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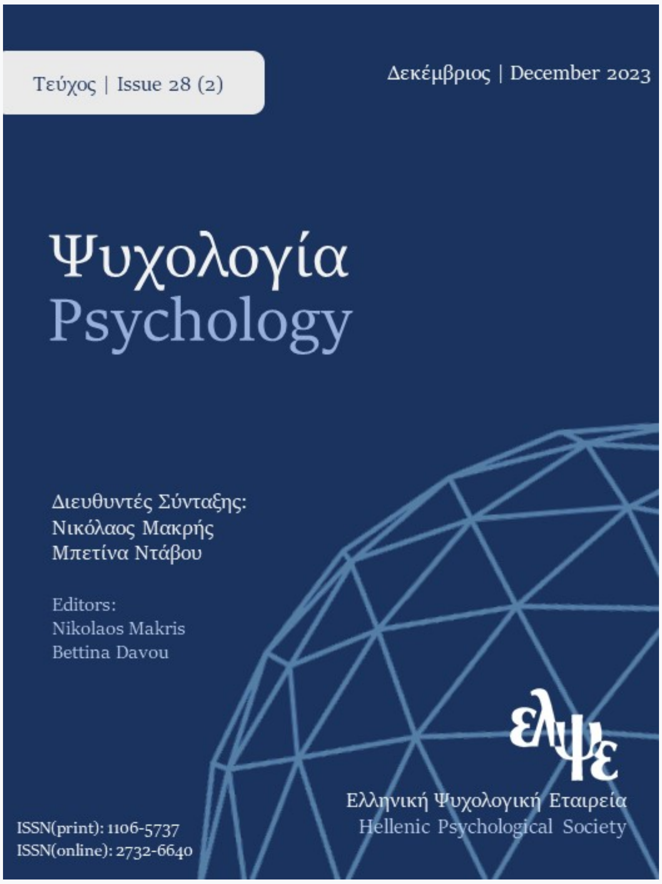

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ΒΙΒΛΙΟΓΡΑΦΙΚΗ ΑΝΑΣΚΟΠΗΣΗ | REVIEW PAPER

The role of working memory in the comprehension of syntactically complex sentences in children with and without developmental language disorder: A literature review

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ABSTRACT

Working memory (WM) components are investigated as correlates of complex sentence comprehension (cSC) in children, under the consideration of WM as a cognitive system of limited capacity. The present study aims to investigate the relationship between WM components and cSC in children of typical language development (TLD) as well as in children with Developmental Language Disorder (DLD), by systematically reviewing relevant studies. First, different tasks that are used to assess three distinct WM components are presented and task purity considerations on each of them are taken into account. Second, syntactically complex sentence types that are considered to constrain the already limited resources of WM are presented. Then, the systematic methods of the PRISMA-P protocol are followed. Based on them, six databases were thoroughly searched. After an initial screening stage and a final evaluation stage, twenty-eight studies were found to meet the inclusion criteria. Narrative synthesis was performed on the included studies. In TLD children, results on the role of verbal short-term memory (vST) and verbal working memory (vWM) in cSC are inconclusive, either supporting or questioning the capacity-limit approach. In DLD children, verbal working memory (vWM) has an important effect on cSC, rather than verbal short-term memory (vSTM). This suggests that a processing-execution component is important in DLD children's cSC. For both children groups, a component serving as an interface between vSTM/vWM and long-term memory (vSTM/vWM-LTM) seems to play an important role; however, it is greatly understudied. Based on the results, future research directions and educational implications are suggested.

Introduction

Working memory components

Working memory (WM) is considered a cognitive system of limited capacity in which processing and execution operations on information take place (Just & Carpenter, 1992; Kane et al., 2007; Baddeley, 2012). According to Baddeley's (2012) multicomponent view of WM, there is a subsystem that is responsible exclusively for the temporary storage of verbal information, called the Phonological Loop (PL); a subsystem in charge of processing and execution purposes, named after the Central Executive (CE); and a subsystem serving as an interface between information stored temporally in short-term memory (STM) and information stored permanently in long-term memory (LTM), termed as the Episodic Buffer (EB). These three subsystems express three distinct yet co-operating WM components: i) verbal short-term memory (vSTM) as an only-storage component; ii) verbal working memory (vWM) as a joint storage–processing/execution component; and iii) a vSTM/vWM-LTM component (i.e., Episodic Buffer) in which information from both vSTM-vWM and LTM are simultaneously being stored and processed. Despite their differences, all three components share the characteristic of limited capacity. Capacity is limited in terms of time as items can be held in memory for a very short period of time until decay occurs, as well as in terms of items as only a very limited number of unconnected items can be simultaneously held in memory (Cowan, 2001).

Working memory tasks

Different tasks are used to assess the three WM components. For the measurement of vSTM (/PL), nonword repetition and forward digit span are mostly used. In nonword repetition, children are asked to repeat one nonword at a time. Task difficulty increases as nonwords' syllable length is gradually increased (e.g., Boyle et al, 2013; Montgomery & Evans, 2009; Montgomery et al, 2008; Ladányi et al., 2017). Nonword repetition has been questioned on whether it taps a pure passive storage subsystem (i.e., vSTM). That is because nonwords that include cues or patterns familiar to those of participants' native language, such as common phonotactic rules, morphological cues, and prosodic cues, are recalled more easily than nonwords with lower familiarity (Hulme et al., 1991; Gathercole, 1995). This suggests the contribution of LTM language knowledge in recall. In forward digit span, children have to recall a series of numbers in the same serial order that it was presented. The task is becoming more and more difficult as the number of digits is being raised (e.g., Arosio et al., 2011; Bentea et al., 2016; Booth et al, 2000; Haendler et al., 2015; Talli & Stavrakaki, 2019). Forward digit span has also been questioned on whether it taps only the short-term capacity (i.e., vSTM). That is because when participants try to recall a series of numbers they group some of the numbers into chunks to facilitate their recall (Dunn et al., 1990; Cowan et al., 2005). For example, when they have to recall the series 7 – 2 – 3 – 4 – 9, they group the 2 – 3 – 4 as one chunk based on their LTM knowledge that they are consequent numbers, in order to conserve their limited resources. This process is known as chunking (Miller, 1956).

