaptive control of difficulty, is flexible, and has different single and multi-tasking configurations. Future research should investigate the task further under various conditions and modifications, such as prolonged testing, relocation of stimuli, and further dual-task applications as well as distractions and interruptions. Findings by Lin et al. (2015) indicate that dual-task performance and task mixing in tasks similar to the CMT are impacted by schizophrenia. Thus, the CMT may be an interesting tool for clinical psychology. The surprising finding that the CMT may increase participants' level of alertness and cause performance increases in other tasks also warrants further investigation.

Mobile and Laboratory Implementations of CMT and Stroop Tasks – Article 4

Münscher, J.-C. (2022). *Mobile and Laboratory Reaction-Time-Based Measurements of Alertness and Attention* [manuscript submitted for publication].

During development of the CMT for application in the laboratory study, the COVID-19 pandemic began. This event not only threatened the feasibility of the study, but also rapidly highlighted the need for smart-device-based testing and interventions. Given the widespread adoption of mobile devices like smartphones and tablets, utilizing these to perform psychological assessments has already been the subject of previous research (Holmlund et al., 2019; Rose et al., 2012). The global pandemic and ensuing lockdowns reinforced these endeavours (Bordini et al., 2020). The CMT was thus also adapted to run on common Android® and iOS® devices.

General Objective and Summary

Transferring laboratory assessments onto participant's personal devices offers a set of advantages and challenges (Holmlund et al., 2019). The measurement can be performed without requiring expensive laboratory equipment or scheduling. Mobile devices have continuously increased in performance and modern devices can perform complex computational operations. Especially for research, the self-administration of measurements is likely more attractive for participants and can facilitate easier data gathering. Respondents are easier to recruit because the tasks can be performed without going through the effort of scheduling and coming to a laboratory. Furthermore, smart devices offer possibilities for collecting data beyond using these devices as testing platforms. As Trull and Ebner-Priemer (2014) point out, sensor data and user interactions with the devices can be informative in assessment and telehealth.

When mobile devices are used as testing platforms, two categories of tasks can be differentiated. Tasks that rely on responses without recording reaction times, like questionnaires and pure power tasks, and speed tasks that employ recording of reaction times. The former category has been well established; especially questionnaires, and power tasks for intelligence, memory, and knowledge have been shown to function in mobile assessment without reducing measurement quality (Song et al., 2020; Steger et al., 2019; Triantafillou et al., 2008).

However, the picture is different for speed tasks. Although Steger et al. (2019) point out that these tasks are less likely to be influenced by cheating and manipulation, their measurement quality is presumably questionable. The uncontrolled circumstances in which self-administered testing takes place, could influence the measurement; although Timmers et al. (2014) reported no relevant influence of the testing environment. More importantly, performing tasks on mobile devices introduces characteristic demands on the participants. Specifically the reduced screen size and limited inputs can confound measurements (Illingworth et al., 2015). Accurate timekeeping can also not be universally assumed as devices are unstandardized. For these reasons, Byun et al. (2018) caution against the implementation of speed tasks on mobile devices and also reported age effects that influence these measurements. Nevertheless, the applications of Stoop tasks on mobile devices have shown some promise (Holmlund et al., 2019).

To highlight the quality of measurements of speed tasks, and specifically the CMT, Stroop tasks and the CMT were also administered on mobile devices. Details and results are presented in Article 4. The primary research question was: Is mobile administration of reaction-time-based attention and alertness tasks comparable to laboratory testing? Three hypotheses were tested to investigate this:

(1) Under the assumption that measurements are equivalent, the performance metrics of CMT and Stroop tasks were assumed to correlate substantially. Based on findings on retest reliabilities of Stroop tasks by Strauss et al. (2005), the thresholds for this assumption were set at r ≥ .4 for Stroop interference scores and $r \geq .7$ other scores.

(2) As age effects were observed in mobile assessments (Byun et al., 2018; Traylor et al., 2020), moderation effects were expected to influence the association between laboratory and mobile measurements. This hypothesis was tested by analyzing the moderation effect of age when predicting laboratory results from mobile measurements.

(3) The tasks were assumed to be internally consistent across modes of measurement. The correlation patterns within a task should be consistent between laboratory and mobile measurements. Testing this hypothesis was performed by comparing the correlation patterns between modes of measurement using χ^2 tests (Steiger, 1980).

The stimulus generation and adaptive testing algorithms were directly transferred to the mobile platform. Instead of using the response boxes, the touchscreen elements of the mobile devices were used. Figure 14 shows how the task is displayed on a mobile device.

