BRNO UNIVERSITY OF TECHNOLOGY
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FACULTY OF INFORMATION TECHNOLOGY
FAKULTA INFORMAČNÍCH TECHNOLOGIÍ

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DIGITAL GAME-BASED EVALUATION OF COMPLEX ATTENTION
HODNOCNÍ KOMPLEXNÍ POZORNOSTI ZALOŽENÉ NA DIGITÁLNÍCH HRÁCH

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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BRNO 2025

BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF INFORMATION TECHNOLOGY

Bachelor's Thesis Assignment

161429

Institut: Department of Computer Systems (DCSY)
Student: **Sobihardová Natália**
Programme: Information Technology
Title: **Digital Game-Based Evaluation of Complex Attention**
Category: Biocomputing
Academic year: 2024/25

Assignment:

1. Identify and elaborate on the cognitive domains of complex attention, including sustained attention, selective attention, divided attention, and processing speed.
2. Conduct a thorough literature review to explore current methodologies and digital games that assess complex attention. Identify their challenges and limitations in accurately measuring impairments in these specific cognitive subdomains.
3. Develop a digital game or a series of games specifically designed to assess each subdomain of complex attention. Ensure that these games are engaging and adequately challenging to measure the targeted cognitive skills accurately.
4. Implement the designed game(s) on a suitable platform, such as Android, with features that support cloud accessibility for broad and flexible user participation.
5. Collect comprehensive data on participants' performance during gameplay, focusing on metrics relevant to assessing complex attention and subdomains.
6. Analyze the data to assess cognitive skills and identify deficits.
7. Conduct critical analysis and discuss achieved results and their contribution.

Literature:

- Based on the supervisor's recommendation.

Requirements for the semestral defence:

- Fulfillment of items 1 to 2.

Detailed formal requirements can be found at https://www.fit.vut.cz/study/theses/

Supervisor: **Hussain Yasir**
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Beginning of work: 1.11.2024
Submission deadline: 14.5.2025
Approval date: 31.10.2024

Abstract

This thesis addresses the challenge of accurately evaluating complex attention, a cognitive domain encompassing sustained, selective, and divided attention, as well as processing speed. Traditional and digital assessment methods often lack ecological validity, cover only a subset of attentional subdomains, or do not provide engaging and scalable solutions. The main objective was to design, implement, and evaluate Attentia-a modular, mobile game-based platform that assesses all four subdomains of complex attention. The solution consists of four mini-games, each based on validated cognitive paradigms, and incorporates standardised metrics, adaptive feedback, and secure cloud data management. Pilot testing and real user data analysis confirmed the feasibility and usability of the platform, with the system successfully collecting and analysing performance metrics relevant to each attentional subdomain. The contribution of this thesis is a scientifically grounded, extensible, and user-friendly tool that advances digital cognitive assessment by combining methodological rigour with engaging, ecologically valid game-based tasks.

Abstrakt

Táto bakalárska práca sa zaoberá hodnotením komplexnej pozornosti, ktorá zahŕňa subdomény ako trvalá, selektívna a rozdelená pozornosť a rýchlosť spracovania informácií. Tradičným a digitálnym metódam hodnotenia často chýba ekologická validita, pokrývajú iba podmnožinu subdomén pozornosti alebo neposkytujú pútavé a škálovateľné riešenia. Hlavným cieľom bolo navrhnúť, implementovať a vyhodnotiť Attentia – modulárnu platformu založenú na mobilných hrách, ktorá hodnotí všetky štyri subdomény komplexnej pozornosti. Riešenie pozostáva zo štyroch minihier, z ktorých každá je založená na validovaných kognitívnych paradigmách a zahŕňa štandardizované metriky, adaptívnu spätnú väzbu a bezpečnú správu cloudových údajov. Pilotné testovanie a analýza údajov potvrdili funkčnosť a použiteľnosť platformy, ktorá umožňuje zber a vyhodnocovanie relevantných ukazovateľov pozornosti. Prínosom práce je vytvorenie vedecky podloženej, rozšíriteľnej a užívateľsky prívetivej digitálnej aplikácie, ktorá posúva možnosti hodnotenia komplexnej pozornosti smerom k vyššej štandardizácii, ekologickej platnosti a praktickému využitiu v oblasti výskumu aj praxe.

Keywords

Complex attention, Digital game-based assessment, Sustained attention, Selective attention, Divided attention, Processing speed, Cognitive evaluation, Mobile application, Standardized metrics, Neurocognitive domains

Klíčová slova

Komplexná pozornosť, Digitálne hodnotenie pomocou hier, Trvalá pozornosť, Selektívna pozornosť, Rozdelená pozornosť, Rýchlosť spracovania, Kognitívne hodnotenie, Mobilná aplikácia, Štandardizované metriky, Neurokognitívne domény

Reference

SOBIHARDOVÁ, Natália. *Digital game-based evaluation of complex attention.* Brno, 2025. Bachelor's thesis. Brno University of Technology, Faculty of Information Technology. Supervisor Yasir Hussain,

Digital game-based evaluation of complex attention

Declaration

I hereby declare that this Bachelor's thesis was prepared as an original work by the author under the supervision of Mr. Yasir Hussain I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

. . . .
Natália Sobihardová
May 14, 2025

Acknowledgements

I want to express my gratitude to my supervisor, Mr. Yasir Hussain, for his guidance and support. faculty.cs

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Chapter 1

Introduction

Attention is vital to how we interact with the world around us. It helps us concentrate on what we are doing, ignore distractions, and respond to different situations. For example, when we are having a conversation, driving, or studying, attention plays a key role in how well we perform. It includes different ways of focusing, such as paying attention for a long time or shifting our focus between tasks. Overall, attention is crucial for our daily lives and our well-being.

The growing complexity of modern life and the prevalence of neurocognitive disorders such as ADHD, traumatic brain injuries, and dementia have heightened the importance of accurately evaluating complex attention. Traditional assessment methods, while reliable, often lack ecological validity and fail to capture the dynamic, multifaceted nature of attention as experienced in real-world contexts. Digital game-based assessments have emerged as a promising alternative, offering engaging, adaptive environments that can simulate real-life scenarios and enhance participant motivation.

However, a critical review of existing approaches reveals significant challenges: many digital and game-based tools assess only a subset of attention subdomains, lack rigorous validation and standardisation, and struggle with scoring and data interpretation complexity. Furthermore, the game elements designed to increase engagement can inadvertently manipulate attention, making it difficult to isolate and measure the intended cognitive constructs. These issues have limited the reliability, generalizability, and practical adoption of game-based assessments in research and applied settings.

This thesis addresses these challenges by proposing and developing a modular, evidence-based digital assessment platform, Attentia, implemented as a native Android application with integrated cloud support. The main goal of this thesis is to create and evaluate a mobile game-based tool that can measure different aspects of attention more accurately and engagingly than traditional tests.

The platform consists of mini-games, each grounded in established cognitive paradigms and specifically designed to assess one subdomain of complex attention. By leveraging standardised metrics, adaptive feedback, and carefully controlled gameplay, the solution aims to deliver valid, reliable, and ecologically relevant assessments accessible to a broad user base via mobile devices. The platform's design emphasises transparency in scoring, robust data security, and compliance with ethical standards, ensuring that sensitive performance data is handled responsibly.

The main contributions of this work include a comprehensive review and synthesis of current digital and game-based assessment methodologies, the design and implementation of four targeted mini-games for each attention subdomain and the development of a unified scoring and analytics framework. The thesis aims to advance the field toward more robust, standardised, and accessible digital tools for evaluating complex attention.

My motivation for this topic comes from my personal experience with several friends who have ADHD. They often told me that the standard attention tests do not really reflect what it is like to deal with attention difficulties in everyday life. At the same time, I have always enjoyed mobile games. I was inspired by the idea that games could be used for something meaningful- helping people understand and measure their attention skills in a way that feels natural and engaging.

The structure of this thesis is organised to provide a logical progression from theoretical foundations to practical implementation and evaluation. Chapter 1 introduces the significance of complex attention and the motivation for adopting digital game-based assessment, clearly outlining the research problem and objectives. Chapter 2 presents a comprehensive literature review, covering the neurocognitive domains, key theories from cognitive psychology, and both traditional and digital methods for assessing attention, while critically analysing their strengths and limitations. Building on these insights, Chapter 3 details the design of the proposed solution, Attentia, by identifying research gaps, justifying the need for a new approach, and describing the conceptual and technical architecture of the platform, including its modular game-based structure and data management strategies. Chapter 4 then describes the technical implementation of Attentia, elaborating on the development workflow, integration of validated cognitive paradigms into mini-games, and the deployment of analytics and feedback systems, as well as addressing challenges such as scientific validity, data privacy, and scalability. Finally, Chapter 5 concludes the thesis by summarising the main findings and contributions, discussing the limitations encountered, and providing recommendations for future development and standardisation in digital cognitive assessment, thereby offering a robust foundation for further research and practical applications in the field.

This thesis seeks to provide a scientifically robust and practically useful tool to inform research, education, and clinical practice by systematically addressing the methodological and practical challenges in the digital game-based evaluation of complex attention.

Chapter 2

Literature Review

Understanding complex attention is fundamental to comprehending cognitive functioning and diagnosing related disorders. As modern life requires multiple information streams, evaluating complex attention for academic and professional success and daily activities requiring high concentration levels and multitasking is essential. Digital game-based assessments offer an innovative approach to evaluating complex attention due to their ability to engage participants, adapt to individual performance, and simulate real-world scenarios more effectively than traditional methods.

To effectively evaluate complex attention through digital game-based assessments, it is crucial to understand the concept of cognitive function and the current state of assessment methodologies. This chapter overviews the six key neurocognitive domains and their subdomains, focusing on complex attention and analysing existing assessment methods. By exploring these areas, we can develop more effective tools for assessing attentional subdomains, ultimately leading to better diagnostic and intervention strategies.

2.1 Neurocognitive Domains

To fully appreciate the complexity of attention, we must first contextualise it within the broader framework of neurocognitive functioning. The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5), published by the American Psychiatric Association (APA), outlines six key neurocognitive domains that serve as the foundation for understanding cognitive processes and diagnosing disorders. Widely adopted in clinical practice internationally, the DSM-5 provides standardised criteria for classifying mental health conditions, including neurocognitive disorders (e.g., delirium, mild/major neurocognitive disorder) and other psychiatric illnesses such as schizophrenia, bipolar disorder, and anxiety disorders [16]. By organising cognitive functions into six core domains—**complex attention, executive function, learning and memory, language, perceptual-motor function, and social cognition**—the DSM-5 enables systematic evaluation of deficits, linking them to specific brain regions and guiding targeted interventions.

2.1.1 Brain Anatomy and Physiology

Each neurocognitive domain is rooted in specific brain regions and networks. Understanding how these areas work is essential to grasp neurocognitive domains and their assessment. There are several major brain regions:

- **The frontal lobe**, the largest brain region, is responsible for decision-making, problem-solving, attention, memory and personality. It also controls voluntary movement through the motor cortex.
- **The parietal lobe** helps process touch and body positioning, which is key in spatial awareness.
- **The occipital lobe** is located at the back of the brain and focuses on visual information, like recognising colours and patterns.
- **The temporal lobe** is involved in memory, language, hearing and facial recognition

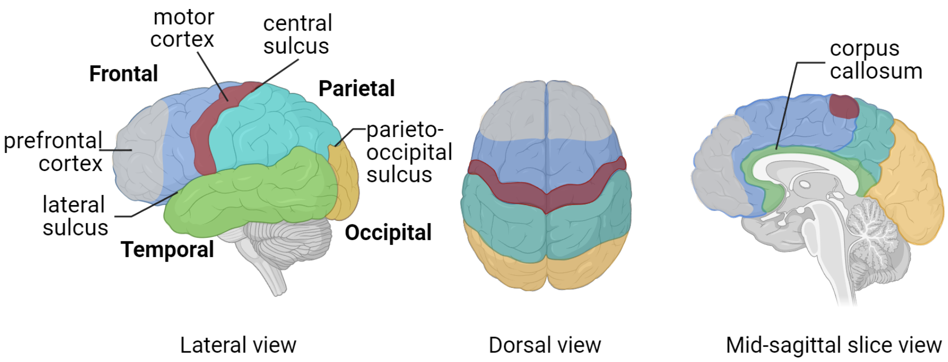


Figure 2.1: The lobes of the brain [13]

Other vital parts include:

- **The limbic system** handles emotions and memory.
  - The hippocampus plays a central role in memory formation,
  - The amygdala is involved in processing emotions,
  - The Cingulate gyrus integrates emotional and cognitive functions.
- **The basal ganglia** help with movement and motivation.
- **The thalamus** acts as a relay station, sending sensory information to the brain
- **The hypothalamus** keeps the body in balance by regulating hunger, thirst, sleep and body temperature

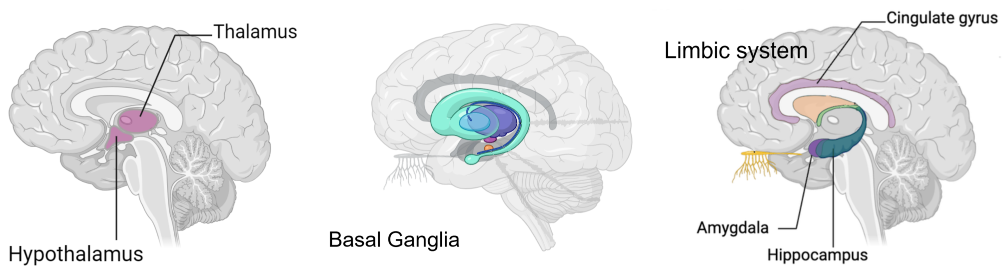


Figure 2.2: (From left) Hypothalamus, thalamus, basal ganglia and limbic system [13]

The brain has several functions that are relevant to cognition.

- **Cognitive functions** - The prefrontal cortex, part of the frontal lobe, is responsible for higher-order cognitive functions such as reasoning, language, consciousness, perception, emotion, personality, decision-making and memory.
- **Memory** - The hippocampus is essential for encoding and retrieving long-term memories.
- **Decision-making and problem-solving** - The prefrontal cortex plays a pivotal role in these executive functions.
- **Attention** - The prefrontal cortex also underpins attentional processes.
- **Social behaviour** - The limbic system, particularly the amygdala, is responsible for emotional and social behaviour.

Cognitive processes rely on distributed neural networks that integrate functions of multiple regions. For example, it coordinates different brain areas to focus on or plan actions. Neurotransmitters like dopamine and acetylcholine help these systems work smoothly, influencing mood, movement and memory [13].