For the assessment of vWM (/PL + CE), backward digit span and sentence span are among the two most common tasks. In backward digit span, children have to recall a series of numbers per try in the reverse order from which it was presented. The task is becoming more and more demanding as the number of digits is being raised (e.g., Boyle et al., 2013; Bentea et al., 2016; Haendler et al., 2015; MacDonald et al., 2020; Poulsen et al., 2022; Schouwenaars et al., 2018). There are two different views regarding the operations involved in performing this task. The first is that subjects start reordering the digits before the presentation of them has been finished. According to this view (Colom et al., 2005; Dunn et al., 1990; Engle et al., 1999), recall performance is underpinned by similar processes to those used in forward digit span such as the grouping of items based on LTM familiarity (i.e., chunking; Miller, 1956), to preserve vSTM limited resources. This means that the backward digit span is not much different from the forward digit span in terms of what is actually measured by it. The second view is that participants start reordering the digits only after the whole series of them has been presented (Gathercole et al., 2004; Oberauer et al., 2000). This implies that the digits are first stored in vSTM (/PL) and then processed by vWM (/CE) to get reversed. Thus, this view sees backward digit span as a measure of processing/execution resources (/CE). In regard to the sentence span task, in its initial version (Daneman and Carpenter, 1980; reading span), children are asked to read sentences aloud without any pausing and then to recall all final words of each set in the correct order. In the auditory variant of this task (Daneman & Carpenter, 1980; listening span), participants listen to sentences and have to value them as true or false. After a set of sentences is completed, they have to recall the last word of each sentence in serial order (e.g., Arosio et al., 2011; Booth et al., 2000; Felser et al., 2003; Montgomery & Evans, 2009; Roberts et al., 2007; Sasaki et al., 2021; Weighall & Altman, 2011). In another variant, children did not have to recall the last word of each sentence, but a number that was presented after each sentence (e.g., Finney et al., 2014). Alternatively, in another variant, children are asked to listen to sentences ending in nonwords (e.g., *The bird is singing at the dopɛdg*); to answer a comprehension question for each sentence right after its presentation (e.g., *Is the bird singing*? *Yes/No*); and lastly to recall the nonwords of each set in serial order (e.g., Montgomery et al., 2008). In all versions, the task is gradually becoming more and more difficult as the number of the presented sentences – items to be recalled is raised. The use of sentence span tasks in sentence comprehension research has been criticized. The argument is that the sentence span task is highly overlapping with sentence comprehension tasks in the sense that in both kinds of tasks participants are involved in sentence processing operations (Waters & Caplan, 2004).

Other tasks aiming to assess vWM (/PL + CE) are presented in turn. In nonword backward repetition tasks, subjects are asked to recall lists of nonwords in the reverse order. The task becomes more difficult as the number of nonwords to be recalled is raised (e.g., Sasaki et al., 2021). In number sequencing and letter-number sequencing tasks, participants have to recall lists of numbers and lists of letters, respectively, after putting them in the correct numerical and alphabetical order (e.g., Poulsen et al., 2022). In high tones/ low tones counting tasks, individuals listen to randomly presented high and low tones and keep count of both types of them (e.g., Finney et al., 2014). Although this task is used as a measure of “attention focus switching” (e.g., Finney et al., 2014), it is also indicative of vWM as it taps a component of both short-term storage (for remembering the number of tones for each type) and processing/execution operations (for switching the focus of attention and updating the number of tones for each type). In n-back tasks, subjects are presented with a running sequence of letters on a computer screen and have to indicate when the current letter was the same as the one presented “n” steps earlier (e.g., Ladányi et al., 2017).

Some studies have used word recall tasks as a measure of WM (e.g., Montgomery, 2000a, 2000b; Montgomery et al., 2009). In these tasks, participants listen to a list of words per trial and have to immediately recall them (immediate memory). The task becomes more difficult as each subsequent level includes more words. This task entails three conditions. In a no-load condition, participants have to recall as many words as they can regardless of their presentation order immediately after the presentation of each list (immediate free recall). This condition is referred to as a “simple memory span” task and it is considered to tap vSTM – since no manipulation of the items is demanded. In contrast, the two following conditions demand the reordering of the items. Thus, they are referred to as “complex memory span” tasks and are considered to tap vWM. In a single-load condition, subjects have to recall the words after reordering them according to physical size (smallest – biggest). In a dual-load condition, children have to recall the words after first putting them into semantic categories (e.g., animals, means of transport) and secondly after reordering them according to physical size (smallest – biggest). From our perspective, recall performance on these two conditions relies heavily on a vSTM/vWM-LTM component (/EB) because participants need first to retrieve semantic information of the words stored in LTM and then to reorder these words based on this LTM information. Indeed, word recall tasks have been suggested as measures of the EB (see Nobre et al., 2013, for a systematic review).

Another task used for the measurement of WM components, and specifically for the assessment of the EB, is sentence repetition (e.g., Boyle et al., 2013). In this task, subjects listen to sentences of increasing length and complexity and have to repeat them as precisely as they can. Sentence repetition is the most controversial task in terms of what exactly is assessed by it. It has been used either as a measure of the EB (e.g., Boyle et al., 2013) or as a measure of language skill (e.g., Poulsen et al., 2022 [“syntactic knowledge”]; Sasaki et al., 2021 [“language skill”]; Talli & Stavrakaki, 2019 [“syntactic production”]). This controversy stems from a current research debate of whether sentence repetition is a memory measure (vSTM/vWM-LTM component/ EB) (Alloway & Gathercole, 2005; Baddeley et al., 2009) or a measure of language knowledge/skills (Klem et al., 2015; Moll et al., 2015). The use of sentence repetition in sentence comprehension research could also be criticized, similar to the critique on sentence span tasks, as both sentence repetition and sentence comprehension tasks may demand common sentence processing operations (MacDonald & Christiansen, 2002). On this, a task that is considered to tap a vWM-LTM component/ EB -yet on a word level- is "word and digit recall". Rusli and Montgomery (2017) administered this task as a measure of "vWM-Extant Language Knowledge". Participants listen to a list of randomly presented words and digits at a time and are asked to recall first the words in a serial order and then the digits in a serial order as well. The task becomes more difficult as the number of words/digits is raised. As this task demands both storage and processing of items, it is considered that taps vWM. More than that, it demands individuals to recall the items based on their extant language knowledge about what is linguistic (words) and what is not (digits). Thus, it also taps LTM knowledge on a basic level of discriminating linguistic versus non-linguistic representations.

