WORKING MEMORY IN ADULTS WITH DOCUMENTED CHILDHOOD DYSLEXIA

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Working memory (WM) is known to be connected to reading skill and dyslexia. The aim of this study was to acquire a better understanding of the connection between dyslexia and WM in adulthood. The study consisted of adults with a childhood dyslexia diagnosis (n = 30) and a control group with no documented dyslexia (n = 26). The participants with childhood dyslexia were recruited from the archival database of the Clinic for Learning Disabilities at the Niilo Mäki Institute. By using the scores of two reading tasks (Tunturilappi text & Vinnittäjiä tenkoja pseudoword text), the group with childhood dyslexia was divided into a group with persistent dyslexia (n = 24) and a group with compensated dyslexia (n = 6). WM performance was assessed using seven WM tasks (Digit Span Forward, Digit Span Backward, Digit Span Sequencing, Arithmetic, Letter-Number Sequencing, Corsi Forward, and Corsi Backward). We compared the groups pairwise with the Mann-Whitney U-test. The persistent dyslexia group performed significantly poorer than the control group in all but the Corsi Forward and Corsi Backward tasks. This result supports previous research in which dyslexia has been associated with deficiencies in phonological rather than visuospatial WM. Conversely, the group with compensated dyslexia differed from the control group's working memory performance only by poorer performance in the Arithmetic task, which was not in line with the previous studies. The two childhood dyslexia groups differed significantly only by the persistent dyslexia group's poorer performance in the Digit Span Backward task. In conclusion, we found a connection between persistent dyslexia and poor performance in verbal WM tasks, while compensated dyslexia group did not differ from the control group. This study raises the need for further research on the relation between dyslexia and WM.

Keywords: compensated dyslexia, dyslexia, persistent dyslexia, working memory

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Työmuistin on havaittu olevan yhteydessä lukutaitoon ja dysleksiaan. Tämän tutkimuksen tavoitteena oli selvittää tarkemmin työmuistisuoriutumisen ja dysleksian yhteyttä aikuisuudessa. Tutkimukseen kuului Niilo Mäki Instituutin klinikka-aineistosta rekrytoitu dysleksiataustaisten aikuisten ryhmä (n = 30), sekä kontrolliryhmä (n = 26). Dysleksiataustaiset tutkittavat jaettiin dysleksian jatkuvuuden perusteella jatkuneen dysleksian ryhmään (n = 24) ja kompensoituneen dysleksian ryhmään (n = 6). Raja-arvo muodostettiin kahden lukutestin (Tunturilappi-teksti ja Vinnittäjiä tenkoja -pseudosanateksti) pisteiden perusteella. Työmuistisuoriutumista arvioitiin seitsemällä työmuistimittarilla (Numerosarjat eteenpäin, Numerosarjat taaksepäin ja Numerosarjat järjestyksessä, Laskutehtävät, Kirjain-numerosarjat, Corsi eteenpäin ja Corsi taaksepäin). Ryhmien välisiä eroja tarkasteltiin käyttämällä Mann-Whitneyn U-testiä parittaisten vertailujen tekemiseen. Tulokset osoittivat, että henkilöt, joilla dysleksian katsottiin jatkuneen aikuisuuteen, suoriutuivat kontrolliryhmää heikommin kaikissa paitsi visuospatiaalista prosessointia vaativissa Corsi-tehtävissä. Tämä tukee aiempaa tutkimusta, jossa dysleksia on yhdistetty erityisesti fonologisen työmuistin heikkouteen. Sen sijaan kompensoituneen dysleksian ryhmä erosi kontrolliryhmästä heikommalla työmuistisuoriutumisella ainoastaan Laskutehtävissä, mikä ei ollut linjassa aiemman tutkimuksen kanssa. Jatkuneen dysleksian ryhmän ja kompensoituneen dysleksian ryhmän työmuistisuoriutuminen erosi tilastollisesti merkitsevästi vain Numerosarjat taaksepäin -tehtävässä. Tutkimuksen mukaan jatkunut dysleksia oli yhteydessä heikompaan suoriutumiseen fonologisissa työmuistitehtävissä. Kompensoituneen dysleksian ryhmän työmuistisuoriutumisen taas ei havaittu poikkeavan kontrolliryhmästä. Tulokset olivat osin ristiriidassa aikaisemman tutkimuskirjallisuuden kanssa, mikä nostaa esiin tarpeen jatkotutkimuksille.

Avainsanat: dysleksia, kompensoitunut dysleksia, jatkunut dysleksia, työmuisti

CONTENTS

1. INTRODUCTION

Working memory (WM) is known to be essential for higher cognitive functions such as thinking, problem-solving, and planning (Diamond, 2013). It is also associated with reading difficulties and dyslexia (Swanson et al., 2009; Peng et al., 2018). Dyslexia can cause extensive problems in academic performance and consequently affect a person's entire life through their career path and mental health (Aro et al., 2019). Although there is a considerable amount of research inspecting the connection between WM and dyslexia, it remains unclear how WM performance is related to the persistence of dyslexia. Due to that and the inevitable importance of the reading skills in our society, more research on adults with documented childhood dyslexia is needed to examine the connection between WM and dyslexia in adulthood. This study aimed to clarify this relation.

1.1. Dyslexia

Dyslexia is described similarly in the two fundamental classifications of diseases. In the 10th revision of the International Classification of Diseases (ICD-10) by the World Health Organisation (2019), a specific reading disorder is described to be "a specific and significant impairment in the development of reading skills that is not solely accounted for by mental age, visual acuity problems, or inadequate schooling". Reading-related deficiencies are more precisely characterized to manifest in reading comprehension, word recognition, oral reading skill, and performance of tasks requiring reading (World Health Organisation, 2019). The fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), created by the American Psychiatric Association (2013), likewise has a separate diagnosis for a specific learning disorder with impairment in reading. The DSM-5 states, similarly to the ICD-10, that the difficulties in specific learning disorders are not due to intelligence, visual or auditory impairment, poor language skills, or poor education (American Psychiatric Association, 2013). Specific impairment in reading is defined as having difficulties in word reading accuracy, reading rate or fluency, and reading comprehension (American Psychiatric Association, 2013).