2.1.2 Overview of the six key domains

As stated, the DSM-5 organises neurocognitive functions into six key domains: **complex attention, executive function, perceptual-motor function, language, learning and memory, and social cognition**. These domains guide the assessment of cognitive abilities in neurocognitive disorders, linking them to neurological and psychological processes. This classification provides examples of symptoms and observations for each domain and ways to assess each domain objectively, but avoids promoting proprietary tests. Identifying the affected domains and subdomains in a particular patient can help determine the aetiology and severity of the neurocognitive disorder [16].

Complex Attention

Complex attention is a cognitive function that enables us to actively process specific information in the environment around us while ignoring other details. Our attention is limited by capacity and duration. There are several subdomains of attention:

- **Sustained attention**, or concentration, is the ability to focus on one task for extended periods.
- **Divided attention**, or multitasking, is dividing our focus between multiple tasks and responding to them at once.
- **Selective attention** involves choosing which task to focus on while ignoring disturbing stimuli.
- **Processing speed** is the speed at which we can process information.

Attention deficits can have a significant impact on daily functioning. Problems with concentration can interfere with multitasking, the ability to maintain attention during conversations, or driving. For example, when driving, selective attention is necessary to watch traffic, and divided attention is needed to check mirrors, observe the surroundings, etc. When studying, we mainly use sustained attention to maintain focus and selective attention to ignore distractions. Processing speed can be affected by various factors, like age, neurological conditions or the number of distractions in the environment.

Attention deficits are central to disorders such as attention deficit hyperactivity disorder (ADHD). People with ADHD often have difficulty focusing on tasks and ignoring irrelevant information. They can also be caused by traumatic brain injuries, Alzheimer's disease and other neurological conditions [8].

Executive function

Executive functions are high-level cognitive processes that govern other cognitive abilities, enabling effective problem-solving and planning for the future. Subdomains of executive functions include **planning, decision-making, working memory, responding to feedback, inhibition and flexibility**. They have a key role in achieving goals and adapting to new challenges.

We use executive functioning in our everyday lives, for example, to solve complex problems requiring planning, analysis, decision-making and flexibility of thinking, or to manage our finances where we need to plan our budgets, decide on our expenses and track our financial goals. Deficits in executive functions can cause impulsivity, poor decision-making, organisational problems and an inability to adapt to change. These deficits are common in different conditions such as ADHD, schizophrenia, depression and obsessive-compulsive disorder. [9]

Perceptual-motor function

Perceptual-motor function is the ability to respond to sensory information motorically, which requires coordination between vision, perception and movement. Its subdomains are:

- **Visual perception** is the ability to interpret visual information, including object recognition, spatial orientation and depth perception. It involves identifying familiar objects based on sensory information and recognising objects and sounds.
- **Visuoconstructional reasoning** is the ability to copy and create drawings of everyday objects.
- **Perceptual-motor coordination** is the ability to coordinate sensory information with motor movements. This includes motor skills such as manual dexterity, speed, reaction time and balance.

Perceptual-motor functions are essential for daily life, and impairment can lead to significant problems in everyday activities. As people age, they may experience changes in their perceptual-motor function, such as delayed reaction times. For example, older drivers have a higher accident rate than younger drivers, which may be related to reduced availability of cognitive resources. Conditions that affect perceptual-motor skills include Parkinson's disease, dementia, right hemisphere damage or injuries and trauma [9].

Language

Language is a cognitive function that includes receptive and productive skills and the ability to understand language, access semantic memory, identify objects by name, and respond to verbal cues with behavioural actions. Subdomains of language include **object naming, word finding, fluency, grammar, syntax and receptive language**, which is the ability to understand spoken and written language. Language is key in communication and cognitive evaluation, allowing people to express thoughts, feelings, and information.

Language abilities develop during childhood. Children learn to recognise and form words, sentence structures, and grammar and develop the ability to understand language. Language development is a complex process that involves the interaction of innate predispositions and experience. Language impairments may be associated with deficits in executive functions or slowed processing speed. For example, verbal fluency may be affected by slow access to semantic memory or slow processing speed. Language deficits are more common in conditions associated with brain damage, such as stroke and degenerative dementia. Aphasia is a language disorder caused by brain damage, such as stroke, and affects the ability to speak, understand speech, read and write [9].

Learning and Memory

Learning and memory are fundamental cognitive functions that enable us to acquire, retain, and use information. Memory is a complex system with multiple subdomains that are involved in different aspects of information processing and storage.

- **Free recall** is the ability to recall information without any prompts or aids.
- **Cued recall** is the ability to recall information with the help of cues that may be semantic or otherwise relevant.
- **Recognition memory** is the ability to recognise previously presented information from a set of options.
- **Semantic and autobiographical long-term memory** is a long-term storage of verbal information and critical personal experiences and events.
- **Implicit learning** is learning that occurs without conscious effort, for example, through repeated practice.

Memory and learning are fundamental as they allow us to adapt to our environment, learn new skills, and maintain identity and personal memories.

Evaluation of specific memory problems can provide important information about underlying causes and aid in diagnosing and treating various memory-related conditions. Deficits in learning and memory are common in conditions such as Amnesia, Alzheimer's disease, dementia or schizophrenia [9].

Social cognition

Social cognition is the ability to create representations of others, ourselves and relationships between them. It consists of these subdomains:

- Recognition of emotions is the ability to identify and interpret emotions, including processing and perception.

- Theory of mind is the ability to infer the intentions and beliefs of other people.
- Insight is understanding our mental and emotional states, behaviours and their effects on others.

Social cognition conditions include schizophrenia, where impaired insight can cause delusions or autism spectrum disorder [10].

In summary, the six neurocognitive domains outlined above- complex attention, executive function, perceptual-motor function, language, learning and memory, and social cognition- provide a comprehensive framework for understanding cognitive functioning and its disorders. Each domain is rooted in distinct but interconnected brain systems, and deficits in any can significantly impact daily life. For this thesis, situating complex attention within this broader neurocognitive context is essential, as it clarifies both the specificity and the interdependence of attentional processes. Given the centrality of complex attention to cognitive performance and daily functioning, a more detailed examination of its subdomains is warranted. The following section delves into these subdomains, highlighting their unique roles and relevance for digital assessment.

2.2 Subdomains of Complex Attention

Building on the preceding overview, this section focuses on complex attention and its four key subdomains: sustained attention, divided attention, selective attention, and processing speed. Understanding these components is crucial for developing practical digital game-based assessments that can accurately capture the nuances of attentional functioning.

2.2.1 Sustained attention

Sustained attention, or vigilance, is an attentional subdomain that describes the state of alertness to respond to infrequent and unpredictable cues. It is defined by the overall ability to detect cues (vigilance level) and the decline in performance over time (vigilance decrement). Brain imaging studies in humans have shown that sustained attention is associated with activating frontal and parietal lobes, particularly in the right hemisphere.

Sustained attention is a fundamental function that influences other subdomains of attention, such as divided or selective attention and cognitive abilities in general. It is essential for various aspects of our daily lives, such as driving a car, detecting social cues or learning and remembering. It can be assessed using multiple tasks including Continuous Performance Tests (CPTs) 2.4.1 where subject has to respond to different signals over an extended period. Sustained attention disorders occur in numerous conditions, such as ADHD or traumatic brain injury, and factors like variables that encumber sustained attention performance, practice, reaction time, number of signals or changes in sensitivity can affect sustained attention performance to [17].

2.2.2 Divided attention

Divided attention, or multitasking, is the ability to focus on and respond to multiple tasks or processes simultaneously. The effectiveness of divided attention depends on the functions performed; more familiar tasks require less cognitive effort and are easier to combine than complex, new tasks. It is a very complex ability; however, what we often call „multitasking“ is just rapid task-switching, so we must be careful with what we label divided attention.

Divided attention is vital in various settings, from work environments where employees must process emails while attending meetings to personal situations such as conversing while driving. It is often measured using tasks requiring the simultaneous performance of multiple activities, such as the 2.4.1, where subjects simultaneously perform two different functions. The ability to effectively divide attention is influenced by task complexity, the individual's cognitive capacity and environmental factors such as noise and interruptions. Individual differences, such as age, mental flexibility, and working memory capacity, also play an essential role [5].

2.2.3 Selective attention

Selective attention allows us to focus on one specific environmental element while ignoring other potential distractions. It is crucial for everyday functioning as it enables individuals to navigate complex environments and focus on the tasks. Selecting and processing relevant stimuli while filtering others considered less critical is essential when multiple stimuli compete for cognitive processing.

Selective attention is dynamic, adaptable to different contexts, and essential for effective interaction with our surroundings. Its importance is evident in routine and complex activities. For example, a student must focus on a lecturer's words despite background noise in a classroom. An athlete must concentrate on the ball and relevant players in sports, ignoring crowds and other pertinent stimuli. Selective attention is often measured using tasks that require participants to respond to specific stimuli amid distractors, such as the Stroop task 2.4.1, in which a person is asked to name the colour of a word that is itself the name of a colour while ignoring the meaning of the word. The effectiveness can be influenced by alertness, stimulus salience and environmental complexity [5].

2.2.4 Processing speed

Processing speed refers to the rate at which individuals can process information and respond to stimuli. It influences cognitive functions such as decision-making, problem-solving, and learning. It is the ability to perform tasks quickly and efficiently, ranging from simple to complex.

Processing speed is essential for a range of cognitive real-world tasks, particularly those requiring quick reactions to stimuli. Processing speed can be affected by various factors such as age, neurological health or psychiatric disorders. Tasks measuring processing speed often include symbol coding exercises or activities like the Trail Making Test 2.4.1, where participants are instructed to connect dots in order as fast as possible. Impaired processing speed can significantly impact daily functioning, from difficulty responding quickly to hazards (crossing a busy street) to challenges maintaining conversation [9].

The subdomains of complex attention-sustained, selective, divided attention and processing speed highlight the multifaceted nature of attentional processes. Recognising their distinct characteristics ensures that assessment tools can be tailored to identify specific deficits, which is a central aim of this thesis's game-based approach. To design robust and ecologically valid assessments, it is crucial to consider the theoretical models from cognitive psychology that explain how attention operates and fails under various conditions.

2.3 Cognitive Psychology

Following the previous discussion, cognitive psychology studies people's thinking, focusing on the interactions between thought, emotion, creativity, language, and problem-solving. It examines knowledge-related mental abilities, including attention, memory, judgment, reasoning, and decision-making. This field seeks to explain the processes of perception, knowledge acquisition, and information organisation, providing insights into how we integrate and use our cognitive experiences. Here, we will explore three key theories that have shaped our understanding of attention [6].

2.3.1 Filter Theory

Broadbent Filter Theory is one of the first information processing models. It explains attention as a filter that selects relevant information on its physical properties. According to this theory, information from the environment passes through several processing stages. The first one is called the **sensory register**; here, the information from the environment is briefly stored in its raw, unprocessed form. Then, based on physical properties such as pitch, loudness, or location, the **filter** selects information for further processing. Lastly, there is **short-term memory**. Selected information is moved to short-term memory, which is further analysed and interpreted. According to this theory, unselected information is lost and not processed further.

The Filter Theory explains how selective attention works when it is necessary to focus on one source of information and ignore other 2.2.3. Although Broadbent's filter theory is a functional starting point for understanding selective attention, its strict filter, „all or nothing," does not correspond to reality, where even inattentive information can gain our attention if it is significant to us (such as our name) [6].

2.3.2 Capacity Theory

The capacity theory of attention focuses on the idea that attention is a limited resource that we can divide between different tasks. According to this theory, we have a particular „pool" of attention that we can allocate to different cognitive processes. Performance will deteriorate if a task requires more attention than we have available.

This theory has important implications for divided attention 2.2.2. If we try to perform multiple tasks simultaneously, our attentional capacity can become overloaded, and performance on one or more tasks can deteriorate. Although the capacity theory helps understand divided attention, it has limitations because it does not precisely define „attentional capacity" and individual differences and does not consider different types of attention [6].

2.3.3 Multiple Resource Theory

Christopher Wickens, in this theory, extends the capacity theory by arguing that attention is not a single entity but a collection of multiple independent resources that we can use to perform different tasks. These resources are divided into these four main dimensions:

- Processing stages: Perception (visual, auditory) versus cognition (information processing, working memory).
- Perceptual modalities: Auditory versus visual.
- Visual channels: Central vision versus peripheral.

- Processing codes: Spatial/analogue versus verbal/symbolic.

According to this theory, multitasking 2.2.2 is more effective when tasks use different resources. Although it offers an interesting perspective on multitasking, its complexity, resource overlapping and lack of consideration of factors like automation or resource allocation make it challenging to test and limit its practical utility [22].

The cognitive psychology theories reviewed offer valuable frameworks for understanding the allocation, limitation, and flexibility. These models explain why individuals struggle with multitasking, filtering distractions, or maintaining focus and underscore the need for assessment methods to capture these complexities. Building on these theoretical foundations, the following section explores how traditional and digital assessment tools have been developed to operationalise and measure the nuanced facets of attention.

2.4 Existing Assessment Methods

To effectively evaluate complex attention and its subdomains, various assessment methods have been developed, each informed by the cognitive psychology theories discussed previously. These methods aim to capture the nuances of attentional processes, as these theories outline. By understanding how these theories apply to real-world scenarios, we can better appreciate the strengths and limitations of different assessment tools. Here, we will explore traditional methods and digital tools, each offering unique insights into the complex nature of attention.

2.4.1 Traditional Methods

Traditional assessment methods have been the foundation for evaluating cognitive functions, including complex attention. These methods mainly consist of **standardised cognitive tasks** conducted in controlled environments to minimise distractions and ensure consistent conditions across different sessions. Each task typically targets a specific attention subdomain, such as sustained, selective, or divided attention. Regular testing ensures their reliability and validity, and the availability of normative data allows for meaningful comparisons with typical performance levels for specific demographics. By leveraging these standardised tasks, researchers and clinicians can gain insights into an individual's attention strengths and challenges, ultimately informing diagnostic and intervention strategies.

Rapid visual information processing (RVP)

The RVP task is primarily used to assess sustained attention 2.2.1. Participants are presented with a rapid stream of digits and must identify specific patterns or target digits. It demands sustained attention to maintain focus on the stimulus stream over time and quick reaction time to respond to the target pattern. While the specific visual presentation of the task can vary, the core principles of sustained attention and rapid information processing (reaction time) remain consistent. However, its limitation lies in its specificity to sustained attention, potentially missing other attentional subdomains [1].

Continuous Performance Test (CPT)

The CPTs are computerised tests designed to assess sustained attention, 2.2.1 and impulsivity. Participants are presented with a series of various shapes, pictures or flashes on the screen and must respond to specific targets, typically by clicking a mouse button. CPTs measure various attentional parameters, including reaction time, accuracy, and error rates. While effective for diagnosing attention-related disorders like ADHD, CPTs may not reflect real-world scenarios and can be time-consuming.