Syntactic complexity

In complex sentence comprehension (cSC) research, children are asked to assign sentence Noun Phrases (NP) into thematic roles. That is to identify the agent of the action (/the Subject) in a manner of "who does what to whom". Studies have used mostly picture-pointing tasks (e.g., Bentea et al., 2016; Boyle et al., 2013; Finney et al., 2014; Montgomery et al., 2018; Montgomery et al., 2009; Montgomery et al., 2008; Rakhlin et al., 2016; Rusli & Montgomery, 2017; Sasaki et al., 2021; Schouwenaars et al., 2018), picture-pointing tasks complemented by eye-tracking (e.g., MacDonald et al., 2020; Schouwenaars et al., 2018), picture-yes/no judgment tasks (e.g., Ladányi et al., 2017; Wu et al., 2022), self-paced listening(/reading) paradigms with comprehension questions after each sentence (e.g., Arosio et al., 2011; Booth et al., 2000; Felser et al., 2003; Weighall & Altman, 2011); act-out tasks (e.g., Kas & Lukács, 2012); visual-world paradigms with eye-tracking and comprehension questions after each sentence (e.g., Haendler et al., 2015); and straight comprehension questions after children listening to sentences (e.g., Poulsen et al., 2022).

The most common type of syntactically complex sentences is object-relatives (OR). Usually OR are compared with subject-relatives (SR) as syntactically simpler counterparts (e.g., Arosio et al., 2011; Arosio et al., 2012; Booth et al., 2000; Boyle et al., 2013; Kas & Lukács, 2012; MacDonald et al., 2020; Montgomery, 2000a, 2000b, 2004; Montgomery et al., 2018; Montgomery et al., 2009; Rakhlin et al., 2016; Robertson & Joanisse, 2010; Sasaki et al., 2021; Talli & Stavrakaki, 2019) or as filler sentences (e.g., Finney et al., 2014; Rusli & Montgomery, 2017). OR are considered more complex than SR in terms of memory because children need to hold both sentence NPs unassigned until they meet the verb of the Relative Clause (RC) (e.g., *The boy [that the girl sees] chases the policeman*). That is because English is a language of strict word order (Bates & MacWhinney, 1989) in which the agent of the action must precede the verb following the canonical Subject-Verb-Object (SVO) (/ Agent-Action-Patient) word order. Thus, the pre-verbal position of the second NP (*the girl*) demands children to hold both NPs (*the boy, the girl*) unassigned until they process the RC verb (*sees*). That is not the case for SR (e.g., *The boy [that sees the girl] chases the policeman*) for which children must hold only the first NP (*the boy*) until they meet the RC verb. After processing the verb, they instantly assign the role of the agent to the first NP (*the boy*), based on its pre-verbal position, and right after the role of the patient to the second NP (*the girl*), based on its post-verbal position, following the canonical SVO word order. Thus, in the case of OR the fact that subjects need to hold two NPs open for assignment until the verb is considered stressful to the limited resources of WM (Gibson, 1998; 2000).

More than that, OR are considered more demanding in terms of syntactic processing because some kind of syntactic movement is demanded for their understanding (Manzini & Roussou, 2000). Upon assigning the second NP (*the girl*) to the role of the agent, a gap emerges at the RC post-verbal position (e.g., *The boy [that the girl sees_] chases the policeman*). This gap is filled by keeping in memory a trace of the first NP (*the boy*) and placing it at the post-verbal gap position (e.g., *The boy [that the girl sees (the boy)] chases the policeman*). This way the SVO is completed. Contrary, in SR the thematic roles are incrementally assigned without the need for syntactic movement (e.g., *The boy [that (the boy) sees the girl] chases the policeman*). Thus, in the case of OR, this process of keeping the NP trace stored for an extended time until its final placement to the gap is considered as consuming WM resources (Gibson, 1998, 2000).

Other types of complex vs simple sentence structures that have been used are: i) object wh-questions (e.g., *Which pupil is the teacher greeting?*) vs subject wh-questions (e.g., *Which pupil is greeting the teacher?*), ii) passive sentences (e.g., *The cat was chased by the dog*) vs active sentences (e.g., *The dog chased the cat*), and iii) sentences with pronouns involving *pronominal reference (e.g., Bugs Bunny says Daffy Duck is hugging him) or reflexive reference (e.g., Bugs Bunny says Daffy Duck is hugging himself)* vs simple SVO sentences (e.g., *Daffy Duck is hugging Bugs Bunny*). Similar to the case of OR, these complex sentence types demand the temporary storage of both NPs simultaneously until the final assignment of the thematic roles is decided, as well as the movement of a NP trace between the elements of the sentence until its final placement at an emerging gap (Manzini & Roussou, 2000). Therefore, these sentence types are also considered to stress the already limited WM capacity (Gibson, 1998, 2000).

Working memory and complex sentence comprehension

It has been suggested that WM plays an important role in cSC as it is a system of limited capacity. The capacity limit is further constrained in the case of syntactically complex sentences for the processing of which more WM resources are required. This leads to a drop in comprehension accuracy. The hypothesis is that individuals with lower WM capacity will perform profoundly lower in sentence comprehension tasks than individuals with higher capacity (Just & Carpenter, 1992; Waters & Caplan, 1996). Another view supports that sentence comprehension performance can be better explained by individual differences in language knowledge and expertise (MacDonald & Christiansen, 2002). These two views have indicated a research field of particular interest. In this field, children of typical language development (TLD) are examined on whether their scores in WM components (vSTM, vWM, EB) tasks are significantly related to their cSC performance (e.g., Boyle et al., 2013; Montgomery et al., 2008). Moreover, in some studies, TLD children are compared with children of non-typical language development, such as those with Developmental Language Disorder (DLD) (e.g., Ladányi et al., 2017; Montgomery et al., 2009). Children with DLD face specific syntactic difficulties (e.g., Moscati et al., 2020) as well as deficits in cognitive control skills such as working memory (e.g., Larson & Ellis Weismer, 2022). Thus, it is examined whether these children underperform in cSC as a result of their lower WM capacity, as compared to their TLD peers. Research so far seems inconclusive about the role of WM (components) in cSC in TLD and DLD children (see Kidd, 2013; for a critical review). The current study aims at systematically reviewing relevant studies in this research field.