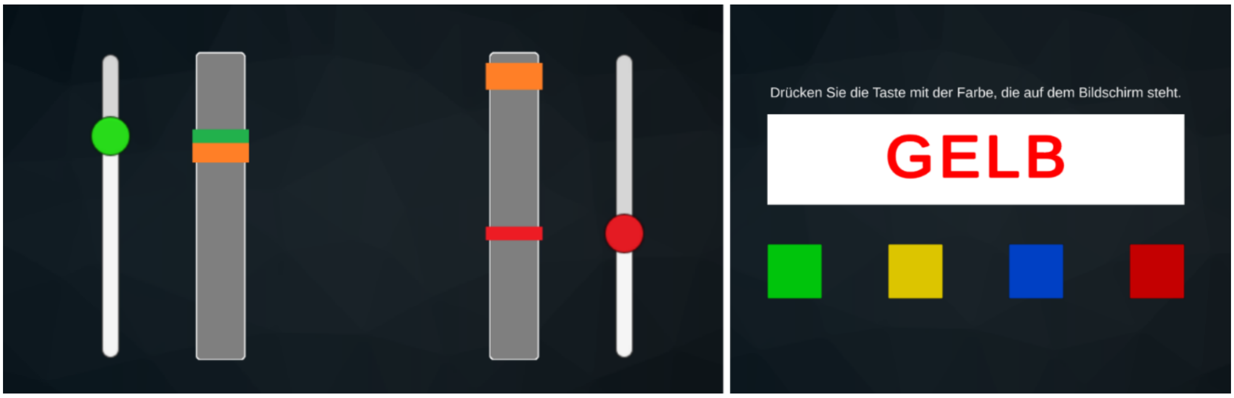

Figure 14. Screenshots from the implementation of CMT and Stroop tasks in the mobile application.

Note. Participants were instructed to hold their device horizontally and use their thumbs to respond to the tasks. Left: the CMT in the dual-task configuration. The sliders on the left and right sides (green and red) control the corresponding response indicators. The orange bars (target indicators) move up and down and their motion must be matched. Right: The implementation of the Stroop task in the word reading condition. Currently, an incongruent stimulus is displayed and the yellow button must be pressed.

The mobile version of the CMT and Stroop task were made available through the Google Play® and Apple® app stores. Participants of the study presented in Article 3 were invited to download the app and perform the test. Therefore, mobile and laboratory test results for almost all participants in the study were linked and can be compared ($N = 125$).

Results and Interpretation

CMT scores in the laboratory measurement correlated in the range of r = [-.36; .68] with mobile measurements, with the strongest correlation being observed for the performances in the dual adaptive trials; the assumed magnitude of $r = .7$ was not observed. For the dual trial with fixed difficulty the correlation was $r = .13$. See Table 3 for all correlations.

Table 3. Correlations between CMT scores in laboratory and mobile testing

Mobile Scores	Laboratory Scores S_o	S_m	DF	DA
S_o	.08	.1	.04	-.04
S_m	-.09	-.07	-.07	.05
DF	< .01	.09	.13	-.06
DA	-.36	-.4	-.64	.68

Note. Abbreviations: (S_o) performance of the offhand, (S_m) performance of the main hand, (DF) performance with both hands in fixed difficulty, (DA) performance with both hands in adaptive difficulty.

Two things can be gathered from this data: First, the CMT does not perform to the expected degree in the mobile implementation. Second, adaptive testing is hugely beneficial in this context and increased the reliability almost to the level of the Stroop task reported by Steiger (1980). The results for the correlations for Stroop metrics were more promising. They lay in the range r = [-.69; .73], and are displayed in Table 4.

Table 4. Correlations between Stroop scores in laboratory and mobile testing

		Laboratory Scores								
		Reading				Colour naming				
Mobile Scores		t	c	i	n	t	c	i	n	I_G
Reading	t	.67	.68	.6	.66	.59	.64	.48	.6	-.47
	c	.64	.64	.57	.63	.57	.61	.46	.58	-.45
	i	.67	.68	.61	.66	.58	.62	.49	.58	-.47
	n	.59	.62	.5	.57	.54	.59	.44	.55	-.42
Colour naming	t	.59	.59	.53	.58	**.73**	**.73**	.68	.67	-.65
	c	.57	.58	.51	.57	**.73**	**.73**	.69	.66	-.65
	i	.58	.58	.53	.57	**.7**	**.71**	.65	.65	-.62
	n	.55	.55	.49	.54	.67	.67	.64	.6	-.6
I_G		-.58	-.58	-.52	-.56	-.68	-.69	-.62	-.64	**.6**