The approximate incidence of dyslexia in the whole population varies moderately in the research field. This ambiguity is essentially due to the cut-off point for dyslexia being variable and artificial. For example, in the meta-analysis of Yang et al. (2022), the cut-off points between studies varied from 1 standard deviation (SD) to 2 SD below the mean of the age group. Nevertheless, Landerl and Moll (2010) estimate that the prevalence of dyslexia lies somewhere between 4 % and 9 %, depending on the cut-off point and definitions used. In addition, the yet unclear factors of the development of dyslexia make it more complex to estimate the incidence of dyslexia through the lifespan.

The studies about the stability of dyslexia from childhood to adulthood have gotten varying results. Eloranta et al. (2019) estimate the percentage of those who have been diagnosed with dyslexia in childhood but do no longer meet the criteria in adulthood to be between 7 % and 60 %. This phenomenon in which reading difficulties no longer meet the criteria for dyslexia in adulthood can also be called compensated dyslexia (Wiseheart & Altmann, 2018).

The reading skills affected by dyslexia consist of various complicated cognitive processes. Vellutino et al. (2004) define reading as a constant action of picking up the necessary information and combining it into an understandable entity. They suggest cooperation of the following mechanisms to be involved in normal reading ability: linguistic coding processes and knowledge, lexical and sublexical knowledge, visual coding processes and knowledge, ability to identify words, language comprehension, and reading comprehension, knowledge of print concepts and conventions, metalinguistic processes and knowledge, and finally, processes of both WM and permanent memory (Vellutino et al., 2004).

According to Vellutino et al. (2004), the most common reason for dyslexia seems to be poor word identification skills. Dyslexia is also closely connected to problems in phonological awareness, alphabetic mapping, and phonological coding that fall into the previously mentioned categories of linguistic coding processes and sublexical knowledge (Vellutino et al., 2004). Phonological awareness refers to the understanding of how spoken language is constructed from smaller fragments of speech sounds (Vellutino et al., 2004). Alphabetic mapping, in turn, is the skill of connecting letter symbols to the sounds they make in spoken words (Vellutino et al., 2004). Lastly, phonological coding refers to the ability to connect the written words with the corresponding speech sounds (Leinenger, 2014). It can also be described as an inner voice we hear while reading (Leinenger, 2014).

WM and permanent memory processes are also considered to be a part of fluent reading (Vellutino et al., 2004). Vellutino et al. (2004) describe both memory functions to be connected to other reading subprocesses through encoding and retaining of the information required in reading. The memory functions also participate in forming a connection between written and spoken words. Similarly, Peng et al. (2018) state in their meta-analysis that WM is related to reading in the context of basic skills of reading but also in reading comprehension. However, when decoding and general vocabulary are controlled, the connection between WM and reading comprehension disappears (Peng et al., 2018).

The current study has Finnish-speaking participants. The Finnish is an example of a transparent alphabetic orthography (Aro, 2006), which makes the characteristics of reading and learning to read slightly different from less transparent orthographies such as English. The transparency in this context refers to the speech sounds or phonemes that in Finnish are predominantly consistent with written letters called graphemes. Due to this transparency, good letter knowledge is the basis of the successful decoding of the letter-sound connection (Aro & Lerkkanen, 2019). Finnish children also grasp the basics of reading relatively fast, due to the clear structure of Finnish phonology (Aro & Lerkkanen, 2019). In addition to the easy orthography, the Finnish language also has qualities that make reading considerably more difficult for example, words are generally long, which might be especially heavy on the WM (Leinonen et al., 2001), most of the Finnish phonemes can vary in length ("tuulla" vs. "tulla"), and the word morphology is complex (Aro & Lerkkanen, 2019).

Besides the basic reading processes, typical dyslexia in Finland also has slightly different characteristics than in English-speaking countries due to the Finnish language-specific factors. For example, a weak phoneme awareness of Finnish readers does not disturb the process of learning to read as much as with English-speaking peers because the word decoding process is clearer in Finnish (Aro & Lerkkanen, 2019). Thus, difficulties in reading are most apparent in the processes of reading fluency (Lohvansuu et al., 2021). However, an adequate naming speed, for example, seems to be an essential skill for fluent reading in all languages (Aro & Lerkkanen, 2019).

1.2. Working memory

WM is a memory system that has the ability to store and manipulate information mentally for short periods of time (Baddeley, 2010). Because of its unique abilities, WM is assumed to be vital for complex cognitive processes (Baddeley, 2010). These processes include, for example, the understanding of language, problem-solving, planning, and thinking (Diamond, 2013). In most theories, WM is separated from short-term memory, which refers to the temporary storage of information without the processing ability (Baddeley, 2012).

The function of the WM can be divided into encoding, maintenance, and retrieval of the information (Proskovec et al., 2016). Encoding is a process in which the information is coded into memory (Proscovec et al., 2016). During maintenance, the information is deliberately kept in mind, in other words, stored in the memory for a period of time (Proscovec et al., 2016). According to Cowan (2010), WM has a limited storage capacity of 3 to 5 items when measured in young adults.

Lastly, retrieval is the action of bringing the information from the memory store to active utilization in cognitive functions (Proscovec et al., 2016).

In the context of cognitive testing and learning difficulties, WM can be separated into verbal, visuospatial, and possibly numerical domains (Peng & Fuchs, 2016). In their meta-analysis, Peng and Fuchs (2016) discovered a significant difference in the numerical WM performance between children with dyslexia and children with mathematical difficulties. Children with mathematical difficulties struggled more severely than children with dyslexia in the numerical WM tasks (Peng and Fuchs, 2016). This finding, amongst other studies (e.g., Cappelletti et al., 2001), suggests that there would be a distinct numerical domain of WM that participates specifically in processing information related to numbers. The verbal domain of WM can be examined by using tasks including phonological factors such as auditory words and sentences. The visuospatial domain is thought to manage the non-verbal, pictorial information. Verbal and visuospatial domains of WM are more established than numerical domain in the field of research, presumably due to their close connection to Baddeley and Hitch's (2000) prevalent model of WM discussed later in the text.