The present study: scope, research goals, and questions

The scope of the present study is to investigate the relationship between verbal WM and cSC in children of typical language development (TLD) as well as in children of non-typical language development (i.e., Developmental Language Disorder; DLD). In particular, our goal is to examine the role of different WM tasks/components in the comprehension of syntactically complex sentences in TLD and DLD children. Based on this goal, the following research questions were developed: Does current research indicate significant relationships between different WM tasks/components and cSC, in children with typical language development (TLD) and with Developmental Language Disorder (DLD)?

Method

Study design

The current systematic review was performed under the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocol (PRISMA-P) (Moher et al., 2015; Shamseer et al., 2015).

Search strategy and inclusion criteria

Six databases, Medline, Scopus, PsycInfo, Embase, ERIC, and Web of Science, were searched by two-independent researchers using the key terms “working memory” AND “comprehension” AND “complex sentences” AND “children”, accompanied by their analogue or underlining terms (see the Appendix for the full list of terms). A time restriction between 2000 and 2022 (June) was applied.

In the first stage of evaluation, the initial resulting records in each database were screened on their titles, abstracts, and keywords checking for their relevance to the scope of the present study. At this point a record was judged as possibly relevant when it included these three basic elements: 1) at least one working memory task – component, 2) at least one sentence comprehension task, and 3) typically developing (TD) children. After this initial screening was completed, duplicate records between the databases were removed.

In the second stage, the remaining articles were read in their full texts to further evaluate their relevance according to the inclusion/exclusion criteria. Inclusion criteria were the following: research articles, English language, children, TD children/ early adolescents (aged 4 to 13 years old), DLD children/ early adolescents (aged 4 to 13 years old), monolingual participants, and participants with normal hearing, vision, and intelligence quotient. Exclusion criteria were case studies, reviews, brief reports, and letters to editors; any other language rather than English, middle adolescents (above the age of 14 years), adults, non-TD participants (e.g., Autism Spectrum Disorder, Down Syndrome, etc.), bilingual participants, and participants with hearing or vision problems or with mental retardation. Moreover, it is noteworthy that the current review is focusing on syntactic sentence comprehension. Hence, studies that examined complex sentence comprehension in regard to other linguistic factors rather than syntactic complexity (such as animacy, context, etc.) were excluded.

Apart from databases, reviews were a source of possibly relevant articles. Researchers distinguished reviews found in the six databases as relevant, as opposed to irrelevant ones, according to the inclusion/exclusion criteria. The relevant reviews were downloaded, read on their full-texts, and scanned on their citation catalogues in order to find any further relevant papers.

Relevant studies conducted on DLD children were found by manually screening all articles on their titles, abstracts, and keywords for the terms Developmental Language Disorder (DLD) and Specific Language Impairment (SLI) at the first stage of the evaluation; as well as during full-text reading at the second stage of the evaluation. Studies were included as DLD-relevant in the present review if their included DLD/SLI participants had been found to perform at or below – *1 SD* on at least two language measures, or -alternatively- at or below the *20th* percentile (*≤0.80*) on at least two standardized language measures, and if simultaneously they had been found to perform between the normal range *(≥0.85)* for their age on at least one non-verbal intelligence test. In particular, children should have been classified as DLD/SLI participants in the studies by the combination of: i) at least one word-level language task in which receptive/expressive vocabulary knowledge and use is assessed, and ii) at least one sentence-level language task in which receptive/expressive morphosyntactic ability is assessed. The whole above-mentioned approach is in line with the criteria set by the Diagnostic and Statistical Manual of Mental Disorders – Fifth Edition (American Psychiatric Association, 2013) for defining “Language Disorder”. Furthermore, following the CATALISE criteria (Bishop et al., 2017) for the definition of

"Developmental Language Disorder", studies that include children in which language disorder is associated with other conditions rather than language development per se, such as neurological conditions, global developmental delay, sensory impairments, motor dysfunction, as well as bilingualism/multilingualism, were excluded.

Data synthesis and outcome measures

Of the articles that were judged as relevant the following data were extracted: article ID (consisted of first author's surname and publication time), number of participants, the age range of participants, working memory components and their measures, sentence types (simple vs complex) and their sentence comprehension measures. Working memory components were the independent variable. Complex sentence comprehension was the outcome.

Characteristics and risk of bias

The included studies were qualitatively evaluated for their methodological characteristics and risk of bias probability by using the Appraisal tool for Cross-Sectional Studies (AXIS) (Downes et al., 2016) (see "Risk of bias assessment" in the supplementary material).

Results

Included studies

Database searches yielded a total of 2604 initial results. After a first-stage screening of titles, abstracts, and keywords according to inclusion/ exclusion criteria, 2211 records were dropped as irrelevant. The remaining 392 records were approved for further full-text evaluation. Among them, 263 records were removed as duplicates. As a result, 130 studies were downloaded and included in the second stage of full-text evaluation. After applying inclusion/ exclusion criteria on full-texts, 28 studies were found to be relevant. From database searches, 12 reviews relevant to sentence processing, WM, or both, were collected and screened on their citations. Of this screening, 68 initial records were retrieved as possibly relevant judging from titles, abstracts, and keywords. After checking for duplicates their number was decreased to 43 records. A second check for duplicates, this time from database records was performed resulting in a final number of 16 studies. After evaluating their relevance based on full texts, no study was found to meet the inclusion/ exclusion criteria. Combining resulting papers from databases and reviews, 28 studies were included in the present review. PRISMA-P flow diagram provides further information (see "Figure 1. PRISMA flow diagram" in the supplementary material).