Note. Coefficients printed in boldface mark those that align with the prior assumptions

Abbreviations: (t) RT for all stimuli, (c) RT for congruent stimuli, (i) RT for incongruent stimuli, (n) RT for neutral stimuli, (I_G) Golden Interference Score (Golden, 1978)

The highest correlations were observed in the color naming condition and the interference score I_G (Golden, 1978) exhibited r = .6. Consequently, the Stroop task largely fulfilled the prior assumptions both for RT and interference.

The moderation effects of age were assessed using regression models. The laboratory results were predicted from mobile measurements and age was entered as a moderator. Table 5 summarizes the results from both regression models.

Table 5. Results from moderation analyses. Predicting laboratory from mobile results.

CMT score moderation

R^2 = 0.427

Effect	Estimate	*SE*	β	*t*	*p*
Constant	9.821	7.233	0	1.358	.177
CMT.m	0.441	0.072	.53	6.135	< .001
age	0.74	1.05	0.061	0.705	.482
CMT.m X age	0.015	0.006	0.228	2.462	.015

Stroop score moderation

R^2 = 0.337

Effect	Estimate	*SE*	β	*t*	*p*
Constant	0.002	0.018	0	0.137	0.891
Stroop.m	0.863	0.134	.543	6.399	< .001
age	-0.002	0.002	-.09	-0.893	.373
Stroop.m X age	0	0.016	-.001	-0.015	.988

Note. Variables are mean centered. Outliers with values exceeding the 95 percentiles were excluded.
Abbreviations: (CMT.l) CMT performance in the laboratory dual adaptive trial, (CMT.M) CMT performance in the mobile dual adaptive trial, (Stroop.l) Stroop performance (Golden) in the laboratory trail, (Stroop.M) Stroop performance (Golden) in the mobile trail

In both models, a significant main effect of the mobile measurement was observed. In the CMT a moderation of age was also present. No such effects were found for Stroop performance. Figure 15 illustrates these results.

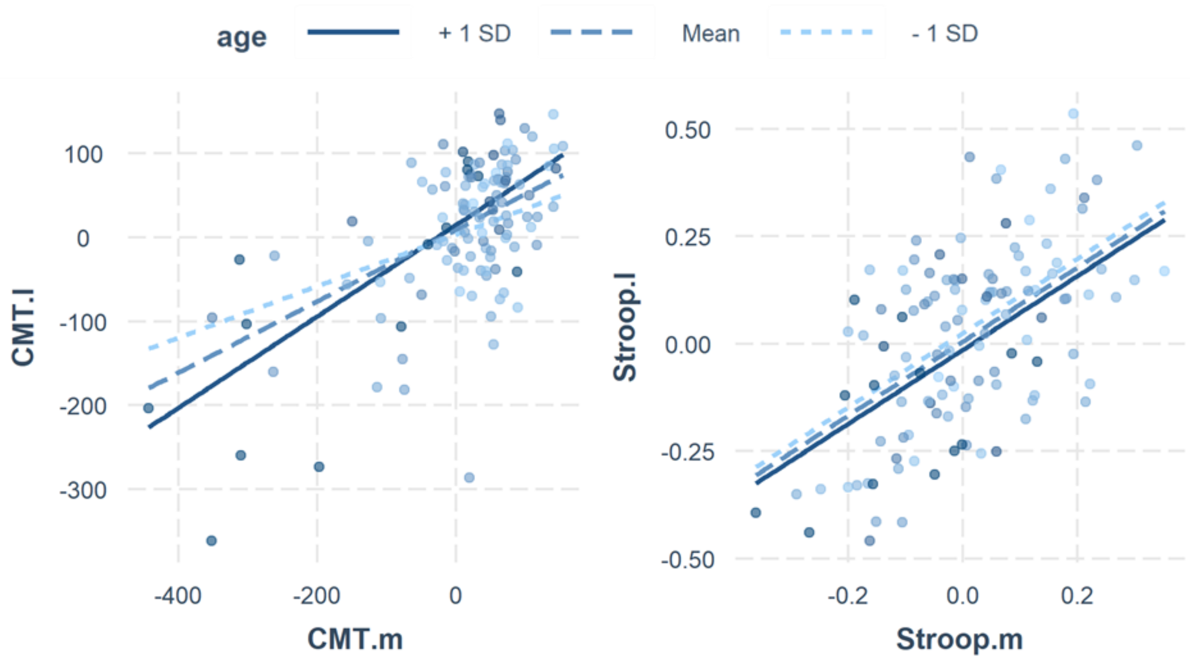

Figure 15. Plots for CMT and Stroop scores in laboratory and mobile measurement, moderated by age.