The Stroop test

The Stroop test is a powerful tool for assessing selective attention 2.2.3 and processing speed 2.2.4. This cognitive task challenges individuals to focus on relevant information (the colour of the text) while disregarding conflicting information (the word itself). Doing so tests our cognitive control and ability to filter distractions, providing valuable insights into our attentional processes.

Stroop's original experiment presented participants with colour words printed in incongruent ink. First, he asked them to name the ink colour of the word and then to read the word itself. Stroop found that participants took significantly longer to name the ink colour of incongruent words than to read the names of colours. The Stroop's effect highlights how automatic reading can lead to cognitive interference when people encounter conflicting information. However, it may not capture the complexity of real-life attentional demands [3].

Figure 2.3: Stroop test comparison

Flanker test

The Eriksen Flanker test assesses selective attention 2.2.3 and inhibitory control. Participants are presented with a central target stimulus flanked by congruent, incongruent or neutral distractors. In congruent trials, the flankers (stimulus presented alongside a target stimulus) point in the same direction as the target, while incongruent trials point in the opposite direction. Neutral trials present flankers that are unrelated to the target.

Participants are required to respond to the target stimulus, ignoring the flanking distractors. Incongruent trials pose a more significant challenge as they require individuals to inhibit responses to the conflicting information provided by the flankers. It helps understand how individuals manage contradictory information, but may not correctly reflect multitasking scenarios.

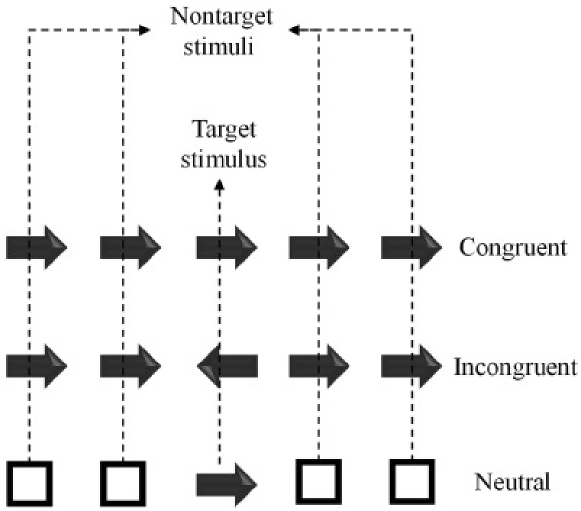


Figure 2.4: A schematic of Eriksen flanker task modes [2]

Dual-task paradigm

Dual-task paradigms assess divided attention by requiring participants to perform two tasks simultaneously. Participants must perform two tasks simultaneously, such as two speeded sensory-motoric tasks, two perceptual tasks, two working memory tasks, or multiple simulated real-life tasks like cooking and shopping. Researchers can assess an individual's multitasking ability by measuring performance on both tasks, but it can be influenced by task complexity and individual differences [21].

Multi-source interference task (MSIT)

The MSIT combines elements of cognitive interference from tasks like the Stroop 2.4.1 and Flanker tasks 2.4.1. During the task, participants are presented with sets of three numbers or letters and must identify the number that differs from the others while ignoring distractors. The task alternates between control trials (where the target number aligns with its position) and interference trials (where the target number does not match its position), which increases cognitive load and tests their divided attention. It is useful for testing how well individuals manage multiple conflicting information sources, but its complexity can make it challenging to interpret results [7].

Trail making test (TMT)

The TMT assesses processing speed by requiring participants to connect dots in numerical order as quickly as possible. It consists of two parts: TMT Part A, where participants connect numbers sequentially, and TMT Part B, which alternates between numbers and letters. Part B is more challenging as it requires task-switching, engaging processing speed and cognitive flexibility. Performance can be influenced by factors such as age, education, and neurological conditions, potentially limiting its generalizability [4].

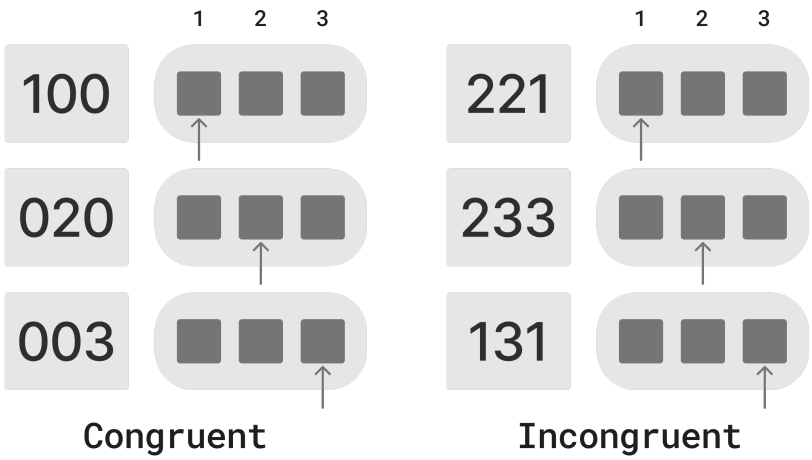


Figure 2.5: MSIT trial examples

Symbol search task

In this task, participants are presented with two target symbols on the left side of each row and a „search set“ of five symbols on the right. The goal is to indicate whether either of the two target symbols appears in the search set by responding „yes“ or „no.“ The overall score is based on the number of correct responses minus incorrect ones within two minutes, providing an index of processing speed. Different versions of the Symbol Search task may exist and be adapted for various settings or research purposes. While quick to administer, it might not capture the full spectrum of attentional abilities [14].

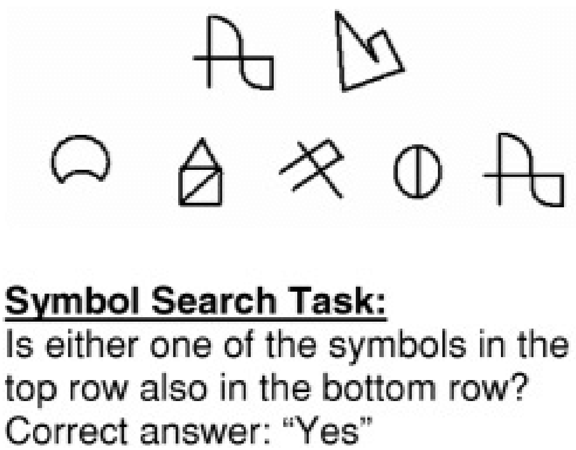


Figure 2.6: Symbol search task [20]

2.4.2 Digital Methods

Digital assessment methods represent a significant advancement in evaluating complex attention. These methods leverage technology to create engaging, interactive, and adaptive testing environments that simulate real-world scenarios more effectively than traditional methods. By incorporating game-like elements, these assessments enhance participant motivation and provide a more accurate and objective evaluation of cognitive functions. Digital tools offer a range of tasks designed to measure various attentional subdomains. Virtual reality assessments immerse users in a controlled yet ecologically valid environment, providing detailed insights into attentional mechanisms and related cognitive functions.

Digital tools

Digital tools for assessing attention are being developed and used in various forms, from game-inspired approaches to traditional but digitised cognitive tasks. Game-based approaches often seek to increase participant motivation and engagement, but non-gaming methods also play a key role in assessing attention and cognitive function.

Game-based approaches include games that measure reaction time, accuracy and other aspects of attention. These games may incorporate various game mechanics, such as points, narratives and avatars, to increase engagement. Games are developed to mimic cognitive tasks or are specifically designed based on theories of cognition. However, game elements can influence attention, which is essential to consider when using them for assessment [23].

Non-game digital tools include digitised standard cognitive tasks, the basis for many game-based assessments. These tasks measure reaction time and accuracy in responding to stimuli and are essential for validating game-based methods. Neurofunctional methods include electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS), which monitor attention-related brain activity. These methods are also used outside of the gaming context to monitor cognitive load, engagement, mental effort, and emotional states. Other non-gaming tools include physiological measurements such as electrodermal activity (EDA) and heart rate, which are obtained using wearable technologies. These data are valuable in detecting cognitive, emotional, and motivational processes [11].

Statistical methods and machine learning are used to analyse data from digital tools. These methods allow for identifying patterns in behaviour and drawing conclusions about cognitive processes [11]. Rayyan software is used in systematic reviews to screen records, which is useful when working with large data sets. Data analysis uses qualitative and quantitative methods [23].

Virtual reality (VR) assessment

Virtual reality (VR) is becoming an increasingly popular tool for assessing cognitive functions, especially attention. Traditional methods, such as questionnaires and tests, have limitations, such as subjectivity or the possibility of manipulation. VR offers a more immersive and controllable environment for measuring attention and recording various variables such as eye movements, reaction time and number of errors.

One of the main advantages of VR is its ability to create a natural and fun environment, which can increase the motivation and engagement of participants. VR games can be designed to simulate everyday situations and tasks, thus improving the ecological validity of the assessment. In addition, VR allows for continuously measuring variables throughout the game, providing a more detailed picture of the user's behaviour.

A VR game, *Treasure Hunt*, involves following a treasure chest while the chests are moved and distracting elements appear. Using VR headsets and controllers, the game records eye movements, pupil dilation, blinks, and other variables. This data is then used to build a machine-learning model that predicts scores on attention and impulsivity questionnaires. The study results of this game showed that the time spent looking at the correct chest and distractors, eye movement variability, and pupil dilation are significant predictors of attention. The more time a player spends looking at the correct chest, the higher their attention. Conversely, the more time they spend looking at distractors, the lower their attention. In addition, the number of errors and reaction time are also crucial for predicting attention [15].

2.4.3 Assessment methods comparison

Table 2.1: Comparison of assessment methods

	Standardized Cognitive Tasks	**Digital Tools**	**Virtual Reality Assessments**
Strenghts	Reliable and validated with normative data	Interactive and engaging, often incorporating gamified elements	Immersive and ecologically valid, simulating real-world scenarios.
	Controlled environment minimises distractions	Real-time feedback	Continuous data collection for detailed analysis (e.g., eye movements, reaction times)
Limitations	May not reflect real-world scenarios.	Game elements can influence attention, complicating interpretation	High cost of equipment and complexity of implementation
	Time-consuming and resource-intensive for repeated use.	Potential biases in participant engagement depending on design (e.g., gamified vs non-gamified).	performance may decline due to increased task complexity compared to traditional methods.

2.4.4 Performance Metrics

A range of metrics informed by cognitive psychology and neuropsychological research is employed to assess attention across various subdomains objectively. These metrics encompass several approaches, including:

1. ***Accuracy*** - percentage of all trials in which a subject makes a correct response [19]

$$Accuracy = \frac{Hits + CorrectRejections}{TotalNumberOfTrials} * 100$$

2. ***Sensitivity index d'*** - measures the ability to differentiate between trials where the target is present[19]

$$d' = Z^{1}(HitRate^{2}) - Z(FalseAlarmRate^{3})$$

3. ***Response bias*** β - the general tendency for a subject's response (liberal = higher hit and false alarm rate / conservative = lower hit and false alarm rate)[19]

$$\beta = \exp\left(Z(FalseAlarmRate)^2 - Z(HitRate)^2\right)/2$$

4. ***Vigilance decrement*** - decline in performance across time (block-by-block analysis) [18]

[1] inverse phi function (inverse of the normal cumulative distribution function)
[2] Hits / Total number of targets
[3] False Alarms / Total number of non targets

5. ***Reaction time*** - mean, variability (standard deviation), and Intra-individual coefficient of variation (ICV) [26]

$$ICV = \frac{SD}{mean} * 100$$

The strengths and limitations identified in this section point to a persistent gap: the need for assessment tools that combine the rigour of traditional methods with the engagement and ecological validity of digital platforms. This gap motivates exploring a game-based assessment hybrid approach that integrates methodological rigour with immersive design, a promising direction for future development.

2.5 Game-Based Assessment

To address the limitations of traditional and digital methods, game-based assessment (GBA) emerges as a hybrid approach that combines standardised measurement principles with engaging, ecologically valid environments. By leveraging gameplay mechanics grounded in cognitive theory, GBA aims to bridge the divide between laboratory-controlled tasks and real-world attentional demands. Games offer a dynamic, interactive, immersive environment that can improve participants' motivation and engagement.

Games can simulate real-world situations, allowing for assessing cognitive abilities in conditions that are more similar to participants' real lives. Complex attention is an area where games have special benefits, as they can simulate situations requiring sustained attention across many stimuli and tasks.

Games are inherently motivating, which can increase the engagement and cooperation of test subjects. As mentioned, they mimic real-world situations, providing more valid data on the player's cognitive abilities. They allow for the collection of extensive data on the player's behaviour throughout the game interaction, providing a detailed view of players' cognitive processes, and they can be easily accessible and applicable to large populations. On the other hand, games can manipulate attention through elements such as graphics and sounds. Therefore, games assessing attention need to be thoroughly tested and validated.

2.5.1 Gamification approaches in assessing complex attention

Gamification uses game elements and principles in a non-game context to increase motivation and engagement. Game elements include points, rewards, challenges, leaderboards, stories and visual effects. This approach is also used in cognitive testing. Game elements make testing more enjoyable and less stressful, increase a sense of achievement, and encourage further activity. Adaptive tests, which change the difficulty level based on performance, help maintain an optimal level of challenge and prevent boredom or frustration.

Examples of gamified methods in cognitive assessment:

- Go/no-go game with dragons
- Stop-signal game with points
- Multiple object tracking (MOT) game
- Whack-a-mole

There are several advantages of gamification for attention assessment, for example, improved engagement of test subjects, increased participation and reduced dropout rates, the possibility of capturing a wide range of data in real-time, the ability to test in different contexts and conditions and an increase in the ecological validity of the assessment. On the other hand, gamification has several limitations. It may be less accurate in capturing specific subdomains of attention compared to traditional methods that are more focused on specific cognitive processes; there could be bias in results due to higher motivation during the game, game elements can influence attention through visual or auditory stimuli, and it may not be suitable for everyone. When creating gamified methods, it is necessary to balance game and assessment objectives [11][24].

2.5.2 Custom-designed games

Custom-designed digital games are specially developed and purposefully designed to assess specific cognitive functions, especially individual subdomains of complex attention. The significance of these games lies in their ability to provide more accurate and relevant data on cognitive abilities than commercial games. They are designed with specific research goals or clinical needs, allowing for customising tasks and measurements. Game mechanics and design are specifically selected to accurately measure the desired cognitive processes.