WM is a relatively dynamic cognitive function that changes markedly across a lifespan (Krogsrud et al., 2021). It increases significantly in childhood, reaching its peak in early to middle adulthood, followed by a slow but increasing decline (Sander et al., 2011). Although the performance in WM tasks changes markedly from childhood to adolescence, the changes between 20 to 39 years of age have been found far less significant (Alloway & Alloway, 2013). This age-related difference in development is presumably due to the benefits in childhood from the overall development of, for example, declarative and procedural knowledge (Alloway & Alloway, 2013). In addition to the age-related differences, WM also ranges notably among individuals of the same age cohort.

1.2.1. Multicomponent model of working memory

There are multiple theories about the operating mechanisms of the WM, of which the multicomponent model of Baddeley and Hitch (1974) is probably the most widely known. According to their original model, WM consisted of three components: the central executive and its two subsystems, the phonological loop and the visuospatial sketchpad (Baddeley, 2012). Later the model was supplemented with a third subsystem, the episodic buffer (Baddeley, 2000).

The central executive is the most complex component of WM (Baddeley & Hitch, 1974). It is important to note that the central executive is primarily a theoretical and functional system, not an anatomically unitary component (Baddeley, 1996). In other words, there is no traceable entity that alone is responsible for executive functions (Baddeley, 1996). The central executive is also not a unitary system but consists of multiple executive functions (Baddeley, 2012), such as switching, maintenance, and inhibition of stimuli (Buehler, 2017). The central executive's primary purpose is to handle attentional control of action, which includes monitoring and manipulating episodic buffer and combining the information from it into relevant entities (Baddeley, 2012). In other words, the central executive is in charge of the information manipulation, and it combines the contents of long-term memory and the WM. Of all components of the WM, the central executive could be thought of as the most important one because of its role in controlling other WM components via the episodic buffer (Baddeley, 2000).

The episodic buffer is the latest substantial addition to the WM model (Baddeley, 2000). Baddeley (2000) suggests that the episodic buffer combines information from multiple sources and acts as a limited storage. The episodic buffer is under the control of the central executive, and it connects the phonological loop and the visuospatial sketchpad while also being able to interact with the long-term memory (Baddeley, 2000).

The phonological loop is the most studied WM component (Baddeley, 2012). It is responsible for the retention of phonological information over short periods of time (Baddeley et al., 1998). According to Baddeley et al. (1998), the phonological loop comprises storage (phonological store) and the maintenance of information. The phonological store upholds information in phonological form, and the rehearsal processes maintain the information by repeating it to sustain it in the phonological store (Baddeley et al., 1998). The phonological loop has been found to have an especially important role in language learning (Baddeley et al., 1998).

According to Baddeley and Hitch (1974), the visuospatial sketchpad is a subsystem of WM that retains visuospatial information in short-term memory in a similar manner than the phonological loop holds phonological information. Baddeley et al. (2011) suggests that the operation of the visuospatial sketchpad can be divided into visual, spatial, and haptic components. The visual component processes color and shape, while information about the surrounding space is managed in the spatial component (Baddeley et al., 2011). The haptic component is responsible for kinaesthetic and tactile information processing (Baddeley et al., 2011).

1.3. Working memory and dyslexia

The relation between WM and dyslexia has been discovered in many studies. According to multiple studies and meta-analyses, lower WM performance has been associated with lower reading scores (Peng et al., 2018) and dyslexia (Swanson et al., 2009; Cowan et al., 2017). WM can also be seen to be related to academic performance in multiple ways, such as managing attention or the capacity to process new knowledge (Bergman et al., 2017). Therefore, it is important to investigate the relationship between WM and dyslexia. These relations also seem to continue from childhood to adulthood (Swanson et al., 2009), highlighting the need to look at the link between WM and dyslexia also in adulthood.

Dyslexia is known to be associated with impaired auditory WM (Lonergan et al., 2019). Consequently, dyslexia is connected to deficiencies in the phonological loop (Maehler & Schuchardt, 2016). It is also hypothesized that children with dyslexia might have deficiencies in the function of the central executive (Maehler & Schuchardt, 2016). These impairments in the phonological loop and the central executive have been found to persist into adulthood regardless of the individual's current reading level; in other words, adults that reach the average reading level are still found to have a poorer performance in tasks measuring phonological and executive functions of WM (Swanson et al., 2009). While the link between the phonological loop and dyslexia is well documented, the link between dyslexia and the central executive is not that clear (Maehler & Schuchardt, 2016). Based on Baddeley's (2012) componential WM model's theory of the importance of the central executive and the results of multiple studies (Brandenburg et al., 2015; Bacon et al., 2013; Alt et al., 2022), it could be argued that the central executive might also play a role in dyslexia.

Phonological awareness has been closely linked with dyslexia (Vellutino et al., 2004). Knoop-van Campen et al. (2018) found a causal connection between WM and word reading efficiency, mediated by phonological awareness. This connection implies that deficiencies in WM result in problems in understanding and manipulating the structure of speech sound fragments (Knoop-van Campen et al., 2018). Phonological awareness is found to be impaired in both dyslexic children (Bruck, 1992) and adults with a childhood diagnosis or presumptive childhood dyslexia (Bruck, 1992; Wilson & Lesaux, 2001). These impairments have been found in adulthood regardless of a person's current reading level (Bruck, 1992). This finding is in line with other studies stating that deficiencies in the WM performance also persist despite an improved reading rate (Swanson et al., 2009).

WM tasks are generally thought to measure different domains of WM (verbal WM, visuospatial WM, numerical WM). However, whether those tasks can reflect the actual performance of the domains independently remains controversial. This debate resulted in two theories: the domain-general theory and the domain-specific theory of WM (Peng et al., 2018). Literature has not attained consensus on these theories (Peng et al., 2018).