Note. Scores are mean-centered. Abbreviations: (CMT.l) CMT laboratory score, (CMT.m) CMT mobile score, (Stroop.l) Stroop laboratory score I_G, (Stroop.m) Stroop mobile score I_G).

For both tasks, an association between laboratory and mobile measurements was observed. Age moderated the association of CMT performance between mobile and laboratory testing.

The moderation analyses revealed that the Stroop task performed well when predicting laboratory results from mobile measurements. No age effects were present for it and it seems to be viable for application in mobile assessment. However, the same cannot be said for the CMT performances. Older participants in the lower range of performance scored much lower in mobile measurements compared to younger individuals with similar performance in the laboratory trial. The increased demand caused by moving the sliders using a touchscreen likely reduced the performance of older individuals who are probably not as proficient in manipulating touchscreens.

Both tasks appear to perform differently in the testing scenarios, as indicated by the consistency of measurements between laboratory and mobile measurements. The correlations of test scored in the laboratory measurement were compared to the correlations in the mobile measurement. The differences in the score correlations were significant for both; χ^2 (6, N = 125) = 300.78, $p < .001$, with a z of difference = 0.66 for CMT, and χ^2 (15, N = 125) = 32.38, $p < .001$, with a z of difference = 0.07 for Stroop. However, the CMT seems to be less consistent than the Stroop tasks. The z of difference indicates that the correlations of the Stroop scores were more similar. Details and correlation matrices are presented in Article 4 and its' supplementary material.

Overall, the results from Article 4 indicate that the Stroop task is more suited for mobile implementation. The correlations between modes of measurement were close to, or exceeded those in regular retests. The CMT also exhibited an association in this regard but did not reach the same level. Furthermore, age effects were observed for the CMT, which coincide with prior results (Byun et al., 2018; Traylor et al., 2020). This indicates that its' use in mobile measurements can be problematic, especially when older participants are recruited. The increased demands caused by the mode of measurement negatively impacted the results, which also corresponds to previous findings (Illingworth et al., 2015).

Administering the Stroop task in mobile testing seems to be viable overall. More technically complex tasks like the CMT must be tested and evaluated thoroughly before application. The fact that both laboratory and mobile implementations are technically identical does evidently not automatically ensure measurement equivalence.

General Discussion

Although the three research projects I presented in this dissertation approached the topic of attention very differently – with the first article even pursuing an unrelated goal – they all contributed to the overall objective: designing and testing novel measurement paradigms for attention in the work context. The initial challenge in this field arose from its varied and complex theoretical foundation, which I hope to have laid out clearly. The second challenge was positioning attention phenomena in the work context, for which the PAW framework was particularly useful. Finally, a series of paradigms were designed based on this framework, of which one was tested and evaluated. The CMT showed the most promise out of all the developed ideas, and its utility primarily lies in the assessment of sustained alertness. Although it was designed as a test of sustained attention, its ability to measure alertness is no less useful within the scope of this dissertation.

Overview

The first article initially sought to identify the position of attention within the landscape of occupational demands. The scope of this project subsequently changed, and ultimately focused on the landscape of occupational demands in apprenticeship occupations in an international context. Although the project no longer highlighted attentional demands and instead provided more general insights, the results still emphasised which groups of occupation may specifically benefit from the subsequently developed attention paradigms.

The PAW framework developed in Article 2 provides a differentiated perspective on the work aspects that create attentional demands. The corresponding job analysis tool PAW36 was constructed to measure these task parameters in a detailed way. Gathering information on how and which attentional demands arise in the workplace is beneficial for assessing and optimizing PJ-fit. The construction and initial validation in Article 2 indicate that the questionnaire is a useful and generally applicable tool that can be used in both research and practice. It allows for a focus on attention in the context of job analysis to a greater extent that any comparable existing instrument. The theoretical framework that underpins the questionnaire is a noteworthy contribution as well, and was instrumental for designing the measurement paradigms.