Relationship between WM components and complex sentence comprehension

Verbal short-term memory/ Phonological Loop capacity

In total, thirteen studies (13/28) tested the role of verbal short-term memory (vSTM) (**TLD:** Arosio et al., 2011; Arosio et al., 2012; Bentea et al., 2016; Booth et al., 2000; Boyle et al., 2013; Haendler et al., 2015; Kas & Lukács, 2012; Montgomery et al., 2008; **DLD vs TLD:** Girbau, 2017; Ladányi et al., 2017; Montgomery, 2004; Montgomery & Evans, 2009; Roesch & Chondrogianni, 2021). In TLD children, six of them (6/13) found a significant relationship between this component and cSC (**TLD:** Arosio et al., 2011; Arosio et al., 2012; Bentea et al., 2016; Kas & Lukács, 2012; **DLD vs TLD:** Girbau, 2017 [TLD+DLD]; Roesch & Chondrogianni, 2021), whereas seven of them (7/13) did not (**TLD:** Booth et al., 2000; Boyle et al., 2013; Haendler et al., 2015; Montgomery et al., 2008; **DLD vs TLD:** Ladányi et al., 2017;

Montgomery, 2004; Montgomery & Evans, 2009). In DLD children, two studies (2/5) indicated a significant role of vSTM (Girbau, 2017 [TLD+DLD]; Roesch & Chondrogianni, 2021), whereas three studies (3/5) did not show strong evidence (Ladányi et al., 2017; Montgomery, 2004; Montgomery & Evans, 2009). It is noteworthy that these three studies which found no significant role for vSTM in DLD children reported the same negative result for their TLD control groups too. A demonstration of the correlations tested for this component is provided in the supplementary material (see "Table 1. Verbal short-term memory – complex sentence comprehension").

Nonword repetition

Eight studies (8/13) tested the role of vSTM by using nonword repetition (**TLD:** Boyle et al., 2013; Kas & Lukács, 2012; Montgomery et al., 2008; **DLD vs TLD:** Girbau, 2017; Ladányi et al., 2017; Montgomery, 2004; Montgomery & Evans, 2009; Roesch & Chondrogianni, 2021). Concerning TLD children groups, three studies (3/8) reported a significant effect of nonword repetition in cSC (**TLD:** Kas & Lukács, 2012; **TLD vs DLD:** Girbau, 2017 [TLD+DLD]; Roesch & Chondrogianni, 2021), whereas five (5/8) found nonsignificant correlations (**TLD:** Boyle et al., 2013; Montgomery et al., 2008; **TLD vs DLD:** Ladányi et al., 2017; Montgomery, 2004; Montgomery & Evans, 2009). For DLD children groups, two studies (2/5) showed a significant role of nonword repetition (**TLD vs DLD:** Girbau, 2017 [TLD+DLD]; Roesch & Chondrogianni, 2021), whereas three studies (3/5) did not (**TLD vs DLD:** Ladányi et al., 2017; Montgomery, 2004; Montgomery & Evans, 2009). Studies that showed a significant effect of nonword repetition can be interpreted as that a passive storage of limited capacity (i.e., vSTM) has an important role in cSC. However, it could be argued that LTM language knowledge, namely familiar language cues/patterns between nonwords in the input and LTM, significantly influenced the results.

Forward digit span

Six studies (6/13) examined the role of vSTM by using forward digit span (**TLD:** Arosio et al., 2011; Arosio et al., 2012; Bentea et al., 2016; Booth et al., 2000; Haendler et al., 2015; Kas & Lukacs, 2012). In regard to TLD children groups, three studies (3/6) reported a significant effect (**TLD:** Bentea et al., 2016; Haendler et al., 2015; Kas & Lukács, 2012), in contrast with three studies (3/6) which found a nonsignificant role (**TLD:** Arosio et al., 2011; Arosio et al., 2012; Booth et al., 2000). Regarding DLD children, no studies were found to use this task. Positive results demonstrated for forward digit span can be interpreted, similarly to those of nonword repetition, as that a passive storage of limited capacity (i.e., vSTM) underpins cSC. On the contrary, it could be argued that participants grouped the digits - based on their familiarity with LTM number patterns- into chunks. This suggests that LTM knowledge may have an indirect yet important effect on cSC.

Verbal working memory/ Phonological Loop capacity + Central Executive

In total, twenty-three studies (20/28) examined the role of verbal working memory (vWM) (**TLD:** Arosio et al., 2011; Bentea et al., 2016; Booth et al., 2000; Boyle et al., 2013; Felser et al. 2003; Finney et al., 2014; Haendler et al., 2015; Kas & Lukács, 2012; MacDonald et al., 2020; Montgomery et al., 2008; Poulsen et al., 2022; Roberts et al., 2007; Schouwenaars et al., 2018; Weighall & Altmann, 2011; Wu et al., 2022; **DLD vs TLD:** Ladányi et al., 2017; Montgomery & Evans, 2009; Montgomery et al., 2018; Rakhlin et al., 2016; Sasaki et al., 2021). Focusing on TLD children, eight of them (8/20) found vWM as a significant correlate (**TLD:** Felser et al., 2003; Finney et al., 2014; Roberts et al., 2007; Montgomery et al., 2008; Booth et al., 2000; Schouwenaars et al., 2018; Wu et al., 2022; Kas & Lukács, 2012; **DLD vs TLD:** Montgomery et al., 2018). In contrast, eight of them (8/20) did not indicate a strong relationship (**TLD:** Arosio et al., 2011; Bentea et al., 2016; Haendler et al., 2015; MacDonald et al., 2020; Weighall & Altmann, 2011; **DLD vs TLD:** Ladányi et al., 2017; Montgomery, 2000a; Montgomery & Evans, 2009). The remaining four studies (4/20) found mixed results (**TLD:** Boyle et al., 2013; Poulsen et al., 2022; **DLD vs TLD:** Rakhlin et al., 2016; Sasaki et al., 2021). Concerning DLD children, all five studies (5/5) found vWM significantly correlated to cSC (Ladányi et al., 2017; Montgomery & Evans, 2009; Montgomery et al., 2018; Rakhlin et al., 2016 [TLD+DLD]; Sasaki et al., 2021[TLD+DLD]). An illustration of the results is provided in the supplementary material (see "Table 2. Verbal working memory – complex sentence comprehension").

Backward digit span

Nine studies (9/20) investigated the role of vWM by administering backward digit span (**TLD:** Bentea et al., 2016; Boyle et al., 2013; Haendler et al., 2015 [BDLS]; Kas & Lukács, 2012; MacDonald et al., 2020 [FDS+BDS]; Schouwenaars et al., 2018; Wu et al., 2022; **DLD vs TLD:** Ladányi et al., 2017; Rakhlin et al., 2016 [FDS+BDS]). As far as TLD children are concerned, six studies (6/9) reported significant associations (**TLD:** Boyle et al., 2013; Kas & Lukács, 2012; Schouwenaars et al., 2018; Wu et al., 2022; **DLD vs TLD:** Ladányi et al., 2017; Rakhlin et al., 2016 [TLD+DLD]), unlike three studies (3/9) (**TLD:** Bentea et al., 2016; Haendler et al., 2015; MacDonald et al., 2020). In regard to DLD children, both relevant studies (2/2) found significant effects (**DLD vs TLD:** Ladányi et al., 2017; Rakhlin et al., 2016 [TLD+DLD]). Positive results suggest that a common factor of both limited capacity (i.e., vSTM/ PL capacity) and processing-execution operations (i.e., CE) has an important role in cSC. However, it is not clear which of these two WM components may have a more significant effect than the other one. Moreover, it could also be argued that children grouped the digits into familiar chunks to facilitate their recall, similar to the assumption made for forward digit span. Based on this, LTM knowledge perhaps influenced the results.