As previously mentioned, Baddeley and Hitch's WM model proposes that the central executive has an essential role in coordinating subsystems (episodic buffer, phonological loop, visuospatial sketchpad), general information processing, and related cognitive skills (Baddeley, 2012). This essential role of the central executive forms an underlying idea of the domain-general theory (Baddeley, 1986). The domain-general theory suggests that the performance of different aspects of WM are hard to segregate from each other (Peng et al., 2018). In other words, the WM test scores would not show the performance of an independent WM domain but the performance of different domains intermingled with deficiencies in the central executive.

Domain-specificity theory, on the other hand, suggests that the domains of WM work more independently from each other and have specialized functions (Baddeley, 1974). Ericsson and Kintsch (1995) also brought up the idea of the importance of long-term memory in WM performance. According to this theory, domain-specific information is retrieved from long-term memory representations into different domains, in which case the extent of the long-term memory representations affects the WM performance (Ericsson & Kintsch, 1995). This more independent functioning of WM domains and the influence of the long-term memory would be reflected as a poorer performance of certain WM components over others in people with dyslexia.

According to a recent meta-analysis, whether the relations between WM and reading are domain-general or domain-specific might depend on the stage of the reading development (Peng et al., 2018). In earlier stages of the reading development, WM tends to be more domain-general while more advanced readers seem to represent a domain-specific hypothesis, emphasizing the role of verbal WM (Peng et al., 2018).

1.4. Aims of the study

The aim of this study was to investigate the WM performance of two groups with childhood dyslexia: adults with persistent dyslexia and adults with compensated dyslexia. First, we wanted to know whether there were any differences in the WM performance between the two dyslexia groups and the control group. The study of Eloranta et al. (2019), which included the participants of our current study in a larger sample, and Wiseheart and Altmann's (2018) study found that deficiencies in the WM performance of people with dyslexia persist into adulthood regardless of the person's current reading level. Based on these results, we hypothesized that both dyslexia groups would have poorer WM performance on average than the control group. We also hypothesized that the differences between the dyslexia groups and the control group is seen in tasks that require phonological processing rather than in tasks requiring visuospatial processing. We made this assumption based on the general view in the research field that dyslexia typically affects WM performance in tasks that require phonological processing, whereas visuospatial processing often stays more intact (e.g., Swanson et al., 2009; Peng et al., 2018).

The second question we were interested in was if the WM performance differs between the two dyslexia groups. We did not form a hypothesis for the second research question because there is no clear consensus on whether the WM performance differs between those who have persistent dyslexia and those who have compensated for their dyslexia (Wiseheart & Altmann, 2018; Hiscox et al., 2014). Because of this lack of consistent results, we approached this question rather from a data-driven perspective than with the forming of a hypothesis.

2. METHODS

2.1 Participants & procedure

The present study consists of adults with documented dyslexia in childhood (n = 30) and a control group with no documented dyslexia (n = 26). The participants with documented dyslexia were selected from the clinical archival database of the Clinic for Learning Disabilities at the Niilo Mäki Institute in Jyväskylä, Finland. The Clinic for Learning Disabilities is a part of the services of Niilo Mäki Institute and the family clinic of Jyväskylä, and it provides neuropsychological assessment and remediation for children with learning disabilities. Children are usually referred to the clinic by a school psychologist or family counseling center. A previous examination by a psychologist and an estimated need for additional examinations after problems with learning have been established are prerequisites for admission to the clinic. Children with global developmental delay or major socioemotional problems are not referred to the clinic.

The participants were included in the research with no comorbid learning disability, no emotional, social, or behavioral problems, no impairments in vision or audition, neurological disorders, or serious head injuries. The data from the Clinic for Learning Disabilities were collected between the 1980s and the 2000s when the participants were approximately 8–14 years old. The participants have been contacted two times in their adulthood for further research: first, in 2015–2016, and then in 2021–2022 during the current measurements. The current study concentrates on the data collected in 2021–2022. During the measurements in 2021–2022, the participants with dyslexia were 26–40 years old, and the mean age of the group was 32 years. 63 % of participants were men. All participants were from Finland and spoke Finnish as their mother tongue.

The initial control group was chosen from the Finnish Population Register Center for the previous measuring point in 2015–2016 and called back for the 2021–2022 measures. These control participants were matched with the participants from the Clinic for Learning Disabilities with variables of age, gender, and hometown at the school starting age of seven. Due to the problems with recruiting control participants from the earlier control group formed for the measurements in 2015–2016, we recruited new participants for the current study. New control participants were recruited from a Finnish Facebook group (n = 5), and the remaining four control participants were either controls from another study or newly recruited from the register of the Social Insurance Institution of Finland (KELA). The mean age of the final control group was 33 years, with the range of 27–43 years. 54 % of the group was men. The cognitive skills of the participants were tested both in the research laboratory at the University of Jyväskylä and at home via computerized tasks and remote testing.

The criterion for dyslexia was the reading fluency test z-score being at least 1.5 SD below the control group's mean score. The group with childhood dyslexia was divided into the persistent dyslexia group and the compensated dyslexia group. The distribution of the two dyslexia groups is explained in more detail later in the text (see 2.3.).

The ethical committee of the University of Jyväskylä gave a positive statement for conducting the study. The participants also gave informed, written consent. Feedback and a thorough summary of the results were provided after the cognitive testing if requested.

2.2 Measures

2.2.1. Reading fluency

In our study, the reading fluency of the participants was measured both in childhood and adulthood. The Finnish language has a transparent orthography with high consistency between written letters and speech sounds (Aro, 2006). Therefore, reading accuracy is often learned in the early stages of reading development, and hence it is not differentiating enough alone to measure reading skills in the Finnish language (Aro & Lerkkanen, 2019). Under those circumstances, reading speed or reading speed combined with accuracy was used as a reading fluency measure in childhood. In adulthood, reading fluency was measured using the reading speed combined with the accuracy.