Examples of custom-designed games in cognitive assessment:

- 21 Tally
- EndeavorRX (EVO)
- Chefmania
- MusVis

Custom-designed games have high specificity for individual cognitive functions because games are precisely targeted to measure specific attention subdomains. They allow game design adaptation to particular goals and testing in different contexts and conditions. These games can also assess cognitive functions in specific groups, such as children with developmental disorders. However, they may be less accurate in determining specific subdomains compared to traditional methods, and there can be bias in results due to higher motivation or learning during the game [11][24].

2.5.3 Commercial games

Commercial games are primarily intended for entertainment, not cognitive assessment. However, they contain mechanisms and game elements that indirectly test attention and can be used to measure it. These games require reaction time, problem-solving, multi-tasking, and other attention-related cognitive functions. Researchers are investigating how commercial games can be used as a replacement for traditional psychological tests. For example, the game Tetris has been used to measure divided attention.

Examples of custom-designed games in cognitive assessment:

- Tetris
- Fruit Ninja
- Candy Crush Saga

- Crash Bandicoot
- Shadow of the Colossus

Commercial games are cheap and commonly available in app stores or online. They are designed to be fun and engaging, which can increase participants' motivation and improve the quality of data collected. The gameplay resembles the real world, which can increase the ecological validity of the research. However, they were not designed for research or clinical purposes and lacked standardisation and validation. They may not accurately assess individual aspects of attention, and researchers do not have control over the design and mechanics of the game. It is difficult to determine which game elements affect player performance and whether attention or other cognitive functions are truly being measured [11][24].

2.5.4 Limitations

A systematic review of digital games used to assess attention, conducted by a team from the University of Saskatchewan [24], reveals several critical limitations in current GBA approaches for attention. While digital games are increasingly adopted to address the shortcomings of traditional attention assessments, such as low engagement, lack of ecological validity, and limited scalability, the review highlights that the field faces significant methodological and conceptual challenges that must be addressed before such tools can be widely trusted or standardised.

One of the foremost limitations is the difficulty of validly measuring attention within a game context. Unlike traditional cognitive tasks, digital games are designed to be engaging, often employing points, graphics, narrative, and feedback. These very features, intended to enhance motivation and enjoyment, can manipulate a player's attention in ways that are not directly related to the cognitive processes under assessment. For example, including points may incentivise faster responses at the expense of accuracy- a classic speed-accuracy trade-off- thus altering what is being measured. Similarly, thematic or narrative elements can temporarily increase engagement but may also lead to disappointment if the gameplay does not sustain initial expectations, further complicating the interpretation of performance data. Even the choice of stimuli, such as using cartoon characters instead of simple shapes, has decreased performance on attention tasks, likely due to increased perceptual complexity.

The review also underscores a pervasive lack of rigorous evaluation and standardisation across studies. Many GBA studies do not systematically assess core psychometric properties such as validity, reliability, sensitivity, and specificity. Of the 33 studies that gamified traditional cognitive tasks, less than half directly compared the game-based version to the original task to determine whether the gamified version retained its measurement properties. Furthermore, only a minority of studies evaluated whether the games were more enjoyable or engaging than traditional tasks, despite this being a primary motivation for their use. This reliance on untested assumptions, such as the belief that any game-like element will automatically enhance engagement or data quality, remains widespread, even though empirical evidence often contradicts these claims.

Another significant barrier is the lack of integration and standardisation in developing and evaluating these games. There is currently no consensus or established framework guiding how assessment games should be designed, what features they should include, or how their measurement properties should be validated. As a result, methodologies vary widely, making it difficult to compare results across studies or to build a cohesive body of evidence. This fragmentation is further exacerbated by the fact that most research teams lack interdisciplinary expertise, particularly in game design, which is crucial for balancing engaging gameplay with rigorous assessment.

Finally, the review points to concerns about generalizability. The high degree of contextualisation in many assessment games, where performance may depend on familiarity with specific game mechanics or digital interfaces, raises questions about whether results can be extrapolated to broader populations or real-world attentional abilities. For instance, older adults or individuals with limited gaming experience may perform poorly not because of attentional deficits but due to unfamiliarity with the digital environment [25][12].

In summary, while digital games hold promise for advancing the assessment of attention, the current landscape is hindered by challenges in isolating the construct of attention from game-induced effects, insufficient psychometric evaluation, lack of standardised development practices, and limited generalizability. These limitations are summarised in Table 2.2 below.

Table 2.2: Limitations of different game-based assessments

Gamified tasks	Game elements (e.g., points, graphics, themes) can unintentionally alter attention measurement	Lack of rigorous validation against original tasks	Assumptions that gamification improves engagement or validity are rarely tested	Limited evaluation of both assessment and engagement properties
Custom-designed games	Diverse and inconsistent design rationales, often lacking theoretical grounding	No standardized frameworks for development or evaluation	Difficult to compare results across studies due to methodological variability	Limited interdisciplinary input, especially from game design experts
Commercial games	Not originally designed for cognitive assessment, so alignment with attention constructs is unclear	Limited evidence on validity and reliability for attention measurement	performance may be influenced by prior gaming experience rather than attention alone	

This literature review demonstrates that while significant progress has been made in understanding the neurocognitive domains and subdomains of complex attention and in developing both traditional and digital assessment methods, notable limitations persist. Conventional tools, though reliable, often lack ecological validity and fail to capture the dynamic, multifaceted nature of attention in real-world contexts. Digital and game-based assessments offer greater engagement and adaptability. However, current approaches frequently suffer from insufficient coverage of all attention subdomains, a lack of standardisation, limited psychometric validation, and challenges isolating attentional constructs from game-induced effects. These methodological and practical gaps underscore the need for a robust, evidence-based solution to deliver valid, reliable, and ecologically relevant assessments of complex attention. The following chapter presents the conceptual framework and justification for the proposed ***Attentia*** platform, designed to address these challenges and advance the field of digital cognitive assessment.

Chapter 3

Solution design

Building on the critical analysis in Chapter 2, this chapter introduces ***Attentia***, a modular digital platform developed to overcome the methodological and practical limitations identified in existing tools. The solution leverages evidence-centred game design, standardised metrics, and cloud-enabled data aggregation to provide valid, reliable, and ecologically relevant evaluations of all four subdomains of complex attention: sustained, selective, divided attention, and processing speed. By directly addressing gaps in measurement validity, standardisation, and generalizability, the platform aims to bridge the divide between laboratory-grade rigour and real-world applicability. This chapter details the conceptual architecture, key components, and design rationale underlying ***Attentia***.

3.1 Problem and requirements

As stated in the previous chapter, traditional game-based assessments (GBAs) for measuring attention often suffer from several limitations:

- **Lack of Validity in Game Contexts:** Many GBAs do not measure attention constructs in a manner consistent with established cognitive psychology, leading to questionable validity of results.
- **Insufficient Psychometric Evaluation:** A lack of systematic evaluation and standardisation makes comparing results across populations or over time difficult.
- **Inconsistent Frameworks:** Existing solutions often lack a unified implementation framework, resulting in fragmented data collection and analysis.
- **Limited Generalizability:** Results from many GBAs are not easily extrapolated to broader or diverse populations due to a lack of normative data and cross-population comparability.

The ***Attentia*** project aims to address these challenges by implementing a standardised, psychometrically grounded, and generalizable framework for attention assessment within a game context.

The solution outlines several key requirements based on the assignment details, literature review, and analysis of existing gaps.

Firstly, the system must implement standardised attention metrics from cognitive psychology, including sensitivity index (d'), response bias, accuracy, and reaction time variability for all game types. Each attention game—sustained, selective, divided, or processing

Table 3.1: Requirements mapping

Requirement	Solution Components	Description/Justification
Standardized attention metrics	MetricCollector, MetricAnalyzer	Implements validated psychological metrics
Task-specific metric collection	Game modules (e.g., DividedAttention)	Specialized metrics for each attention construct
Population-based normative data	MetricDistributionManager	Aggregates data for percentile calculations
Unified data collection & analysis	Core framework services	Ensures consistency across all game types
Comparative result presentation	stats.tsx, result presentation layer	Displays percentile ranks and trends
Data privacy	Data storage and anonymization logic	Anonymizes and secures user data
Scalability	Modular architecture, efficient storage	Supports large and growing user base
Extensibility	Modular codebase, plugin support	Allows easy addition of new games/metrics
Usability	stats.tsx, UI components	Clear, standardized result presentation

speed—should capture task-specific metrics relevant to its construct, such as error asymmetry for divided attention.

Furthermore, the system should aggregate user data to create population-based normative data for percentile-based performance comparisons. A unified framework for data collection and analysis across game modules is essential to ensure that results are presented as percentile ranks and trends, not just absolute scores.

Non-functional requirements also play a crucial role. Data privacy must be prioritised by ensuring user information is anonymised and securely stored. The system should be scalable to accommodate increasing users and datasets while being extensible to integrate new attention games and metrics. Lastly, usability is important; the interface should present results in a clear format accessible to users and researchers.

3.2 Assumptions and constraints

Several key assumptions were established to guide the development process when designing Attentia. First, it is assumed that users are genuinely motivated to perform their tasks to the best of their abilities, and their performance will accurately reflect their true attention capabilities. Additionally, it is anticipated that, over time, sufficient user data will be collected, allowing for the reliable calculation of normative percentiles. Another important consideration is that users will access the system on compatible devices, whether desktop or mobile(Android), capable of running the games with minimal performance issues.

The metrics implemented within the system, such as sensitivity (d') and response bias, are believed to be valid indicators of attention constructs in a gamified context. Furthermore, there is an expectation that the user base will be diverse enough to support the development of generalisable normative data.

However, the project also faces several constraints. Technically, the system must function within the performance limitations of web and mobile platforms, and data storage and processing must adhere to privacy regulations, such as GDPR. The system's architecture needs to be modular to allow for future extensions.

From an organisational perspective, the project is limited by the available development time and resources, and user recruitment for the necessary population-level data relies on voluntary participation. Scientifically, it is important to note that the current implementation lacks direct validation against traditional, non-gamified attention tasks. Additionally, there is no explicit measurement of user engagement or familiarity with the interface included in the design, which could influence performance outcomes for various user groups.

3.3 Overview of the proposed solution

Attentia employs a modular, component-based architecture designed to deliver standardised cognitive assessments through an engaging game interface. The solution integrates frontend user interfaces, specialised cognitive games, a comprehensive metrics system, and secure backend services within a coherent framework.

The architecture is structured into four primary layers, as illustrated in Figure 3.1:

1. **Frontend Layer**: Provides user interfaces across multiple platforms
2. **Game Engine Core**: Centralises gameplay mechanics and state management
3. **Cognitive Assessment Modules**: Implements specialised attention assessment games
4. **Metrics and Backend Services**: Handles data collection, analysis, and storage

The frontend layer provides a consistent user interface across platforms, featuring reusable UI components to enhance design consistency. The Game Engine Core centralises state management, visual rendering, and input processing and controls the game lifecycle. Four cognitive assessment modules focus on sustained attention, selective attention, divided attention, and processing speed. The metrics system transforms gameplay data into assessments using a metric collector, analyser and threshold manager, while an analytics service identifies trends. Backend services manage data persistence and authentication with Firebase, storing user profiles and performance metrics.

Utilising React Native with Expo allows platform independence while maintaining native performance, enabling iOS, Android, and Web deployment from a single codebase. This component-based architecture promotes a clear separation of concerns, enhancing maintainability and allowing independent component updates. It is also designed for extensibility, making it easy to integrate new cognitive games and improving testability by allowing components to be tested in isolation.

The metrics system is isolated as a separate component for standardised assessments using established psychological metrics. It enables effective population comparisons and maintains statistical rigour by addressing outliers and conducting distribution analyses while supporting longitudinal change tracking.

Security and privacy considerations are integral, employing secure authentication via Firebase and anonymising data to protect user information with role-based access controls in place.

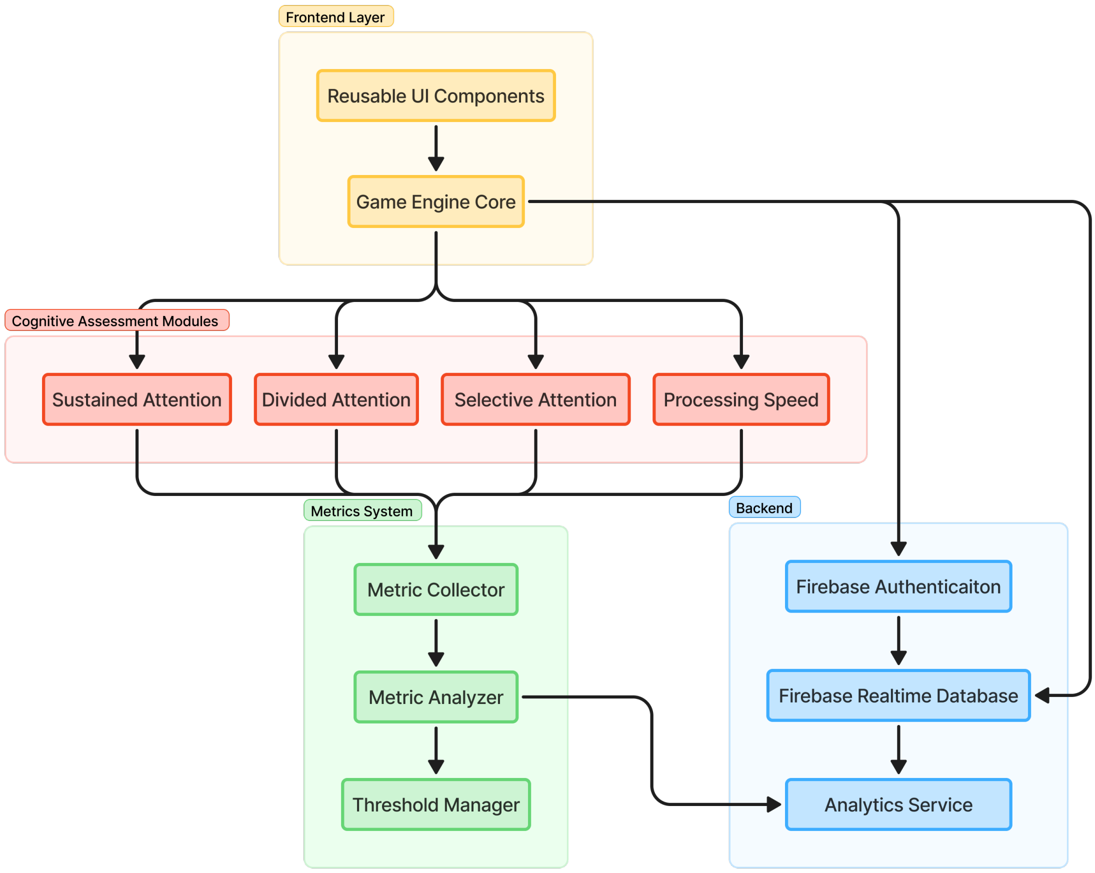


Figure 3.1: System architecture diagram

This architectural approach balances development efficiency with scientific validity, user experience, and data security- all critical requirements for a cognitive assessment application with potential clinical applications.