Sentence span

Nine studies (9/20) investigated the role of vWM by using the sentence span task (**TLD:** Arosio et al., 2011; Booth et al., 2000; Felser et al., 2003; Finney et al., 2014; Montgomery et al., 2008; Roberts et al., 2007; Weighall & Altmann, 2011; **DLD vs TLD:** Montgomery & Evans, 2009; Sasaki et al., 2021). With respect to TLD children, six studies (6/9) showed a significant effect of sentence span on cSC (**TLD:** Felser et al., 2003; Finney et al., 2014; Montgomery et al., 2008; Roberts et al., 2007; Weighall & Altmann, 2011; **DLD vs TLD:** Sasaki et al., 2021 [TLD+DLD]), whereas three studies (3/9) did not (**TLD:** Arosio et al., 2011; Booth et al., 2000; **DLD vs TLD:** Montgomery & Evans, 2009). Concerning DLD children, the two studies that used this task found significant correlations (2/2) (**DLD vs TLD:** Montgomery & Evans, 2009; Sasaki et al., 2021 [TLD+DLD]) whereas one reported a nonsignificant role. Results that showed a significant effect of sentence span on cSC are interpreted as that a WM subsystem of both limited capacity and processing-execution operations (vWM/ PL + CE) underpins cSC. Nonetheless, these results could be questioned because sentence span tasks highly overlap with SC tasks in terms of processing operations reinforced in them, as both of them demand sentence processing skills.

Other vWM tasks and composite scores

Five studies (5/20) used other tasks (and composite scores) as vWM measures (**TLD:** Finney et al., 2014; Poulsen et al., 2022; **DLD vs TLD:** Ladányi et al., 2017; Montgomery et al., 2018; Sasaki et al., 2021). In TLD groups, four of them (4/5) reported significant associations (**TLD:** Finney et al., 2014 [low tones/high tones counting]; Poulsen et al., 2022 [backward digit span + number-sequencing + letter-number sequencing]; **TLD vs DLD:** Montgomery et al., 2018 [word & digit recall + high tones/low tones counting]; Sasaki et al., 2021 [nonword backward repetition, LTD+DLD]), whereas one of them (1/5) did not find an important role of vWM (**TLD vs DLD:** Ladányi et al., 2017 [n-back]). In DLD children, both studies reported significant correlations (**TLD vs DLD:** Ladányi et al., 2017 [n-back]; Montgomery et al., 2018 [word & digit recall + high tones/low tones counting]).

vSTM/vWM – LTM component /Episodic Buffer (EB)

Eight studies (8/28) investigated the role of a STM/WM – LTM component (/EB) (**TLD:** Boyle et al., 2013; Poulsen et al., 2022 [sentence repetition as "syntactic knowledge" measure]; Rusli & Montgomery, 2017; **TLD vs DLD:** Montgomery, 2000a, 2000b; Montgomery et al., 2018 [comprehension and production of narrative language as "long-term memory – language knowledge" measure]; Montgomery et al., 2009; Sasaki et al., 2021 [sentence repetition as "language measure"]). In TLD children, six of them (6/8) reported a significant relationship (**TLD:** Boyle et al., 2013; Poulsen et al., 2022; Rusli & Montgomery, 2017; **TLD vs DLD:** Montgomery, 2000b; Montgomery et al., 2018; Sasaki et al., 2021 [TLD+DLD]), whereas two of them (2/8) did not (Montgomery, 2000a; Montgomery et al., 2009). Regarding DLD children, four studies (4/5) found STM/WM – LTM as a strong correlate (Montgomery, 2000b; Montgomery et al., 2018; Montgomery et al., 2009; Sasaki et al., 2021 [TLD+DLD]), whereas one of them (1/5) did not (Montgomery, 2000a). Results regarding this component are demonstrated in the supplementary material (see "Table 3. vSTM/vWM-LTM – complex sentence comprehension").

Sentence repetition

Three of the studies (3/8) which examined the role of STM/WM – LTM (/EB) used the sentence repetition task. All of them (3/3) reported sentence repetition as a significant correlate of cSC in TLD children (**TLD:** Boyle et al., 2013; Poulsen et al., 2022; **TLD vs DLD:** Sasaki et al., 2021 [TLD+DLD]). These results can be interpreted as that a STM/WM – LTM component (/EB) has an important role in cSC. Alternatively, they could be interpreted as suggestive that language knowledge/skill is an important factor of cSC. Moreover, similar to the case of the sentence span task, these results could be questioned as to whether both sentence repetition and sentence comprehension measures are sentence-level tasks that share some common sentence processing demands.

Word recall

Three studies (3/8) used word recall tasks (**TLD vs DLD:** Montgomery, 2000a, 2000b; Montgomery et al., 2009). In TLD children, one study (1/3) reported significant results (Montgomery, 2000b), unlike two studies (2/3) that did not find significant correlations (Montgomery, 2000a; Montgomery et al., 2009). In DLD children, significant effects were found in two studies (Montgomery, 2000b; Montgomery et al., 2009) in contrast with one study (Montgomery, 2000a).

Word & digit recall

One study (1/8) assessed STM/WM – LTM by using word and digit recall (**TLD:** Rusli & Montgomery, 2017). This study demonstrated a significant correlation.

Discussion

The scope of the present study was to review studies that have examined the relationship between WM components and cSC in TLD and DLD children.

In regard to vSTM (/PL), it seems unclear whether this component has a significant effect on cSC for both TLD and DLD groups. Significant correlations can be interpreted as that a passive WM system dedicated to short-term storage (i.e., vSTM/PL) has an important role in children's comprehension of complex sentences, in support of the capacity-limit approach (Just & Carpenter, 1992; Waters & Caplan, 1996). On the contrary, nonsignificant results seem to question this view.