Tests used in the Clinic for Learning Disabilities varied over the years. Four different reading tests were used to assess reading skills in childhood (Lukilasse, ÄRPS, Misku, and Markkinat). The use of the test varied based on the availability of the tests at the time of measurements. All tests were age-normed and developed in Finland. *Lukilasse* is a test battery for reading, spelling, and mathematical skills (Häyrinen et al., 1999). The test is normed for Grades 1 to 6. Only the Word Reading Subtest of the Lukilasse test was included in the present study. The subtest contains a list of gradually longer and more complex words. The child was asked to read the word list aloud as quickly and correctly as possible. *Misku* text is a reading test normed for 8- to 12-year-old children (Niilo Mäki Institute, 1992–1994). It requires a child to read a one-page text as fast and accurately as possible. *Äänekoski Reading Performance Scale* (ÄRPS; NMI, 1992–1994) is a reading test normed for Grades 2 to 4 (Niilo Mäki Institute, 1992–1994). The test contains a text-reading part, a one-page story that the child reads aloud, and a word/pseudoword-list reading task. *Markkinat Word List* is a word list test that consists of 13 words, and it is normed for 8- to 12-year-old children (Niilo Mäki Institute, 1992–2004). Depending on the test, either the reading speed or the reading speed combined with the accuracy was used as a measure of the reading fluency.

Two tests were used to assess reading fluency in adulthood. *Tunturilappi* (Leinonen et al., 2001) is a text reading task that consists of 210 words. Participants were instructed to read the text aloud as fast and accurately as possible. The test had no time limit, but the performance time was measured, and errors were counted. In this study, we used the correctly read words per 60 seconds as a measure of reading fluency. The other reading fluency test used was the pseudoword reading task *Vinnittäjiä tenkoja* text which consists of 38 pseudowords. There was no time limit on this test either. Participants read the text aloud, and the time and errors were counted similarly to the Tunturilappi text reading task. Correctly read words per 30 seconds were used as a result of the test. The Spearman's correlation between the Tunturilappi score (correct words per 60 seconds) and Vinnittäjiä tenkoja score (correct words per 30 seconds) was 0,888 with $p < 0,001$. Based on this correlation, we combined the two reading text scores to make a new composite variable, reading fluency.

2.2.2. Working memory

The working memory index (WMI) from the Wechsler Adult Intelligence Scale-IV (WAIS IV, Wechsler, 2012) was used to evaluate the WM. Both subtests, the Digit Span and the Arithmetic, along with the supplemental subtest Letter-Number Sequencing, were included in the current study. Each of these tests, except the Arithmetic, was conducted in the present measuring point in 2021-2022. The participants took the Arithmetic test only during the earlier measuring point in 2015-2016. In the present study, the data from the Arithmetic test were used alongside the other tests carried out in 2021-2022.

Digit Span tasks (Wechsler, 2012) measure short-term auditory memory, auditory WM, executive functions, attention, and concentration (Lichtenberger & Kaufman, 2013). The test comprises three sections: Digit Span Forward, Digit Span Backward, and Digit Span Sequencing. Each section emphasizes slightly different cognitive skills. In the Digit Span Forward, the participant was read a random sequence of numbers and asked to repeat it in the same order. The Digit Span Forward requires information coding, auditory processing, and memorizing. In the Digit Span Backward, the participant was read a random sequence of numbers and asked to repeat it in reverse order. The Digit Span Backward measures WM, mental processing, and information manipulation (Groth-Marnat, 2003). In the Digit Span Sequencing, the participant was asked to repeat the sequence of numbers from lowest to highest. The Digit Span Sequencing section requires both storing and manipulating information in the WM (MacDonald et al., 2001). Each Digit Span section had eight parts, and each part had two sequences equal in length. If the sequence was repeated correctly, it would steadily increase in length. Each task started with a length of two digits, with eight digits being the maximum in Digit Span Forward and Digit Span Backward tasks and nine digits in the Digit Span Sequencing task. We used each subtest as a separate variable since each of them measures slightly different aspects of WM. Correlation between these subtests is found to be relatively low ($r \approx .5$), which supports the use as separate variables (Gignac et al., 2019).

Arithmetic subtest (Wechsler, 2012) measures WM emphasizing, for example, information processing in short- and long-term memory, numerical reasoning, quantitative knowledge, and serial processing. In the test, the examiner reads aloud arithmetic problems which the participant solves mentally. The test has a time limit.

Letter-Number Sequencing (Wechsler, 2012) assesses short-term auditory memory, serial processing, information processing, attention, and concentration. In the test, the examiner read aloud sequences containing numbers and letters, and the participant was asked to first recall numbers ascending and then letters in alphabetical order. If one or more sequences per section were repeated correctly, sequences would steadily increase in length. The subtest had ten sections with three sequences in each, and the length of the sequences varied from two to eight digits.

Corsi block-tapping task is designed to measure visuospatial short-term memory and WM (Kessels et al., 2008), and it is widely used in neuropsychological research. In our study, the Corsi block-tapping task was implemented using an online version of the task, either in the research laboratory or via a Zoom meeting at home. A block sequence was first demonstrated on the computer screen with sporadically arranged squares turning yellow one by one. After the demonstration, the participant had to click the squares in the shown order and press "Done" after choosing. The task began with two squares, and if the order was remembered correctly, the length of the sequence grew by one. The length could increase up to nine squares. The participant had three attempts to remember the same number of squares. The Corsi task was done both forwards, as described, and backwards, in which case the participant had to start clicking from the last square shown and proceed in reverse order. The longest remembered sequence was used as a test score.

2.3. Statistical analyses

We used IBM SPSS Statistics 26 (IBM, New York, United States) to analyse our data. We started by creating a reading fluency variable to define the cut-off point for persistent dyslexia and compensated dyslexia.