3.4 Component-level design

This section briefly outlines the main components of the ***Attentia*** platform, focusing on their role, data flow, and key design decisions.

3.4.1 Game Engine Core

The purpose of this component is to centralise the game mechanics and manage the state for all attention games. It receives various game configurations, such as the duration and type of the game, and in return, it outputs the current game state, control functions, and performance metrics.

The logic behind the system involves managing the game's timing, tracking performance in terms of hits and misses, and coordinating the saving of statistics. This centralised approach is essential as all game-specific modules utilise it, and it interfaces with Firebase for data storage, ensuring seamless interaction and data management across the platform.

3.4.2 Game-specific modules

A central element of the ***Attentia*** platform's solution design is the implementation of four distinct game modules, each systematically targeting a core subdomain of complex attention. These modules are grounded in validated cognitive paradigms and are engineered to provide standardised, reliable, and ecologically meaningful assessments. Their design directly addresses the requirements for measurement validity, standardisation, and generalizability outlined earlier in this chapter.

Sustained Attention Game

This module is designed to measure the user's capacity to maintain focused attention and vigilance over extended periods, a critical facet of real-world cognitive functioning.

The game is modelled after the Continuous Performance Test (CPT). Users monitor a grid for infrequent target stimuli among frequent non-targets, responding as quickly and accurately as possible when a target appears. The task duration and stimulus frequency are calibrated to induce a measurable vigilance decrement.

Performance is quantified using metrics such as hit rate, false alarms, mean reaction time, and vigilance decrement (performance decline over time). Each trial's response and timing are recorded for detailed analysis.

The Continuous Performance Test (CPT) is a reliable measure of sustained attention and impulsivity, backed by extensive normative data. Attentia enhances this by using a gamified format that maintains validity while providing adaptive feedback and multitasking assessments for a comprehensive cognitive profile.

Traditional CPTs can be monotonous, leading to disengagement, especially in children. Attentia addresses this with interactive graphics and immediate feedback, improving engagement and potentially yielding more valid data.

While standard CPTs offer basic metrics, Attentia captures detailed trial data, enabling deeper analysis of attention lapses and performance trends over time. Designed for mobile use, Attentia supports remote assessments with automated scoring and cloud data management, simplifying administration.

Selective Attention Game

This module evaluates the ability to filter out irrelevant information and focus on task-relevant cues, reflecting cognitive control and interference resolution.

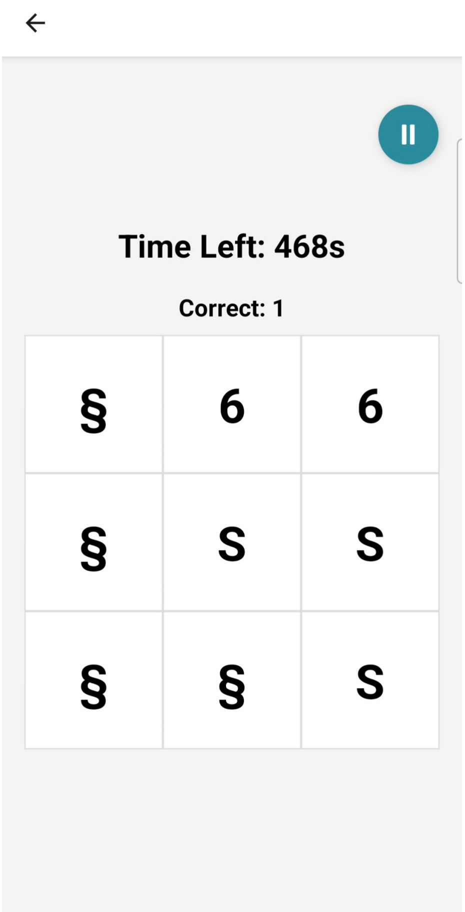
Drawing on the Stroop test paradigm, users are presented with colour words displayed in congruent or incongruent font colours. The task is to identify the font colour, not the word itself, thereby eliciting interference effects.

Key metrics include accuracy, reaction times, and the interference effect (performance difference between congruent and incongruent trials). Each response is logged to calculate interference indices.

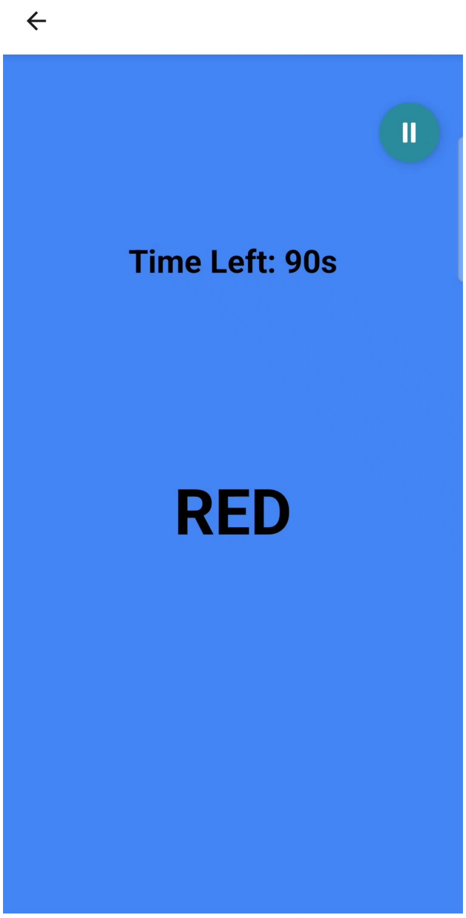
The Stroop paradigm is widely recognised for its sensitivity to selective attention and cognitive control.

Divided Attention Game

This game assesses the user's ability to monitor and respond to multiple streams of information simultaneously, modelling real-world multitasking demands.



(a) Sustained attention



(b) Selective attention

Inspired by dual-task paradigms, users must track and respond to both shape and number stimuli presented in parallel, requiring rapid switching and divided focus.

Metrics include accuracy and reaction times for each stimulus type, as well as measures of task-switching cost and error asymmetry. Data is collected for each stream independently and in combination.

Dual-task paradigms are a standard in cognitive assessment for divided attention, providing both ecological validity and methodological robustness.

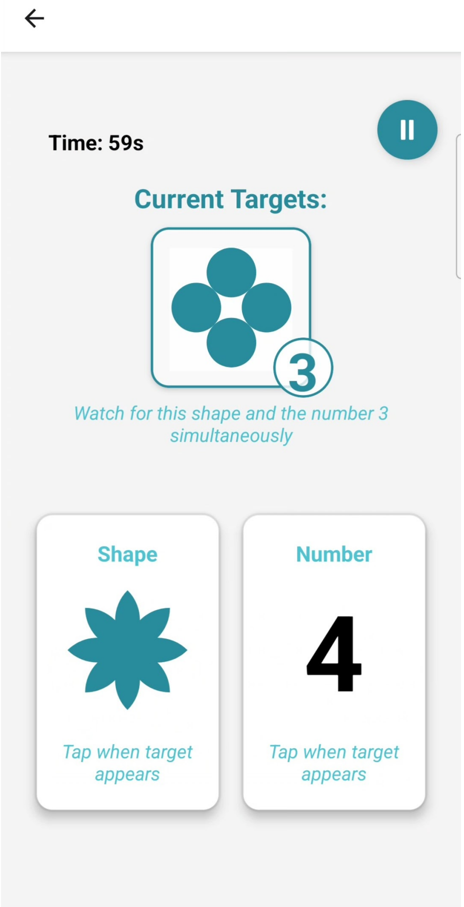
Processing Speed Game

This module measures the speed and efficiency of cognitive processing, particularly in tasks requiring rapid visual search and sequencing.

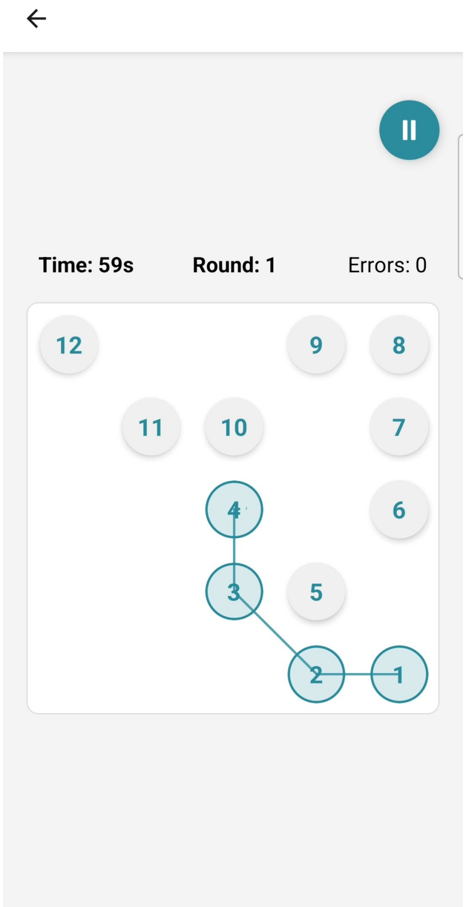
Modelled on the Trail Making Test (TMT), users are required to connect a sequence of numbers in the correct order within a grid as quickly as possible.

Collected data includes completion time, sequence accuracy, and error rates, with detailed tracking of the order and timing of each connection.

The TMT is a benchmark tool for measuring processing speed and executive function, supporting the platform's goal of standardised and interpretable assessment.



(a) Divided attention



(b) Processing speed

Component	Based-on	Key Logic	Interactions
Sustained Attention	CPT	Generates targets, tracks vigilance	Uses core engine, feeds UI
Selective Attention	Stroop test	Mixes congruent/incongruent stimuli	
Divided Attention	Dual-task	Manages dual streams, task-switching	
Processing Speed	TMT	Grid-based sequencing, error tracking	

Table 3.2: Game-specific modules

3.4.3 Game UI Components

The game UI components serve a critical purpose by rendering interactive interfaces for players while displaying the results of their actions. These components rely on inputs derived from the game state and various metrics that the logic modules provide. The underlying logic is responsible for managing user input, offering feedback to players, and handling the game's flow through its different screens, including the start screen, gameplay, and results presentation.

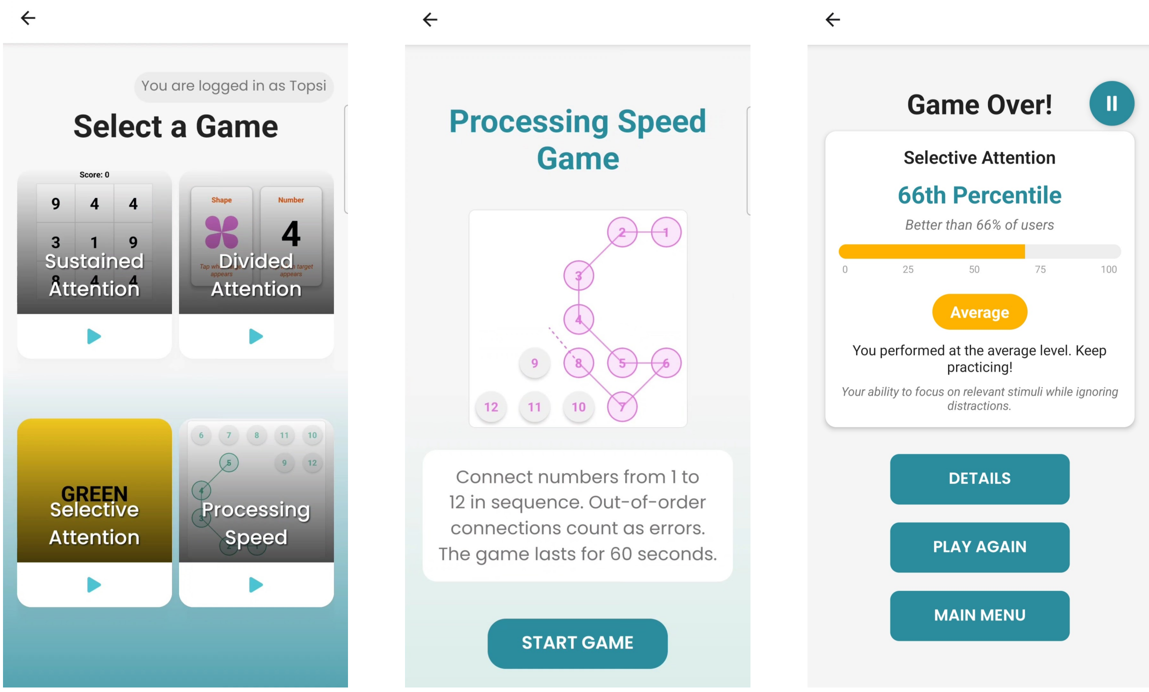


Figure 3.4: Main screens of the app

3.4.4 Statistics and analytics

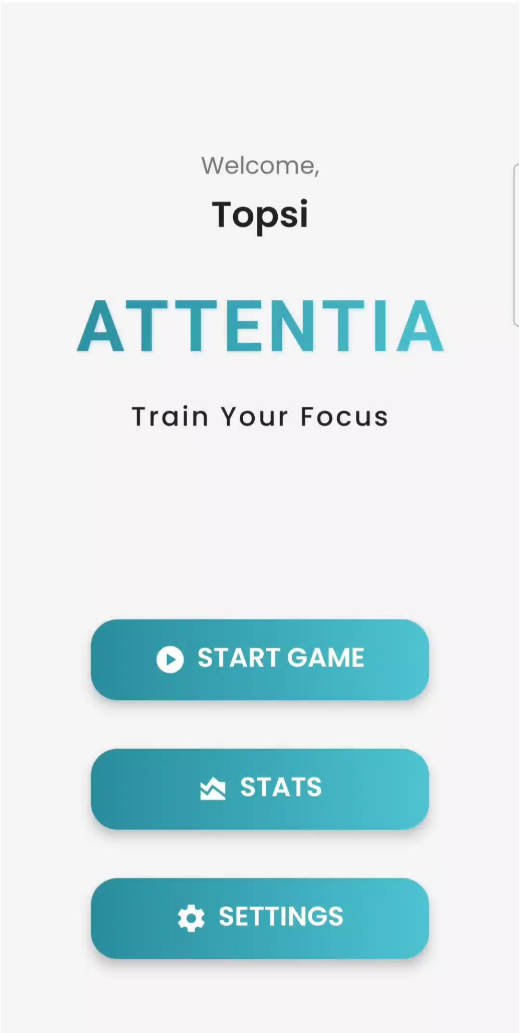
The purpose of the Statistics and Analytics system is to calculate and visualise user performance across various games. It receives raw game data and processes this information to generate essential metrics such as accuracy, reaction time, and percentiles. The logic behind this system involves standardising the metrics and comparing them to population norms while dynamically updating thresholds based on the data analysed. Additionally, the system interacts with Firebase to read and write data, providing valuable feedback to users based on their performance.