The most studied WM component is vWM. In TLD children, there is inconclusiveness on whether vWM is significantly related to cSC similar to the findings for vSTM. In contrast, in DLD children vWM is shown as a strong correlate of cSC by most of the studies. It is noteworthy that vSTM is contained by definition in vWM (i.e., short-term storage [vSTM] + processing). Thus, significant results regarding vWM can be interpreted similarly to those of vSTM as the limited capacity of WM constrained cSC, following the capacity-limit approach. More than that, vWM refers to a WM system of both temporary storage and processing-execution operations. This means that the significant results might suggest that processing-execution operations (i.e., CE/ executive functions) underpin cSC. Focusing on DLD children in which vWM is shown as a strong correlate, the observed contrast between vSTM's and vWM's role in cSC suggests that DLD children's difficulty in comprehending complex sentences could be attributed to a processing-execution component (i.e., Central Executive), rather than to passive temporary storage (i.e., vSTM/ PL). On the other hand, nonsignificant results for TLD and DLD children are questioning both the capacity-limit approach as well as the role of processing-execution operations.

To date, the least studied WM component is vSTM/vWM-LTM (/EB). In TLD children all three studies indicated a strong relationship. This seems to be true for DLD children too. Nonetheless, studies in TLD children used sentence repetition; a task referred to either as a measure of "episodic buffer" (i.e., LTM-WM) or as a measure of "language skills" (or "syntactic knowledge" or "syntactic production"). This disagreement on what exactly is measured by this task raises questions regarding the role of a STM/WM-LTM component (/Episodic Buffer) in cSC, as well as on how to reliably measure this component in order to obtain meaningful results. Moreover, the reported significant correlations between sentence repetition and sentence comprehension tasks may be an artifact of the similar demands of the two tasks, since both tasks demand sentence processing skills. An effort to address this matter has been made by Rusli and Montgomery (2017) and Montgomery et al. (2018) which used a word-level task, i.e., word and digit recall, tapping (extant) language knowledge stored in long-term memory on a basic level of what is linguistic (words) and what is not (digits). Both studies found significant correlations between word & digit recall and cSC in both TLD (Montgomery et al., 2018; Rusli & Montgomery, 2017) and DLD (Montgomery et al., 2018) children. Word-level tasks have also been used by Montgomery et al. (2009), Montgomery (2000a), and Montgomery (2000b) as measures of "complex working memory". In these tasks, children have to recall words after putting them into semantic categories (e.g., animals – means of transport) and after reordering them according to their physical size (smallest - biggest). These tasks seem to measure a STM/WM-LTM component because in them children need to retrieve semantic information about the words from their long-term memory and use this information to reorder the items. We interpret the significant results of these studies as indicative of the important role of STM/WM-LTM (/Episodic Buffer) in TLD and DLD children. The positive results of STM/WM-LTM's role in cSC could be interpreted as supporting either the capacity-limit view (Just & Carpenter, 1992; Waters & Caplan, 1996) or the language experience view (MacDonald & Cristiansen, 2002). Based on the capacity-limit view, it could be that STM/WM-LTM (/Episodic Buffer) functions as a distinct WM buffer of its own storage/processing capacity limitations. These limitations constrain children's ability to efficiently use language knowledge stored in long-term memory to facilitate comprehension. Based on the language experience/expertise view, it could be that -in a unitary cognitive system such as memory- the quantity and quality of language knowledge (i.e., the well-shapeliness of the linguistic representations in LTM) is what matters the most for effectively comprehending sentences. Language knowledge of a higher level leads to more refined linguistic representations during sentence processing which in turn contributes to higher comprehension accuracy. Taken together, results indicate two crucial factors for cSC: i) a processing-execution mechanism and ii) language knowledge/skill. The interplay of them could be expressed as STM/WM-LTM (/ Episodic Buffer) functioning.

Limitations of the studies and future directions

Some limitations of the included studies are discussed. Most studies tested a wide age range of participants as one unitary age group (e.g., Bentea et al., 2016: 5-11 years; Finney et al., 2014: 7-12 years; Montgomery & Evans, 2009: 6-12 years; Montgomery et al., 2008: 6-12 years; among others). Thus, any possible age differences between early, middle, and late childhood participants have not been taken into account. Cross-sectional and longitudinal studies would move research on this topic forward, by examining if different WM components and different linguistic factors contribute to cSC at a higher level in one age stage compared to another age stage. For instance, perhaps younger children rely more on a processing-execution mechanism (i.e., Central Executive) to extract meaning from complex sentences, whereas older children having shaped language knowledge/skill to a sufficient level rely more on a vSTM/vWM-LTM component (i.e., Episodic Buffer) or on other linguistic factors (e.g., morphosyntactic knowledge, vocabulary knowledge). Another limitation of some studies is that they have used a very narrow range of complex structures; thus, it is difficult to generalize to cSC as a unitary construct. The use of a wider range of complex structures for which the same (or very similar) syntactic processing operations are demanded would be helpful. Such efforts have been made by Montgomery et al. (2008), Montgomery and Evans (2009), and Boyle et al. (2013). Similarly, a narrow range of tested factors is observed in some studies regarding WM components. Future studies should use different WM tasks to examine the contribution of different WM components. More particularly, these different WM factors could be simultaneously included in regression and/or mediation models to find which of them has a greater effect than the other ones or to identify the nature of a unitary mechanism that better explains variation in the data. Such efforts have been made by Montgomery et al. (2018) and Boyle et al. (2013). Furthermore, a limitation of the studies that found a significant role for vSTM/vWM-LTM, or -alternatively interpreted- for language knowledge/skill, stems from the use of the sentence repetition task. As a sentence-level task, sentence repetition overlaps highly with sentence comprehension tasks questioning the interpretation of the results. This issue could be addressed by the use of word-level tasks to test this component (vSTM/vWM-LTM). Lately, Rusli and Montgomery (2017) followed this direction in TLD. This could be attempted in DLD children as well. Last but not least, future studies could test how children learn different linguistic patterns from the input, through chunking, and if/how this knowledge influences the relationship between cognitive mechanisms (such as WM) and cSC. Relevant to this, an emerging research field that attempts to describe how individuals implicitly learn new linguistic patterns from the input is that of statistical learning. Future research on this path could shed light on how syntactically complex sentences are acquired from children and, subsequently, facilitate comprehension.