The measurement paradigms that were developed were designed to fulfil specific goals. The main objective was to implement computerized testing, including the novel approaches it allows. The complexity of the phenomenon of attention required a decomposed perspective that highlights specific aspects, and the CMT as a specific measure of alertness fulfils this goal. Furthermore, the CMT incorporates adaptive testing and algorithmically generated stimulus material in the context of attentional assessment, which can be seen as two further contributions to the field. The remaining paradigms and modifications will have to be tested and evaluated at a later stage. Ideally, this would result in a set of attention scales enabling the distinct measurement of different types of attentional performance. The role of mobile testing, using personal devices, was highlighted in Article 4. Results indicate that the CMT is less suited for application in mobile assessment.

Limitations

The primary shortcoming of the first article is that it is entirely theoretical in nature. While the underlying datasets were collected by professionals and with practical applications in mind, the analyses performed using these data were theoretical. No external validation was performed. This was outside of the scope of the project, but would be a much-needed addition before practical application. Additionally, combining the results for the Austrian and German labour markets was an interesting way to increase data density and create a unified perspective; however, it is unclear whether these benefits outweigh the increased complexity.

In Article 2, the means of assessing validity were a limitation. The scales that were used to explore nomological validity were of suboptimal quality in some cases. While this further highlights the need for quality assessment tools in this field, which the PAW36 aimed to provide, it negatively affected the analysis of validity. In addition, criterion and predictive validity were not evaluated in this first deployment. Regarding the relation between the PAW framework and the questionnaire, it is important to point out that the theoretical parameters did not translate directly into questionnaire scales. Instead, the theoretical structure was collapsed into only a few scales, and some aspects of the framework were not represented. Consequently, some aspects that were deemed relevant from a theoretical perspective were not part of the questionnaire.

The overarching project of this dissertation – test construction – was not seen through to the end for most of the conceived paradigms. Only the CMT was tested to a sufficient degree for in-depth evaluation. Additionally, the paradigms focused solely on visual and spatial attention, as is typical in attentional assessments. Different sensory modes and aspects of internal attention were not addressed. The former were included in the PAW framework, but did not make it into the questionnaire due to complications in sufficiently differentiating these aspects. Differences in sensory modes, such as auditory, haptic, or olfactory stimuli, have been found to be relevant for attentional performance (Krumm et al., 2012). However, constructing paradigms that include these modes and perhaps even allow for shifts between them would have exceeded the scope of this project.

With regards to the evaluation of the CMT, the primary shortcoming is that long test durations were not employed. Due to the limitations of the laboratory study, the maximum length of uninterrupted CMT testing was seven minutes. Performance declines due to prolonged testing are usually expected after roughly 50 minutes in the case of simple reaction tasks (Langner et al., 2010). Therefore, extended testing periods would have been informative. Additionally, TLX ratings were not gathered for all trials, but only for a selection. This, and the fixed order of trials, as compared to randomized trials or blocks, reduces the inferences that could be drawn from the data. Specifically, the lack of variation in the trial sequence caused the reduction in performance, which is to be expected over the roughly 70 minutes of combined testing, to impact the later trials more than the early ones. The statistical analyses compensated for these influences by including the individual level of relaxation, determined by changes in HRV throughout the testing session, as a covariate, but variable sequences would have allowed for more precise inferences. Another limitation to the third article is the sample size. A smaller sample size than initially planned was used in this study. Due to the COVID-19 pandemic, recruiting and testing the planned number of individuals $N > 200$ was not possible, and a smaller sample $N = 122$ was deemed sufficient. The analyses still had sufficient power, but a bigger sample would have been beneficial.

Similar shortcomings can be observed in the analyses for Article 4. The small sample size limited the methods that could be applied. The analyses are restricted to correlation and regression methods. A larger sample size would have enabled latent modelling of measurement invariance and method factors. Echoing the sentiment for Article 3, a longer task duration would also be informative. In the mobile implementation, the CMT was not administered long enough to truly assess its' function as a measure of sustained alertness. Here, limits of participants' motivation and assessing the implementation on a basic level had priority over gathering data for longer periods. Another related shortcoming is that only Stroop and CMT were applied in this study as to not loose participants to dropout. Including other measures like the CCPT would have enabled multi-trait-multi-method analysis and a more precise inquiry into the effects that influence mobile assessments.

Overall, the present dissertation project reached many of its goals and was very successful. However, the subject matter and its multifaceted structure caused the overall endeavour to be slightly disjointed. After the change in focus, the first article is only loosely connected to the primary objective, and the number of paradigms constructed and tested was lower than initially planned. Nevertheless, I believe these shortcomings highlight the complexity of the field and do not negatively impact the overall success of the project.