3.4.5 Authentication and user management

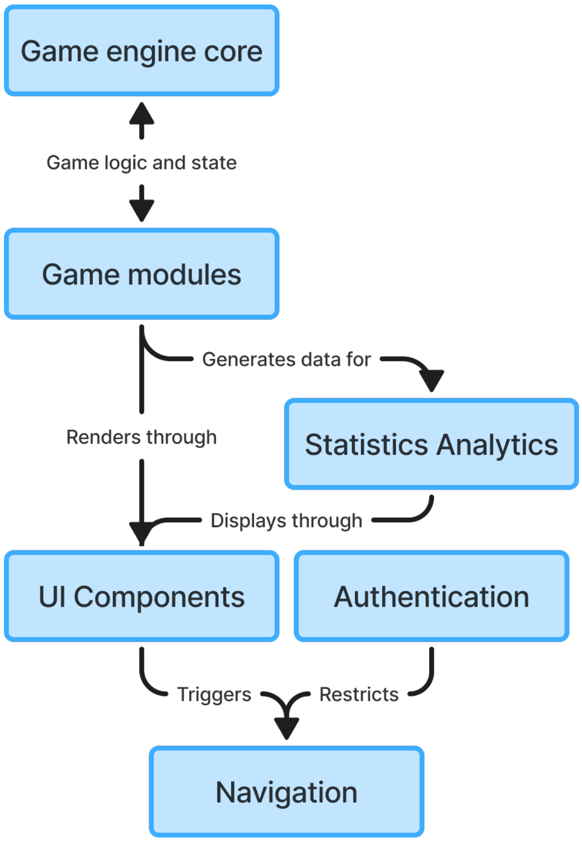
Handles user login, registration, and session management. This system integrates with Firebase Authentication to ensure a secure and reliable authentication process while maintaining a secure user context throughout the user's interactions.

3.4.6 Navigation and app structure

It serves a crucial purpose by managing game selection and guiding users through the app. It effectively displays the available games, ensuring users can easily find what they seek. Additionally, the system routes users seamlessly from one section to another, adapting to various device screens to enhance the overall user experience.



(a) Main menu



(b) Component diagram

3.5 Data Management Strategy

A recurring challenge in the field of game-based attention assessment is the absence of standardised metrics and universal thresholds for interpreting user performance. As highlighted in recent reviews, studies often differ in what data they collect and how they interpret results, making it difficult to compare findings or provide meaningful feedback to users. To address this gap, a hybrid threshold system was designed to evolve as more data is collected, ensuring that performance feedback is both evidence-based and adaptive to the growing user base.

3.5.1 Data collection

Attentia systematically collects both universal and game-specific metrics across all four attention assessment games (sustained, selective, divided attention, and processing speed).

- **Universal metrics** include accuracy, reaction times (millisecond precision), session duration, signal detection metrics (hits, misses, false alarms, correct rejections), and session metadata (device info, timestamp, completion status).

Data type	Firebase path	Structure
User-Specific Metrics	*users/${userId}/gameStats*	Session timestamps, raw/processed metrics
Anonymized Population	*anonymizedMetrics/${autoId}*	Game type, numeric metrics, no PII
Statistical Norms	*metricDistributions/${game_metric}*	Mean, σ, percentiles (p5-p95)

Table 3.3: Storage architecture

- **Game-specific metrics** are tailored to each subdomain, such as vigilance decrement for sustained attention, congruency effects for selective attention, error asymmetry for divided attention, and path completion time for processing speed1.

All user interactions are logged in real time, ensuring high-resolution data for subsequent analysis.

3.5.2 Data processing pipeline

The data pipeline follows a structured, multi-stage process:

1. **Raw data validation:**
   - Invalid entries (e.g., negative reaction times) are discarded.
   - Derived metrics are calculated using cognitive formulas.
2. **Standardization:**
   - Signal filtering removes anticipatory responses (<100 ms).
   - Outlier detection filters responses beyond 3 standard deviations.
   - Real-time calculations provide immediate feedback.
3. **Population Comparison**
   - Percentile ranks generated against anonymised Firebase distributions.
   - Aggregate metrics percentiles to show the user's total percentile.

3.5.3 Adaptive Thresholds and Feedback

A key innovation is the hybrid threshold system:

- **Initial thresholds** are based on pilot data, using descriptive statistics (mean, standard deviation, percentile bands).
- **Ongoing refinement**: Thresholds are recalculated weekly as more anonymised data accumulates, ensuring feedback remains accurate and representative.
- **Manual adjustment**: Administrators can recalculate thresholds when needed to account for demographic shifts or outliers.

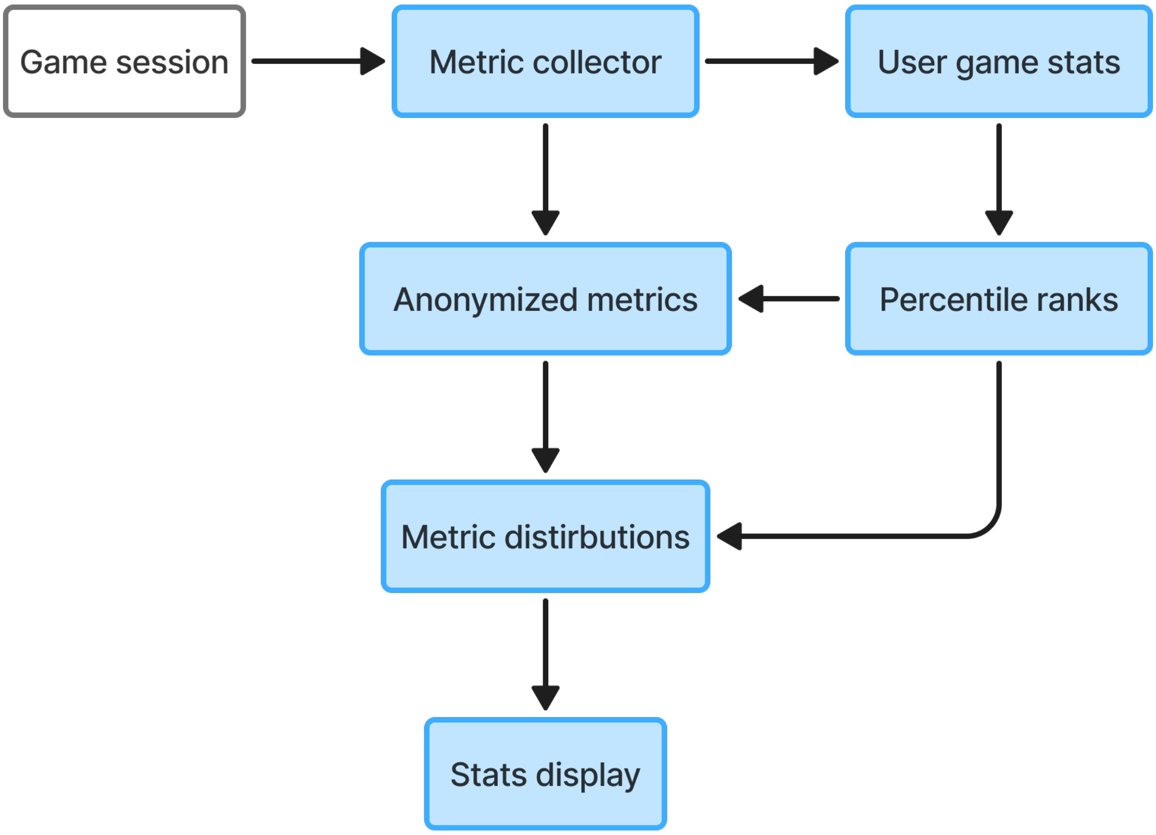


Figure 3.6: Data flow diagram

This approach enables individualised, context-aware feedback and supports robust, evolving benchmarking for users. The feedback on specific performances was designed to follow the table 3.4.

Table 3.4: Performance bands

Excellent	$>\mu+1.5\sigma$
Good	$(\mu+0.5\sigma\ ,\ \mu+1.5\sigma)$
Average	$(\mu-0.5\sigma\ ,\ \mu+0.5\sigma)$
Below average	$(\mu-1.5\sigma\ ,\ \mu-0.5\sigma)$
Needs improvement	$<\mu-1.5\sigma$

μ - mean of specific performance
σ - standard deviation of specific performance

3.5.4 Validation, integrity and privacy

To ensure validation, input sanitisation is implemented to constrain reaction times to 100 to 2000 milliseconds, and TypeScript interfaces are utilised to maintain type consistency, such as requiring that the vigilance decrement in SustainedAttentionMetrics is a number.

For integrity, Firebase transactions prevent partial writes during concurrent updates, and unique session IDs generated with UUIDv4 help create conflict-free records.

Finally, privacy is upheld through anonymisation by stripping population data of user IDs and IP addresses, along with strict access controls enforced by Firebase security rules to limit read and write permissions.

3.6 Technology and Tool Choices

This section summarises the main technologies, frameworks, and tools used in the ***Attentia*** platform, with justifications tied to project requirements and constraints.

3.6.1 React Native with Expo

React Native, paired with Expo, enables cross-platform development, allowing the application to reach iOS and Android users from a single codebase. This was essential for maximising accessibility and user base, as required for cognitive assessment tools. Expo further streamlines the development process by simplifying deployment, device testing, and over-the-air updates, accelerating iteration and ensuring consistent performance across devices. The component-based architecture of React also supports modular game design, making it easier to reuse and maintain code across different attention games.

3.6.2 Firebase (Authentication, Real-time Database, Cloud Functions)

Firebase provides a robust cloud backend that meets several critical needs:

- **Authentication** ensures secure user accounts, enabling longitudinal tracking of cognitive performance while protecting user privacy.
- **A real-time database** offers efficient storage and synchronisation of user metrics and session data, crucial for immediate feedback.
- **Cloud Functions** (code implemented and ready for activation) are intended for automated server-side processing, such as recalculating population thresholds and managing aggregate statistics. This serverless approach supports scalability and reduces maintenance overhead.
- The hierarchical data structure in Firebase naturally fits the organisation of game sessions and metrics by user and game type, simplifying data management and retrieval.

3.6.3 TypeScript

TypeScript enforces type safety throughout the codebase, which is vital for reliable metric calculations and data processing in a scientific context. Defining interfaces for each metric type (e.g., SustainedAttentionMetrics, SelectiveAttentionMetrics) ensures consistency and reduces runtime errors, which is especially important when handling complex statistical logic. TypeScript also improves maintainability and developer productivity as the project grows.

3.6.4 Custom Hooks Pattern

Game-specific custom hooks (e.g., useSustainedAttentionGame, useSelectiveAttentionGame) separate game logic from UI, improving code clarity and maintainability. This modular approach allows for standardised metric calculation across games and supports independent testing of logic, which is crucial for scientific validation and future extensibility.

3.7 Risk Analysis and Mitigation

A systematic risk management approach is essential to ensure the reliability, security, and scientific validity of the Attentia platform. The following summarises the principal risks identified during the design process and the corresponding mitigation strategies and contingency plans.

1. **Data Integrity and Statistical Validity**: A primary risk concerns the reliability of statistical benchmarks and percentiles in insufficient or low-quality data. This is addressed through bootstrapping with pilot data, automated alerts for low sample sizes, outlier detection, and the implementation of graceful fallback mechanisms (e.g., displaying "N/A" when data is missing). As a contingency, advanced feedback features are restricted until adequate data is available to support valid comparisons.

2. **User Privacy and Data Protection**: Given the sensitive nature of cognitive performance data, robust privacy measures are implemented. These include Firebase Authentication, strict separation of anonymised and user-identifiable data, and using session-based metrics to prevent exposure of raw user information. Regular security reviews and prompt responses to identified vulnerabilities serve as contingency measures.

3. **Scalability**: To mitigate the risk of performance degradation as the user base expands, the platform employs efficient data structures, separates user-specific and population-level metrics, and utilises server-side processing for statistical calculations.

In summary, the solution design chapter established the conceptual architecture and outlined the rationale behind each component of the ***Attentia*** platform. These design decisions provide a blueprint for the system's realisation and set the stage for the technical implementation

Chapter 4

Implementation

Building on this conceptual foundation, this chapter details how the ***Attentia*** platform was developed as a fully functional, modular mobile application. It outlines the technology choices and development workflow, showing how theoretical principles were translated into practice. The chapter covers the implementation of core modules, the integration of cognitive assessment games, and the design of the metrics and feedback system. It also discusses key challenges encountered, such as maintaining scientific validity, ensuring data privacy, and achieving cross-platform scalability, and describes the practical solutions adopted throughout the development process.

4.1 Overview

The ***Attentia*** platform was implemented as a modular, cross-platform mobile application for the digital assessment of complex attention. The system architecture was designed to ensure scientific validity, scalability, and maintainability while providing users with engaging and ecologically valid cognitive games. The implementation translates validated cognitive paradigms into four interactive mini-games, each targeting a specific subdomain of attention: sustained, selective, divided attention, and processing speed. The application features a unified metrics pipeline for collecting, processing, and visualising cognitive performance data. A hybrid threshold system was developed to provide adaptive feedback and normative comparisons, evolving as more user data is collected. The entire solution is structured to support secure user authentication, robust data privacy, and seamless cloud integration.

4.1.1 Technologies, Platforms, and Environments

- **Core Framework:**
  - **React Native with Expo**: Enables cross-platform development for Android and the web using a single codebase. Expo simplifies device testing, deployment, and over-the-air updates, while React Native's component-based architecture supports modular game and UI development.
  - **TypeScript**: The codebase is written in TypeScript, ensuring type safety and reducing runtime errors, which is critical for processing complex cognitive metrics.
- **Navigation and UI:**

- **Expo Router**: Implements file-based routing for intuitive navigation between screens.
- **Custom React Native Components**: Used for building game interfaces and reusable UI elements.
- **Theme System**: Ensures consistent styling, supports light/dark modes, and adapts to various screen sizes.

- **Data Visualisation:**
  - **React-native-chart-kit**: Provides customisable charts (line, bar, pie) for visualising performance metrics and trends.
  - **SVG Support**: Enables rendering of custom game elements and connection paths.

- **Backend and Storage:**
  - **Firebase Platform**:
    - Firebase Authentication: Manages secure user login and account management.
    - Firebase Real-time Database: Stores user profiles, game sessions, and performance metrics with real-time synchronisation.
    - Firebase Cloud Functions: (Implemented and ready for activation) Intended for serverless processing of population statistics and automated threshold recalculation as the user base grows.