Conclusions

In conclusion, vSTM does not seem to have a certain strong impact on cSC either for TLD or for DLD children. The role of vWM seems more important, especially for DLD children. Thus, the crucial factor which constrains cSC is perhaps the capacity of a processing/-execution element, rather than the capacity of passive temporary storage. This underlines the role of the Central Executive or, to put it differently, processing strategies and executive functioning skills like inhibition, updating, and switching. The enhancement of these skills by well-structured and well-administered interventions could lead to better sentence comprehension for all children, especially for those with DLD. Future intervention studies in this direction would greatly move research in this field forward. On the other hand, vSTM/vWM-LTM is also shown as a strong correlate of cSC for both groups, indicating that language knowledge in general and syntactic knowledge in particular, stored in LTM, may have an important role. However, this component is so far understudied as it is difficult to measure it per se, independently of sentence processing skills. To address this issue, word-recall tasks of different conditions of complexity in terms of LTM retrieval demands could be used in future studies. In regard to the role of STM/WM-LTM, it could be either that the quantity and quality of the language knowledge stored in LTM influence comprehension the most, supporting the language experience/expertise view (MacDonald & Christiansen, 2002); or that the capacity limitations of the processing ability while using language knowledge contributes to comprehension the most, supporting the capacity-limit approach (Waters & Caplan, 1996). Either way, the enhancement of language-syntactic knowledge/awareness in clinical and educational settings could lead to better sentence comprehension. Putting together these factors that seem to shape comprehension, namely executive functioning and language knowledge/skill, it could be that each of them might be more important in children's comprehension than the other one in different age stages. Future studies could follow this direction by adopting developmental approaches.

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Appendix

Terms used in the database search

("working memory" OR "short-term memory" OR "long-term working memory" OR "long-term memory" OR "memory span" OR "central executive" OR "phonological loop" OR "episodic buffer" OR "attention* control" OR "controlled attention" OR "control of attention" OR "focused attention" OR "focus of attention" OR "executive control" OR "executive function*" OR "working memory updating") AND (comprehension OR interpretation OR processing) AND (sentence* OR "complex sentence*" OR "sentence complexity" OR "complex syntax" OR "syntactic complexity" OR "relative clause*" OR "object relative*" OR "passive voice" OR "passive*" OR "noncanonical sentences" OR "long-distance dependencies") AND child*

ΒΙΒΛΙΟΓΡΑΦΙΚΗ ΑΝΑΣΚΟΠΗΣΗ | REVIEW PAPER

Ο ρόλος της εργαζόμενης μνήμης στην κατανόηση συντακτικά πολύπλοκων προτάσεων σε παιδιά με και χωρίς αναπτυξιακή γλωσσική διαταραχή: Μία βιβλιογραφική ανασκόπηση

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ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ

Εργαζόμενη μνήμη,
Κατανόηση προτάσεων,
Πολύπλοκες προτάσεις,
Παιδιά,
Τυπική γλωσσική ανάπτυξη,
Αναπτυξιακή γλωσσική διαταραχή

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ΠΕΡΙΛΗΨΗ

Συστατικά της Εργαζόμενης Μνήμης (ΕΜ) μελετώνται ως προς την συμβολή τους στην κατανόηση πολύπλοκων προτάσεων (ΚπΠ) σε παιδιά, υπό την θεώρηση της ΕΜ ως ένα γνωστικό σύστημα περιορισμένης χωρητικότητας. Η παρούσα έρευνα στοχεύει να διερευνήσει τη σχέση μεταξύ συστατικών της ΕΜ και ΚπΠ σε παιδιά τυπικής γλωσσικής ανάπτυξης (ΤΓΑ) καθώς και σε παιδιά με Αναπτυξιακή Γλωσσική Διαταραχή (ΑΓΔ), ανασκοπώντας με συστηματικό τρόπο τις σχετικές έρευνες. Αρχικά, παρουσιάζονται οι διαφορετικές δοκιμασίες που χρησιμοποιούνται για να αξιολογήσουν τρία διακριτά συστατικά της ΕΜ και λαμβάνονται υπόψη οι προβληματισμοί σχετικά με την εγκυρότητά τους. Έπειτα, παρουσιάζονται οι τύποι συντακτικά πολύπλοκων προτάσεων που θεωρούνται ότι επιβαρύνουν τους περιορισμένους πόρους της ΕΜ. Στην συνέχεια, ακολουθούνται οι συστηματικές μέθοδοι του πρωτόκολλου PRISMA-P. Με βάση αυτές, διενεργήθηκαν αναζητήσεις σε έξι βάσεις δεδομένων. Εικοσι-οκτώ έρευνες βρέθηκαν να πληρούν τα κριτήρια ένταξης. Διενεργήθηκε αφηγηματική σύνθεση των σχετικών ερευνών. Στα παιδιά ΤΓΑ, τα αποτελέσματα σχετικά με τον ρόλο της λεκτικής βραχύχρονης μνήμης (λΒΜ) και της λεκτικής εργαζόμενης μνήμης (λΕΜ) στην ΚπΠ είναι μη-καταληκτικά, υποστηρίζοντας ή αμφισβητώντας την προσέγγιση της περιορισμένης χωρητικότητας. Στα παιδιά με ΑΓΔ, η λΕΜ δείχνει σημαντική επίδραση στην ΚπΠ, σε αντίθεση με την λΒΜ. Αυτό δείχνει ότι ένα συστατικό επεξεργασίας-εκτελεστικών λειτουργιών είναι σημαντικό στην ΚπΠ από παιδιά με ΑΓΔ. Και για τις δύο ομάδες παιδιών, η λΒΜ/λΕΜ-ΜΜ (ή αλλιώς Διαχειριστής Επεισοδίων), ένα συστατικό που λειτουργεί ως γέφυρα ανάμεσα στην λΒΜ/λΕΜ και στην μακρόχρονη μνήμη (ΜΜ), δείχνει να παίζει σημαντικό ρόλο. Παρόλα αυτά, δεν έχει μελετηθεί αρκετά. Βάσει των αποτελεσμάτων, προτείνονται μελλοντικές ερευνητικές κατευθύνσεις και εκπαιδευτικές εφαρμογές.