The cut-off point for persistent dyslexia was obtained by first calculating the reading fluency scores for the two reading texts by using correct words read per 60 seconds in Tunturilappi text and the correct words read per 30 seconds in Vinnittäjiä tenkoja pseudoword text. Spearman's correlation was used to explore the expediency of the composite variable. We then standardized the scores of the two variables among all participants and computed the mean of the standardized scores for each participant. This mean was coded as a new variable, reading fluency. Our next step was to calculate the mean and SD, including only the control group's reading fluency scores, to form a cut-off point for persistent dyslexia. The cut-off point was defined to be 1.5 SD below the mean score of the control group. With the cut-off point, our participants with childhood dyslexia were divided into two groups, a group with continued reading difficulties called the persistent dyslexia group (n = 24) and a group without continued reading difficulties, which we named compensated dyslexia group (n = 6).

Closer inspections of WM task data disclosed normality issues and outliers. Under these circumstances, we chose Spearman's rank-order correlation to examine the correlations between the reading fluency variable and the WM tasks.

To answer our research questions, we used the nonparametric Mann-Whitney U-test. In accordance with our first research question, we started by comparing the WM performance of both childhood dyslexia groups separately to the control group. We then repeated the test to compare the WM scores of the two childhood dyslexia groups as it was our interest in the second research question. The means, medians, and SDs of each WM task of the three groups were observed separately.

3. RESULTS

Spearman's rank-order correlations were conducted between the reading fluency variable and the WM tasks (Table 1). All correlations between the variables were positive. The correlations between the reading fluency and all three Digit Span tasks, Arithmetic, and Letter-Number Sequencing tasks were significant. Corsi Forward and Corsi Backward tasks were the only WM tasks that did not correlate significantly with reading fluency. The medians, means, and SDs of the WM tasks of three reading level groups of our study can be seen in Table 2.

Table 1

Spearman's correlations between reading fluency and WM tasks.

	1	2	3	4	5	6	7	8
1. Reading fluency	-							
2. Digit Span Forward	.453***	-						
3. Digit Span Backward	.533***	.629***	-					
4. Digit Span Sequencing	.311*	.460***	.462***	-				
5. Arithmetic	.564***	.336*	.318*	.517***	-			
6. Letter-Number Sequencing	.587***	.442**	.489***	.509***	.632***	-		
7. Corsi Forward	.121	.257	.169	.540***	.367*	.387**	-	
8. Corsi Backward	.122	.342**	.211	.324*	.356*	.283*	.416**	-

Note. Spearman's correlations of the working memory tasks. * p < .05, ** p < .01, *** p < .001

Table 2

The medians, means, and SDs of the WM tasks for the three groups

	PD (n=24)			CD (n=6)			Control (n=26)		
	M	MD	SD	M	MD	SD	M	MD	SD
Digit Span Forward	7.29	7.00	2.07	9.00	8.00	3.10	8.81	9.00	1.65
Digit Span Backward	7.17	7.00	1.79	9.50	9.50	2.66	9.27	9.00	2.34
Digit Span Sequencing	8.38	8.00	2.22	8.83	9.00	2.23	9.81	10.00	2.14
Arithmetic	7.33	7.00	2.35	6.83	7.50	1.94	9.76	10.00	2.20
Letter-Number Sequencing	8.38	7.50	2.96	10.17	10.50	1.84	11.69	10.50	3.39
Corsi Forward	6.79	7.00	1.06	7.17	7.00	1.17	7.08	7.00	1.26
Corsi Backward	6.63	7.00	1.38	7.83	8.00	1.17	6.77	6.00	1.31

Note. M = mean, MD = median, SD = standard deviation, PD = persistent dyslexia group, and CD = compensated dyslexia group.

The results of the Mann-Whitney U-test can be seen in Table 3. In accordance with the first research question, we explored the differences between the two dyslexia groups and the control group. The group with persistent dyslexia performed significantly poorer than the control group in all but Corsi Forward and Corsi Backward tasks. Similarly, effect sizes (Cohen, 1988) were moderate ($0.3 < r < 0.5$) for all but Corsi Forward and Corsi Backward tasks. The compensated dyslexia group and the control group differed significantly in the Arithmetic task, in which the group with compensated dyslexia had lower scores than the control group. Besides this, there were no significant differences in WM performance between the compensated dyslexia group and the control group. However, the effect size for the Corsi Backward task was moderate, with the compensated group having higher scores than the control group.

For the second research question, we compared the WM performance of the two childhood dyslexia groups (Table 3). The persistent dyslexia group performed significantly poorer than the compensated dyslexia group only in the Digit Span Backward task. However, the effect sizes were moderate also for the Corsi Backward and the Letter-Number Sequencing tasks, in which the compensated dyslexia group had higher scores than the persistent dyslexia group.

Table 3

Mann-Whitney U-test results for pairwise comparison of the three reading level groups.

	PD vs. Control (n= 50)				CD vs. Control (n=32)				PD vs. CD (n=30)			
	U	z	p	r	U	z	p	r	U	z	p	r
Digit Span Forward	153.500	-3.119	.002**	.441	66.500	-.571	.588	.101	41.500	-1.609	.119	.294
Digit Span Backward	138.000	-3.429	.001**	.485	82.000	.198	.869	.035	32.000	-2.096	.038*	.383
Digit Span Sequencing	193.000	-2.336	.019*	.330	62.500	-.758	.464	.134	56.500	-.813	.432	.148
Arithmetic	86.500	-3.133	.002**	.443	17.500	-2.369	.016*	.419	76.500	.236	.820	.043
Letter-Number Sequencing	137.000	-3.422	.001**	.484	60.500	-.851	.408	.150	39.500	-1.702	.093	.311
Corsi Forward	262.500	-.998	.318	.141	78.500	.025	1.000	.004	59.500	-.679	.527	.124
Corsi Backward	302.000	-.201	.841	.028	113.500	1.824	.087	.322	36.500	-1.872	.065	.342

Note. r = effect size (Spearman's correlation), PD = persistent dyslexia group, and CD = compensated dyslexia group,

* $p < .05$, ** $p < .01$, *** $p < .001$.