Research perspectives

Over the course of this dissertation, many avenues for future applications and research have arisen. Besides tackling the previously described shortcomings, I see the greatest potential for future work in building on and expanding the insights that were gathered as part of the included projects.

For instance, the landscape of apprenticeship occupations and demands described in Article 1 could be developed further and used in coaching and career guidance. The differences observed when comparing this landscape to the theoretical structure found in common models in the field showed that special considerations need to be made. The structure of demands in apprenticeship occupations could also be used to construct a set of assessment scales. In its simplest form, this could take the form of an interest questionnaire based on the demands and groups of demands. The results could then be interpreted using the structure found in Article 1. Such a tool has the potential to result in more suitable apprenticeship recommendations in Germany and Austria.

With regards to assessment of attention, the PAW framework shows promise as a guide for test construction, as was already performed in this dissertation. The developed set of paradigms is by no means comprehensive, and further measurement paradigms could and should be designed. This is especially the case for the paradigms that were designed but not developed further. Including controlled distractor conditions, like interfering tasks, and changes in location could be a way to incorporate everyday demands into assessment. Additionally, the existing paradigms could be further developed. Follow-up studies could employ these paradigms and yet untested configurations of the CMT. The nature of the CMT also showed some potential utility for clinical assessment in the context of schizophrenia. Also, the ambulatory application of the CMT and the other paradigms is a potential avenue for further research.

As was pointed out in the theoretical deliberations on attention, executive control and effort are essential to performance. Motivational aspects thus play a vital role and could be the subject of further research endeavours. Concerning the PAW36 questionnaire, work motivation and job satisfaction are aspects that were not part of the second article but can be assumed to be relevant in the context of work-related attentional demands.

Another promising avenue is the potential use of the CMT as an objective personality test. The ability to modify the difficulty dynamically and immediately could be implemented in a configuration in which the participant controls the difficulty themselves. Comparing self-selected difficulty to the difficulty achieved under adaptive conditions could be an indicator of performance-related self-esteem and ambition. These aspects are relevant to many personal and work-related fields, and both play an important role in the impostor phenomenon (IP). This term was first coined by Clance and Imes (1978) and describes a complex configuration of self-criticism, perfectionism, and achievement pressure that results in self-doubt and fear of being exposed as underqualified, as an impostor. The construct has enjoyed much publicity and research attention; Ibrahim et al. (2021) outline the concept and research on it. In this context, the initial expectation could be that individuals exhibiting impostor tendencies adjust the difficulty to be lower than those not exhibiting IP.

Conclusion

The theoretical landscape of attention as well as the results presented in this dissertation highlight the complexity of the topic. Viewing attention as the result of a bundle of processes that shape and guide perception resulted in a corresponding set of parameters that mold attentional demands in the workplace. These parameters then guided the construction of paradigms for measuring individual performance. One of these was deployed in a laboratory study, revealing further points of interest. Over the course of the four articles and the process of test construction, including hardware and software development, a substantial and innovative set of tools for research and practice was developed. In the end, the phenomenon of attention presents itself as a varied bouquet with many interesting perspectives. In this dissertation, I hope to not only have displayed the complexity of the subject but also the opportunities that arise within.

Appendix: Research articles

The following articles were produced in this dissertation project.

Article 1

Münscher, J.-C., Greiff, S., Sander, N., Bliem, W., & Herzberg, P. Y. (2022). *A European Perspective on Apprenticeship Occupations and Their Psychological Demands* [manuscript submitted for publication].

Impact factor: NA

Article 2

Münscher, J.-C., Bürger, M., & Herzberg, P. Y. (2021b). Parameters of Attention at Work (PAW36)—Construction of a Questionnaire. *Trends in Psychology.* Advance online publication. https://doi.org/10.1007/s43076-021-00086-y

Impact factor: 0.464

Article 3

Münscher, J.-C., Bürger, M., & Herzberg, P. Y. (2021a). The Continuous Matching Task (CMT) - real-time procedural stimulus generation for adaptive testing of attention. *Applied Neuropsychology. Adult*, 1–14. https://doi.org/10.1080/23279095.2021.1969399

Impact factor: 2.437

Article 4

Münscher, J.-C. (2022). *Mobile and Laboratory Reaction-Time-Based Measurements of Alertness and Attention* [manuscript submitted for publication].

Impact factor: NA

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