- **State Management:**
  - **React Context API**: Manages global state such as authentication and theming.
  - **Custom React Hooks**: Encapsulate game logic, metrics collection, and shared functionality for each cognitive test.

- **Game Assessment Features:**
  - Four distinct cognitive games, each implementing validated paradigms from cognitive psychology.
  - Real-time calculation and storage of accuracy, reaction times, and other domain-specific metrics.
  - Percentile ranking and adaptive feedback based on population data.

- **Developer Tools:**
  - **Metro Bundler**: Used for local development and hot module reloading.
  - **EAS Build**: Facilitates production builds and deployment across platforms.

4.2 System setup and configuration

This section describes the initial setup, deployment environment, and configuration steps required to run the ***Attentia*** platform. It also outlines key dependencies and prerequisites necessary for development and production deployment.

4.2.1 Development environment

The Attentia project is built using **Expo SDK 52**, providing a robust foundation for cross-platform React Native development. The application targets Android and web platforms from a single codebase, ensuring broad accessibility and ease of maintenance.

Prerequisites and Dependencies

- **Node.js and npm/yarn:** These are required for managing packages and running development scripts.
- **Expo CLI:** The primary command-line interface for initialising, developing, and building Expo projects.
- **Firebase Account:** Needed for authentication, real-time database, and analytics services.
- **Mobile Device or Emulator:** This is used to test the application on Android.
- **Google Fonts API:** Used for custom font integration.
- **Metro Bundler:** Handles local development and asset transformation, including SVG support.

4.2.2 Initial setup steps

1. **Project Initialisation**
   - The project was initialised using create-expo-app with the TypeScript template, as confirmed in the project's README.
   - All dependencies are managed via npm or yarn.
2. **Firebase Configuration**
   - A dedicated Firebase project (ID: attentionquest-3172e) was set up.
   - Configuration details are stored in firebase.ts, specifying platform-specific app IDs for web and Android.
   - **Firebase Services Used:**
     - Authentication (with platform-specific persistence: browser local storage for web, AsyncStorage for mobile)
     - Real-time Database (hosted in the Europe-west1 region)
     - Cloud Functions (code implemented and ready for activation if needed)
3. **Expo and App Configuration** The app is configured in app.json with:
   - Name: „Attentia“
   - Slug: „attention-quest“
   - Bundle identifiers for Android: com.natkasobi.attentia
   - EAS Project ID for build automation
   - Hermes JavaScript engine is enabled for improved performance

- Expo Updates are configured for over-the-air (OTA) updates

4. **Project Plugins and Extensions**

   - **expo-router:** Enables file-based navigation.
   - **expo-splash-screen:** Provides a loading screen during app startup.
   - **expo-font:** Integrates custom typography (e.g., Poppins font).
   - **@react-native-firebase/app:** Manages Firebase integration.
   - **react-native-svg-transformer:** Allows SVG files to be bundled and rendered.
   - **react-native-chart-kit:** Used for in-app data visualisation.

4.2.3 Local development and testing

The development process begins by starting the development server with the command 'npx expo start'. Through the Expo Go application, this setup enables live testing on Android emulators and physical devices. The Metro Bundler is configured for efficient asset management and supports hot reloading, allowing for a seamless development experience.

4.2.4 Build and deployment

For building and deploying applications, EAS Build is employed to create a production-ready build for the Android platform, with configurations managed in the 'eas.json' file. Additionally, runtime versioning adheres to the application version policy, ensuring compatibility with over-the-air (OTA) updates and enhancing stability and usability.

4.2.5 Admin and database setup

The initial setup of the admin user is accomplished through the 'bootstrapFirstAdmin' function, which establishes the first administrator. The system incorporates role-based access control that supports distinct USER and ADMIN roles, allowing for effective management of user permissions and capabilities. Admin users are granted the authority to oversee thresholds and adjust system configurations as needed.

Regarding the threshold system, initial statistical metrics are established with minimal data, but these can be recalculated as the user base expands. Additionally, the statuses related to thresholds and admin setups are diligently tracked in the database under a section designated for 'systemStatus'.

User data is organised meticulously, with individual user profiles and game statistics stored for each authenticated user. The system maintains metrics for all four cognitive tests, while role-based permissions are handled within a separate collection to ensure proper access management.

The Attentia system is designed for rapid setup and robust operation in a modern cross-platform environment. With clearly defined dependencies, modular configuration, and a scalable Firebase backend, the platform supports secure authentication, persistent data storage, and flexible administrative management. This setup ensures that both development and production deployments can be performed efficiently and reliably.

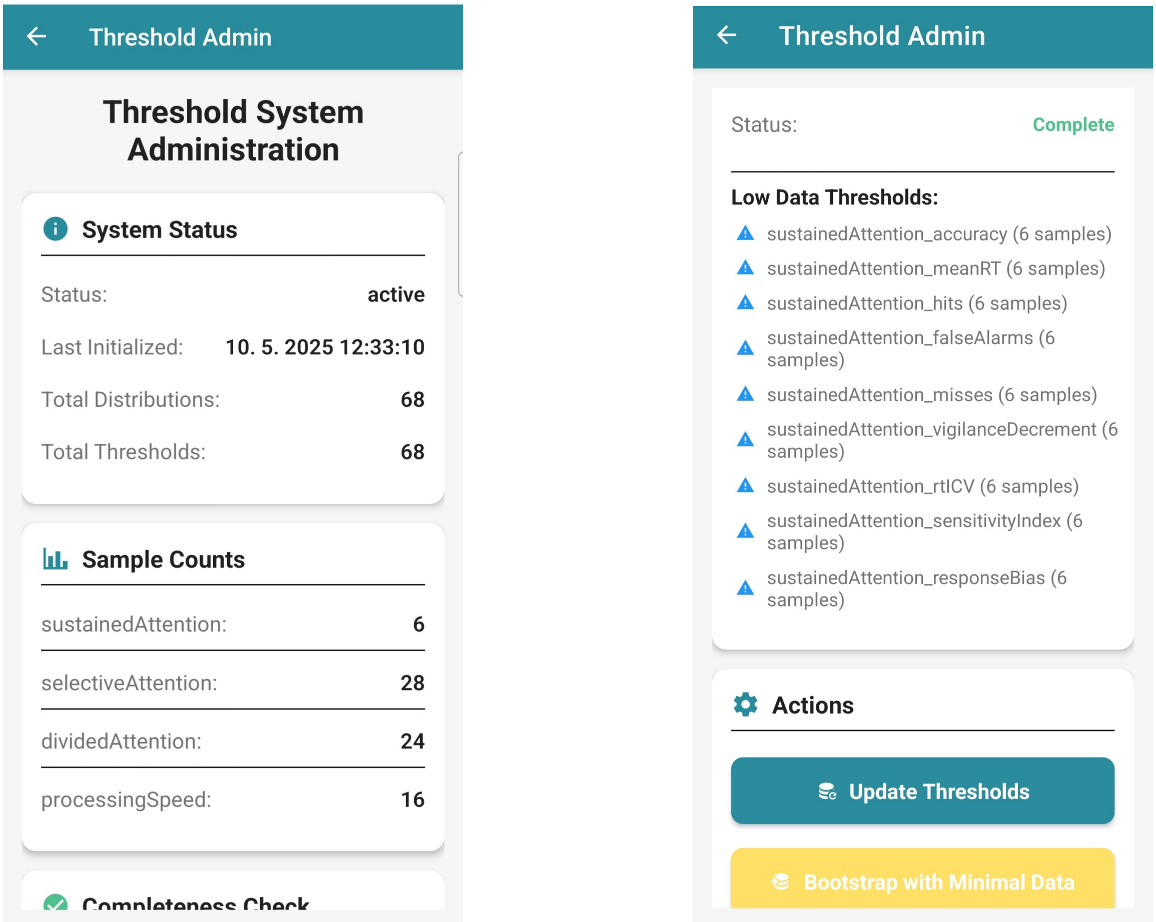


Figure 4.1: Admin screens

4.3 Implementation of major components

This section outlines how each significant component of the Attentia platform was implemented, the key challenges encountered, and any deviations from the original design. The focus is on the practical realisation of the conceptual architecture and the rationale behind critical decisions.

4.3.1 Core game framework

The backbone of the application is a centralised game engine realised through custom React hooks. The useGameEngine hook provides shared state management for timers, pause/resume logic, and score tracking, ensuring consistency across all cognitive games. Game-specific hooks (e.g., useDividedAttentionGame) extend this core functionality with specialised behaviours unique to each assessment. Integration with Firebase enables real-time data synchronisation and secure user authentication.

Throughout the development process, key challenges emerged, notably the balance between flexibility and consistency. Designing an architecture that could accommodate a variety of cognitive tasks while maintaining a unified structure proved to be a complex task. To address this challenge, a hooks-based composition pattern was adopted. This approach enabled specialised game modules to effectively inherit and extend the core logic.

Another significant challenge was ensuring timing accuracy, which is crucial for the validity of cognitive assessments. The asynchronous rendering cycles of React complicated this aspect, leading to the careful management of timers and effect hooks. This was essential for achieving precise stimulus presentation and accurate recording of responses.

4.3.2 Cognitive test suite

A dedicated game module represents each cognitive domain:

- **Sustained Attention:** Grid-based vigilance task with prolonged focus requirements.
- **Selective Attention:** Stroop-like colour-word matching/mismatching.
- **Divided Attention:** Dual-task paradigm monitoring shapes and numbers.
- **Processing Speed:** Sequential number connection (trail-making) task.

One of the key challenges faced was striking a balance between scientific validity and user engagement. Drawing from cognitive psychology literature, it became essential to calibrate task parameters, such as stimulus timing and target frequency, to create a gameplay experience that was both rigorous and enjoyable. Additionally, standardisation played a critical role in ensuring that each game consistently measures its intended construct. This was achieved through fixed, validated task settings and reliable metric collection. However, some gameplay elements were simplified to maintain user engagement and mitigate cognitive overload. Despite these adaptations, the focus remained on preserving the scientific validity of the experience.

4.3.3 Performance analytics system

A comprehensive metrics collection framework was developed using the MetricCollector service. This system calculates standard (accuracy, reaction time) and advanced metrics (Signal Detection Theory measures like d' and response bias). Results are visualised with React Native Chart Kit, and a threshold-based categorisation system provides users with normalised feedback.

The project encountered several key challenges that necessitated innovative solutions. One significant hurdle involved the need for real-time complex calculations, particularly in computing advanced metrics like d' and response bias. To address this, efficient, dedicated statistical utility functions were developed and decoupled from the user interface logic, ensuring seamless performance.

Another challenge was the provision of normative feedback despite having sparse user data. Establishing meaningful performance thresholds proved difficult early, but bootstrapping thresholds with pilot data mitigated this issue. This approach allowed for initial benchmarks to be manually recalibrated as more data became available.

Additionally, automatic threshold recalculation was initially implemented using Firebase Cloud Functions. However, this feature is inactive due to resource constraints, leading to administrators' reliance on manual recalibration to maintain accuracy in performance assessments.

4.3.4 User interface components

The UI comprises modular React components, clearly separating concerns between game-specific visual elements and shared core components (e.g., GameOverScreen, PauseOverlay). The centralised theme module ensures consistent styling and supports light and dark modes.

One key challenge was ensuring that layouts were responsive and could adapt seamlessly to various device sizes. Dynamic scaling techniques and flexible grid systems were implemented to address this, allowing for a smooth user experience across different screens. Additionally, managing complex transitions between various game phases—starting, playing, pausing, and game over—required careful attention. This was tackled by utilising well-structured state machines within hooks, providing a clear and organised way to handle these transitions efficiently.

4.3.5 Data management system

User and performance data are stored in a hierarchical structure within the Firebase Realtime Database. Role-based access control supports administrative functions, and a dedicated thresholds management system enables performance categorisation and feedback.

One of the key challenges we faced was efficient data handling, which we addressed by optimising the data structure and implementing caching strategies to manage large volumes of performance data effectively. Additionally, we needed to balance user privacy with aggregate analytics requirements. We accomplished this by separating anonymised population data from user-specific records, allowing us to maintain privacy while still deriving valuable insights from the data.

4.4 Testing and validation

Implementing the ***Attentia*** platform was verified using a comprehensive, multi-level testing and validation approach, ensuring the correctness of game logic and the reliability of cognitive assessment metrics.

4.4.1 Automated Logic Testing (Python Test Suite)

A dedicated, auto-generated Python test suite was developed to rigorously validate the core mechanics of all four cognitive games outside the main application.

- **Unit tests** check the correctness of individual functions and components (e.g., target detection, scoring, error handling).
- **Integration tests** simulate realistic user interactions and complete game flows, verifying that each game module (sustained, selective, divided attention, and processing speed) behaves as intended.
- **Visualisation tools** generate performance charts and metrics to facilitate rapid evaluation of test outcomes.
- The test suite can be run in full or by a specific game/module, supporting rapid iteration during development.

4.4.2 Real User Data Analysis

The system collects detailed metrics from gameplay sessions and stores this information in Firebase for further analysis. Each session is designed to record various universal metrics, such as accuracy and reaction times, alongside game-specific metrics, which include aspects like vigilance decrement and response asymmetry. Analysing data from numerous sessions allows for the confirmation of the consistency of the metrics, detection of any anomalies, and validation that the games effectively capture the intended cognitive constructs.

4.4.3 Threshold System and Statistical Validation

The hybrid threshold system is designed to facilitate ongoing statistical validation by calculating performance distributions for each metric. Through rigorous statistical analysis, specific thresholds are established to ensure accurate assessments. Additionally, the system is capable of identifying outliers and flagging metrics that lack sufficient data. In such cases, it employs bootstrapping techniques to adjust thresholds as necessary. Administrative tools play a crucial role in this process, enabling the initialisation of thresholds, conducting completeness checks, and allowing for either manual or automatic recalculation as new data becomes available.

4.4.4 Pilot testing

A small pilot testing round was conducted with about ten friends and family members who tried out the different games and gave informal feedback. Several of them pointed out bugs, confusing instructions, or parts of the interface that did not work as expected. Based on their comments, the most common issues were fixed, and the app was made more user-friendly before moving on to broader testing. This informal pilot phase helped catch problems not obvious during development and made the overall experience smoother for new users.

4.5 Usage example

To illustrate the practical use of the Attentia platform, consider a typical scenario in which an adult user seeks to evaluate and monitor their attention abilities using the mobile application.