4. DISCUSSION

The aim of this study was to acquire a better understanding of the connection between dyslexia and WM in adulthood. To investigate this relation, we compared the WM performance of three groups: a group with persistent dyslexia, a group with compensated dyslexia, and a control group. In accordance with the research questions, the comparisons were first done between the persistent dyslexia group and the control group and then between the compensated dyslexia group and the control group. We then continued by comparing the persistent dyslexia group and the compensated dyslexia group together.

Our first hypothesis was that both childhood dyslexia groups would have poorer WM performance on average compared to the control group. In line with our first hypothesis, the group with persistent dyslexia performed poorer than the control group on the WM tasks on average. More specifically, the group with persistent dyslexia performed significantly poorer in all but Corsi Forward and Corsi Backward tasks, which are known to measure the visuospatial WM rather than verbal WM (e.g., Kessels et al., 2008). All tasks that significantly differed between groups showed moderate effect sizes. These results support the hypothesis that the differences between the dyslexia groups and the control group appear in WM tasks that require phonological processing rather than visuospatial processing. Hence, our results are in line with former research that has discovered that dyslexia is linked especially with verbal WM (e.g., Swanson et al., 2009; Lonergan et al., 2019; Maehler & Schuchardt, 2016).

Conversely, the group with compensated dyslexia did not perform significantly poorer than the control group in any WM task but the Arithmetic. This was not in line with our hypothesis that also the compensated dyslexia group would have poorer WM performance on average compared to the control group. This finding differs from the research of Eloranta et al. (2019), where all the participants with dyslexia in childhood, regardless of its continuance into adulthood, had a poorer WM performance than the control group. Wiseheart and Altmann (2018) also reported that the WM scores of the participants with compensated dyslexia were significantly lower than the scores of the control group. In conclusion, the hypotheses of our first research question were only partially supported by our results. More specifically, when comparing with the control group, the results of the persistent dyslexia group were in line, and the results of the compensated dyslexia group were not in line with our hypotheses.

It is suggested that not all people with dyslexia suffer from deficiencies in the WM (Gray et al., 2019). The current study had a cross-sectional design hence reliable data on childhood WM performance were not available. Consequently, it is possible that individuals in the compensated dyslexia group have not suffered from deficiencies in WM and that they might have compensated deficiencies in reading skills with WM (Gray et al., 2019).

The study of Eloranta et al. (2019) includes the participants of the current study in a larger sample of participants recruited from the Clinic for Learning Disabilities. The contradiction between the results from the current study and the study of Eloranta et al. (2019) is probably due to the differences in the determination of the cut-off point for persistent dyslexia. In the current study, the cut-off point was rather strict, with only 20 % of participants with childhood dyslexia having compensated for their dyslexia (vs. 60 % in Eloranta et al., 2019). The strict cut-off point also led to the small size of the compensated dyslexia group (n = 6, versus n = 29 in Eloranta et al., 2019), which increases the need for caution in interpreting the results of our study. The discrepancy between the results of the current study and the study of Eloranta et al. (2019) might also be due to different reading fluency definitions. Eloranta et al. (2019) used reading speed to measure reading fluency and combined it with a separate accuracy score formed by only using correctly read words in a pseudoword reading task. Whereas both reading speed and accuracy in both Tunturilappi and Vinnittäjiä tenkoja texts were taken into account in the current study. The reading tests were also different between the two studies.

Compared to the control group, the persistent dyslexia group had significantly poorer performance also in the Arithmetic test. Children with dyslexia are consistently discovered to have problems with mathematical processes that consist of the manipulation of verbal codes, such as counting speed and the recalling of numerical facts (Simmons & Singleton, 2007). De Smedt and Boets (2010) found a similar connection between weak phonological processing and the ability to recall arithmetic facts when studying adults with developmental dyslexia. The Arithmetic test also has a more direct phonological component, as the mathematical problems are expressed to the participant orally. These factors could partially explain why the persistent dyslexia group performed poorer than the control group in the Arithmetic task, even though there were no comorbid mathematical difficulties among the participants.

The sample size was smaller in the Arithmetic task than in the rest of the tasks. This was due to the missing values of nine new participants in the control group. These participants had not participated in the earlier measuring point in 2015–2016. Therefore, the participants had not completed the Arithmetic task since it was not included in the measuring point in 2021–2022 when the rest of the data of the current study was collected. The Arithmetic test is also criticized for being affected by the level of education (Egeland et al., 2009) and math anxiety (Buelow & Frakey, 2013).

These factors might also explain the results of this study, but closer inspections of these possible mediators are needed.

Even though the compensated dyslexia group and the control group significantly differed only in the Arithmetic task, the effect size was also moderate in the Corsi Backward task. The compensated dyslexia group performed poorer than the control group in the Arithmetic but better in the Corsi Backward task (seen in Table 2). The better numerical values in the Corsi Backward task on a group with compensated dyslexia could be explained by the possible distortion due to the small sample size of the compensated dyslexia group.

Finally, we wanted to inspect the WM performance between the two childhood dyslexia groups. No hypothesis was formed due to the lack of consensus in the research field, and the research question was approached from a data-driven perspective. The comparisons between the persistent dyslexia group and the compensated dyslexia group showed that the groups differed significantly only in the Digit Span Backward task, in which the compensated dyslexia group performed better. However, effect sizes were moderate also in the Letter-Number Sequencing and Corsi Backward tasks, similarly referring to better performance in the compensated dyslexia group.

The Corsi Backward task relies on the central executive, and it could be thought of as a marker of poor functioning of the central executive in people with dyslexia (Bacon et al., 2013). It could also be hypothesized that the better performance of the compensated dyslexia group compared to the control group in the Corsi Backward task might reflect a more efficient performance of the central executive of the compensated dyslexia group. The better performance of the central executive could compensate for the problems in reading (Alt et al., 2022). This idea could also be supported by the results between the persistent dyslexia group and the compensated dyslexia group. The results showed moderate effect sizes in Digit Span Backward, Letter-Number Sequencing, and Corsi Backward tasks implicating better performance in these tasks in the compensated dyslexia group compared to the persistent dyslexia group. Based on Baddeley and Hitch's multicomponent working memory model (2000), the central executive is in charge of manipulating and combining information in WM. Hence, the tasks mentioned above could be thought to be especially heavy on the central executive. The presumably better functioning of the central executive in the compensated dyslexia group compared to the control group was visible only in the effect size for Corsi Backward task and not in other tasks that are thought to be heavy on the central executive. This could be due to the lack of the phonological component in the Corsi Backward task. However, our comparisons between the persistent dyslexia group and the control group do not seem to support this idea, at least when considering the Corsi Backward task.

The domain-general and domain-specific theories of the relation between the WM and dyslexia are the topics of ongoing debate. In the current study, the persistent dyslexia group had significantly poorer WM performance than the control group in all but Corsi Forward and Corsi Backward tasks. In other words, the performance was poorer in the tasks requiring the use of verbal and numerical WM rather than visuospatial WM. This result supports the domain-specific theory (Ericsson & Kintsch, 1995), which suggests that performance in WM tasks depends on the content; more specifically, poorer performance would be seen in WM tasks containing verbal content (Peng et al., 2018). Peng et al. (2018) state that WM and dyslexia have both domain-general and domain-specific relations and that the domain-specific relations could be more dominant in later stages of reading development. The current study concentrated on the relation between WM and dyslexia in adulthood which makes the results to be in line with the findings of Peng et al. (2018) about WM's more domain-specific nature in the later stages of reading development.

It is also important to note that the Corsi Backward task suffered from the ceiling effect, which might have affected its effect size. The ceiling effect raises the question of how reliable the online version of the Corsi Backward task were as measures. This issue is good to acknowledge since the Corsi tasks were the only tasks in our study that measured specifically the visuospatial WM. For future research, the reliability issues of the online Corsi Backward task should be examined more carefully to eliminate the possible distortion caused by the ceiling effect.

The use of Baddeley and Hitch's multi-component model (2000) is supported by the correlations of our study (see Table 1) since most of the WM tests correlate with each other regardless of the differing content. The tests that are thought to be particularly heavy for the central executive (e.g., Letter-Number Sequencing and Arithmetic) seem to correlate stronger with each other, whereas tests that are lighter for the central executive (e.g., Digit Span Forward and Corsi Forward) seem to have smaller or no correlations between them. These results implicate the general influence of the central executive component in overall WM. In addition, tests with phonological aspects seemed to correlate with each other regardless of rather differing content (e.g., Digit Span Forward and Arithmetic)

4.1. Strengths and limitations

Our tests for measuring WM were relatively versatile, as we had up to seven different tests measuring the WM performance of our participants. When looking into Baddeley and Hitch's multi-component model (2000), the tests covered at least the phonological and visuospatial components of the WM, alongside the central executive. The three Digit Span tasks, Letter-Number Sequencing, and Arithmetic task all require the storing of auditory information (Groth-Marnat, 2003; Wechler, 2012), and thus use the phonological loop as it is portrayed by Baddeley (1998). The Corsi Forward and Backward tasks require the use of the visuospatial sketchpad, as both tests require memorizing visual information. Corsi tasks are often thought to be a visuospatial equivalent for the Digit Span tasks (Bacon et al., 2013).

The archival database of the Clinic for Learning Disabilities was used to recruit the participants with dyslexia in childhood, which led to all adults of our dyslexia groups having a documented and thereby highly reliable dyslexia diagnosis. Besides this, the participants with dyslexia in childhood were included in the research only if they had no comorbid learning disability, no emotional, social, or behavioral problems, no impairments in vision or audition, neurological disorders, or serious head injuries. This minimizing of comorbidities makes our results more reliable and more likely to be due to dyslexia than comorbid deficiencies.

Limitations of our study include the artificial nature of the dyslexia cut-off point and the small sample size. The cut-off point for either having or not having dyslexia can vary, which leads to discrepancies in the research field. We set the cut-off point to be at 1.5 SD below the mean of the reading fluency of the control group, as it is an often-used limit in both research and clinical practice, but it is also common for the cut-off point to be anywhere between 1 and 2 SD below the presumed population mean score (e.g., Yang et al., 2022).

Our sample size was relatively small ($n = 56$), which led to the compensated dyslexia group having only six participants. With the compensated dyslexia group being so small, the comparisons with the other groups can only be thought of as a rough estimate of the real situation. However, despite the small size of the compensated dyslexia group, the size of the persistent dyslexia group was moderate.

4.2. Future research

This study highlights the need for further research on dyslexia and WM. We only studied the WM performance of the participants cross-sectionally in adulthood. A longitudinal approach would give a more detailed view of the development of the relation between dyslexia and WM performance. In particular, it would be interesting to examine whether the differences in WM performance between the compensated dyslexia group and the persistent dyslexia group compared to the control group seen in this study would be seen already in childhood or if they developed later on. In order to acquire more reliable results in the future, a larger sample size is needed. Interesting directions for future research would also be to explore if the domains of WM had unique connections to different components of reading, such as phonological awareness, alphabetic mapping, or phonological coding (Vellutino et al., 2004). Including tests measuring specifically executive functions, for example, auditory and visual n-back tasks could clarify the role of the central executive in dyslexia. The current study also highlights the need for further investigations of the characteristics of persistent dyslexia, compensated dyslexia, and the possible predictive factors behind them.

4.3. Conclusions

We discovered a clear connection between persistent dyslexia and deficiencies in the verbal WM tasks. There were also indications of possible deficiencies in the central executive. These findings are strongly supported by former research (e.g., Swanson et al., 2009; Cowan et al., 2017; Bacon et al., 2013; Alt et al., 2022). However, the connection between compensated dyslexia and poor WM performance was not evident. This result was not in line with our hypothesis, and hence it provides a good starting point for discussion and further research. Persistent dyslexia and compensated dyslexia groups only differed on one test. In general, the results of this study supported the domain-general theory on the relation between dyslexia and the WM by emphasizing the deficiencies in the phonological loop in people with persistent dyslexia in adulthood. To conclude the present study, our findings provide a basis for future research on persistent and compensated dyslexia from childhood to adulthood.

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