4.5.1 Initial Assessment

Upon installing Attentia, the user registers an account and is guided through a baseline assessment session. This session includes all four cognitive games:

- **Sustained Attention Game**: The user monitors a grid of numbers, responding only to specific target stimuli (e.g., tapping when the number „5“ appears) over an extended period. The game measures the ability to maintain focus, tracking reaction times, accuracy, and changes in performance (vigilance decrement) throughout the session.
- **Selective Attention Game**: The user is presented with colour words displayed in various font colours and must respond only when the word's meaning matches the

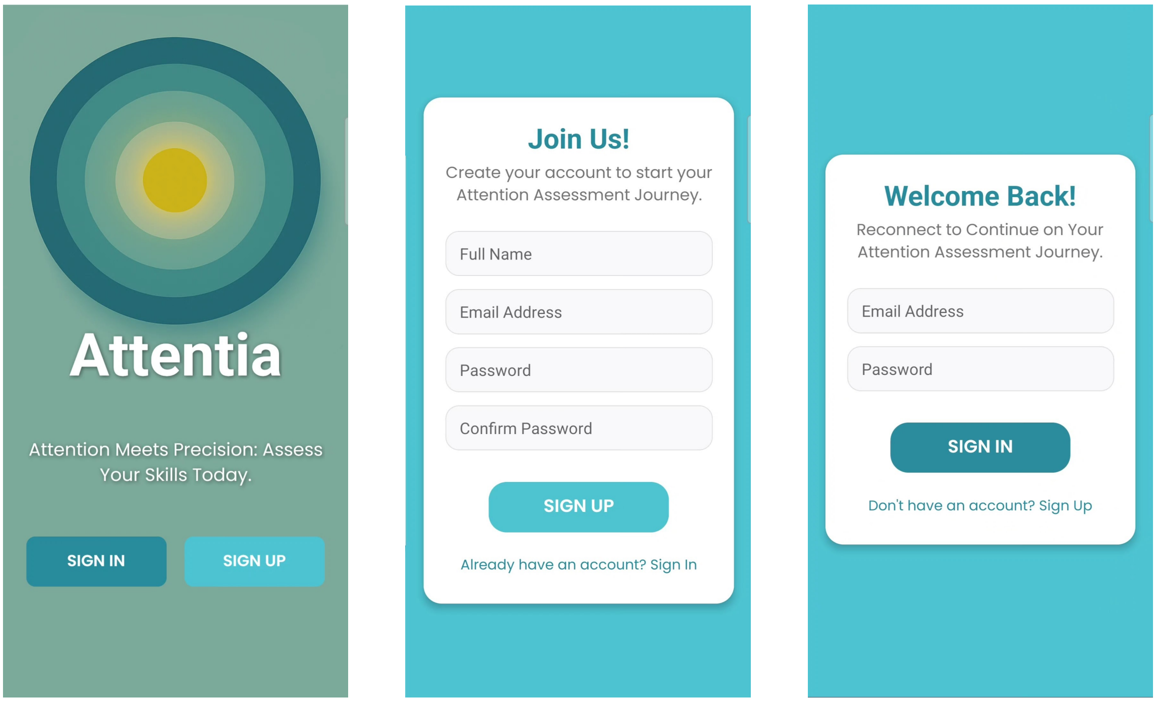


Figure 4.2: Registration and authentication

font colour. This task evaluates the ability to filter out distractions and measures accuracy, reaction time, and response bias.

- **Divided Attention Game**: The user simultaneously monitors two streams of stimuli (such as shapes and numbers) and must respond to targets in either stream. This assesses multitasking ability and tracks performance asymmetry between the two streams.
- **Processing Speed Game**: The user connects numbers in ascending order as quickly as possible within a grid. The game records completion time, accuracy, and first error occurrence, providing a measure of cognitive processing speed.

4.5.2 Reviewing Results

After completing the assessment, the user accesses a comprehensive statistics dashboard. Here, they can review:

- **Overall Performance**: Percentile rankings compared to the broader user population.
- **Game-Specific Metrics**: Detailed statistics for each attention domain, including accuracy, average and variability of reaction times, sensitivity index (d'), response bias, and game-specific measures such as vigilance decrement.
- **Visual Analytics**: Interactive charts display performance trends across sessions, reaction time distributions, and breakdowns of correct and incorrect responses.

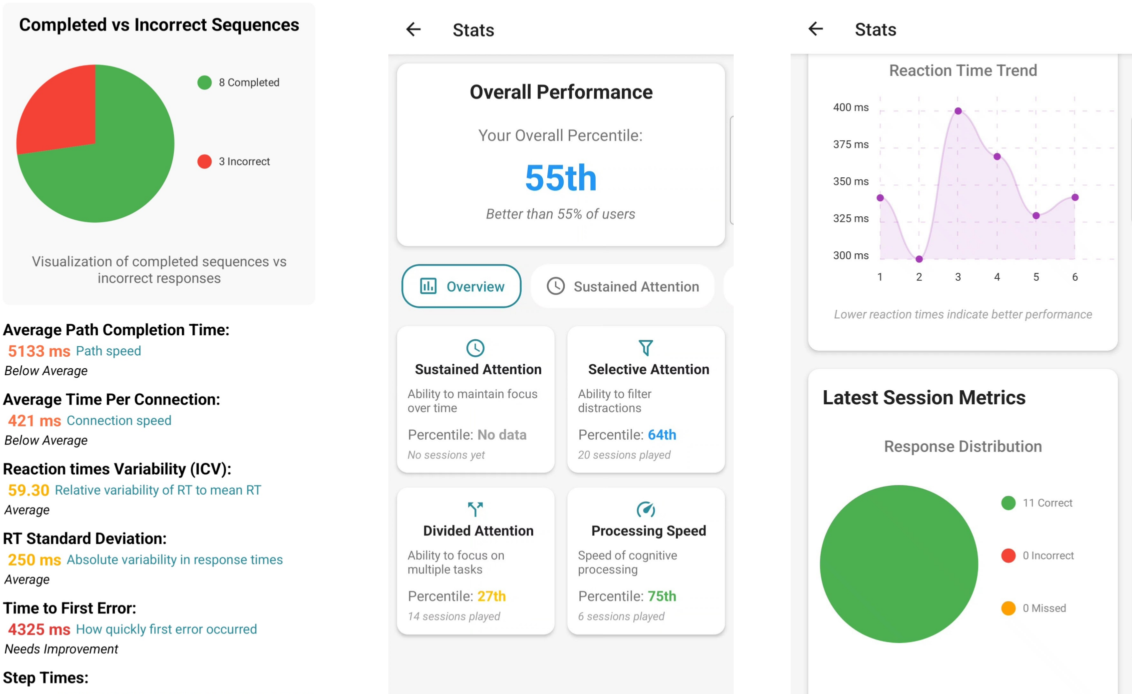


Figure 4.3: Result analytics

4.5.3 Ongoing Use and Progress Tracking

Users are encouraged to repeat the assessments regularly, either following a self-set schedule or as part of a training regimen. Over time, the app tracks changes in key metrics, enabling users to observe improvements or identify areas needing further attention. The adaptive feedback system provides updated percentile ranks and highlights trends, supporting both self-monitoring and motivation.

4.6 Limitations and known issues

While the ***Attentia*** platform demonstrates the feasibility and value of digital game-based attention assessment, several limitations and unresolved issues remain. Recognising these constraints is essential for interpreting the results, guiding users, and informing future development.

4.6.1 Platform and performance limitations

Device performance can exhibit variability, particularly in reaction time measurements, which are crucial for assessing attention. These variations arise due to differences in hardware, input latency, and screen refresh rates among different devices. No calibration mechanism is available to each device to mitigate these discrepancies. Even though React Native with Expo enables cross-platform development, the application has not been tested on iOS devices due to a lack of access to Apple hardware, which means its performance and compatibility with iOS remain unverified.

Additionally, during extended sessions, such as the 8-minute Sustained Attention game, users may experience performance degradation, especially on lower-end devices. This could be attributed to specific React hooks that do not effectively clean up timers and subscriptions, leading to potential memory leaks. Furthermore, the performance of animations may be inconsistent on older devices, which can adversely affect the timing accuracy of tasks related to processing speed.

4.6.2 Game-Specific Limitations

- **Divided Attention Game:** Occasionally, stimulus streams may synchronise, unintentionally simplifying the task. The game does not prevent rapid, repeated taps, which can inflate false alarm rates.
- **Sustained Attention Game:** The default session duration (8 minutes) may be too long for mobile users, leading to disengagement. No mechanism exists for saving progress or partial scoring if a session is interrupted.
- **Processing Speed Game:** The grid layout algorithm does not always generate optimal or unique arrangements.
- **Selective Attention Game:** A fixed set of colour-word stimuli may lead to learning effects with repeated play. There is no adaptive difficulty or progression based on user performance.

4.6.3 Data management limitations

The app relies entirely on Firebase for both authentication and data storage, which means it functions without an offline mode. Consequently, if there are any connectivity issues during gameplay, users may experience a loss of performance data. Additionally, when user data is insufficient, thresholds are created using artificial distributions. This method may not accurately represent real user performance, leading to less reliable percentile calculations, especially when the data samples are limited.

4.6.4 User Experience and Accessibility

- **Accessibility:** The games rely heavily on visual cues, with minimal auditory feedback and no accommodations for colour blindness or visual impairments. The text size is fixed, but it may be difficult for some users to read.
- **Feedback Mechanisms:** In-game feedback is limited; users only see detailed metrics after completing a session, and there is no progressive guidance or adaptive difficulty to support improvement.

4.6.5 Technical Debt and Testing

- **Testing Gaps:** While a Python test suite exists for core logic, it is separate from the main codebase and not integrated into continuous integration workflows. Automated testing for game components and user interactions is limited.
- **Configuration Management:** Many game parameters are hardcoded.

4.6.6 Areas for Future Improvement

To enhance device capabilities, calibration processes and offline data storage could be implemented to ensure optimal performance in varied environments. Additionally, automated and integrated testing could be integrated across all platforms, including iOS, to improve reliability and user experience.

To cater to a broader audience, adaptive difficulty levels and personalised training regimens could be introduced, allowing adjustments based on individual user progress. Expanding accessibility features could be prioritised by incorporating elements such as colorblind modes, larger text options, and alternative input methods to support users with diverse needs.

Enhancing in-game feedback could create a more seamless experience for players. Furthermore, analytics could be refined to enable longitudinal tracking and progress visualisation, helping users monitor their development over time.

To maintain efficiency and adaptability, the codebase could be refactored for better modularity and maintainability. This approach could facilitate the integration of automated testing into continuous integration and delivery (CI/CD) pipelines, resulting in a smoother development process.

Lastly, a more diverse range of engaging cognitive game modules could be added, expanding the variety of experiences available to users and enhancing the overall user experience.

This chapter presented the implementation of the ***Attentia*** platform, highlighting its modular architecture and evidence-based design for comprehensive attention assessment. The system uses a centralised game engine with custom React hooks to support four scientifically grounded cognitive games, each targeting a different subdomain of attention. Advanced analytics and a hybrid threshold system enable adaptive, standardised feedback for users. Data management leverages Firebase for secure storage and privacy, while the user interface is designed for modularity and responsiveness. The implementation was validated through automated tests, real user data analysis, and a small pilot phase that helped resolve usability issues. Key challenges addressed included balancing scientific rigour with user engagement, ensuring timing accuracy, and managing device variability. Despite some limitations, such as a lack of ios testing and limited accessibility features, ***Attentia*** demonstrates a scalable and scientifically valid approach to digital attention assessment.

Chapter 5

Conclusion

The primary objective of this thesis was to design, implement, and evaluate a modular digital game-based platform named Attentia. This platform enables a comprehensive assessment of complex attention through engaging, scientifically grounded mini-games, each targeting a specific subdomain: sustained attention, selective attention, divided attention, and processing speed. The motivation for this work stemmed from the limitations of traditional and existing digital assessment methods, which often lack ecological validity, cover only a subset of attentional domains, or fail to provide engaging and scalable solutions. By leveraging validated cognitive paradigms within an accessible mobile application, the aim was to deliver a robust, standardised, and user-friendly tool that can more accurately and meaningfully measure attentional abilities in real-world contexts, supporting research and practical applications in cognitive assessment.

The main goal of this thesis was successfully achieved: Attentia was developed as a cross-platform mobile application featuring four mini-games grounded in established cognitive psychology paradigms. The platform integrates a unified metrics pipeline, adaptive feedback, and a secure cloud backend, enabling detailed and standardised assessment of all major subdomains of complex attention. The solution was validated through automated logic testing, real user data analysis, and a pilot phase that informed usability improvements. Key achievements include the implementation of standardised attention metrics (e.g., accuracy, reaction time, sensitivity index d', response bias), a hybrid threshold system for adaptive feedback, and a modular architecture that supports scalability and extensibility.

Evaluation of results demonstrates that Attentia provides a scientifically valid and engaging approach to digital attention assessment. The modular design and adherence to validated cognitive paradigms ensure methodological rigour, while the gamified interface enhances user motivation and ecological validity. Pilot testing confirmed that users could complete the assessments and receive meaningful feedback, and the adaptive threshold system enables ongoing refinement as more data is collected. However, several limitations were encountered: device variability can affect reaction time measurements, iOS compatibility remains untested, and accessibility features (such as support for colour blindness) are limited. Additionally, the current implementation does not include direct validation against traditional non-gamified attention tasks, and normative data is still being developed as the user base grows.

The contribution encompassed the entire design and technical implementation of the Attentia platform, covering aspects from system architecture and game logic to data management and analytics. Each mini-game was designed and developed, metrics and feedback systems were implemented, and secure, privacy-conscious data handling was ensured. This process fostered significant expertise in cross-platform mobile development, cognitive assessment paradigms, and the challenges of balancing scientific rigour with user engagement. The project deepened the understanding of the complexities involved in digital cognitive assessment, particularly the importance of standardisation, data privacy, and the nuanced effects of gamification on measurement validity.

For future work, several concrete steps are recommended. In the short term, expanding accessibility features (such as colourblind modes and larger text), improving device calibration for reaction time accuracy, and integrating automated, continuous testing across platforms would enhance usability and reliability. Further development should focus on collecting larger-scale normative data, conducting formal validation studies against established cognitive tests, and refining adaptive difficulty and feedback mechanisms. In the longer term, extending the platform to include additional cognitive domains, supporting multi-language interfaces, and exploring integration with wearable or physiological data could significantly broaden the platform's impact and applicability.

In conclusion, this thesis demonstrates that a modular, evidence-based digital game platform can provide a robust, engaging, and scientifically valid tool for assessing complex attention. Attentia advances the field by addressing key methodological gaps and offering a scalable solution that bridges laboratory-grade rigour with real-world applicability. The platform lays a strong foundation for future research, clinical practice, and broader adoption of digital cognitive assessment tools, with the potential to make meaningful contributions to scientific understanding and practical support for individuals facing attentional challenges.

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