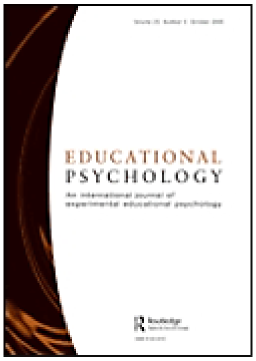

Working memory resources in children: Stability and relation to subsequent academic skills

Journal:	*Educational Psychology*
Manuscript ID	CEDP-2018-0094.R2
Manuscript Type:	Original Article
Keywords:	working memory < Cognition, mathematical skills, reading skills, longitudinal study

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Abstract

This study aimed to investigate the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress), and the extent to which WM measured at kindergarten predicts academic performance at second grade (N = 94). The results showed that WM skills significantly increase during the time span from Finnish kindergarten to second grade. Verbal (VWM) and visuospatial WM (VSWM) resources seem to develop quite independently, whereas individual progress showed some stability. WM resources measured just before the start of formal school predicted later academic performance, and VWM acted as more powerful predictor than VSWM resources. The results have two important educational implications: first, individual or group-based intervention designed to enhance children's WM skills would be most important even before the start of school, and second, poor WM skills should be addressed when planning the learning environment beginning in kindergarten.

Key words: Working memory, mathematical skills, reading skills, longitudinal study

Introduction

Working memory (WM) is an important and impassable information processing system behind learning. It stores and processes information for a short period of time during a range of cognitive tasks, and has a limited capacity. Several studies have shown that WM skills are related to academic skills both at preschool (Fuhs, Nesbitt, Farran, & Dong, 2014; Kroesbergen, Van Luit, Naglieri, Franchi, & Taddei, 2010; Kyttälä, Aunio, & Hautamäki, 2010; Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003) and school years (Alloway, et al., 2005; De Weerdt, Desoete, & Roeyers, 2012; Gathercole, Tiffany, Briscoe, Thorn & ALSPAC team, 2005; Reuhkala, 2001; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011; Passolunghi, Vercelloni, & Schadee, 2007). Previous studies have also shown that, based on WM resources measured before school start, it is even possible to predict future WM resources (Alloway, & Alloway, 2010), and academic performance at school (Passolunghi, Mammarella, & Altoè, 2008; Stipek, & Valentino, 2015; Toll, Kroesbergen, & Van Luit, 2016; Östergren & Träff, 2013). In the current study, we investigate the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress) and the extent to which WM measured in kindergarten predicts academic performance in second grade in the Finnish educational context.

There are various theoretical frameworks that address WM organisation (e.g., Barrouillet, Bernardin, & Camos, 2004; Cowan, 2005; Engle, Kane, & Tuholski, 1999). One common view is Baddeley's multicomponent WM model (1986, 2000) which includes a passive storage system (short-term memory) and an active processing system (working memory). According to that model, separate WM subcomponents are specialised to different functions. While the phonological loop (PL) stores verbal information for a short time, the visuospatial sketchpad (VSSP) is responsible for the temporal storage of visuospatial information. The central executive (CE) is the coordinator responsible for information processing, inhibitory control, and cognitive flexibility. The episodic buffer (EB) integrates information from subcomponents and from long-term memory in the WM.

Even though Baddeley's three-component model is widely used in research related to WM and academic skills, and although it clearly has its advantages in separating the passive storage and active processing functions, it also has some problems in operationalising the framework. Although the CE is presented as a single component in the original model, it has been stated that the CE might not, in fact, be a unitary component (Baddeley, 1996). Some researchers have even suggested that there might be separate CE units for verbal and visuospatial information (e.g., Shah & Miyake, 1996). In fact, previous results show that verbal and visuospatial CE tasks are related to different academic skills (Jarvis & Gathercole, 2003). However, rather than proving that there are modality-specific CE units, these results may reflect the fact that most of the typical CE tasks also depend on short-term storages (PL or VSSP) (Duff & Logie, 2001; for a meta-analysis, see Tillman, 2011). Because of these difficulties in separating pure CE functioning from short-term modality-specific storing, we rather adopted the continuity model proposed by Cornoldi and Vecchi (2003) in this study. They divide WM functions into modality-specific continuums, and these modality-specific WM functions are more or less dependent on storage or processing. Following this idea of continuity between passive storing and active processing, we did not try to separate the passive storage and active processing functions. Instead, we divided the WM function modality (specifically, into visuospatial and verbal functions) in order to investigate whether these two contribute differently to later academic skills. We refer to these horizontal dimensions as the verbal working memory (VWM) and the visuospatial working memory (VSWM).

During childhood years, WM capacity increases rapidly (Gathercole, 1999; Pickering, 2001). It has been suggested that the adult level of WM capacity is reached at approximately

15 to 16 years of age (Gathercole, Pickering, Ambridge, & Wearing, 2004). Even after that, WM resources continue developing, but are more related to growing expertise that helps to process information more efficiently than just to simple developmental factors. It has also been suggested that there is a developmental shift from visuospatial WM resources to verbal WM resources. Young children rely mostly on visuospatial resources because they are unable to use verbal rehearsal strategies (McKenzie, Bull, & Gray, 2003). At about seven to eleven years of age, when they first learn to read and then begin to use language efficiently, they begin to prioritise verbal WM resources (Andersson & Lyxell, 2007; McKenzie, et al., 2003; Rasmussen & Bisanz, 2005). Even though WM resources rapidly develop during childhood years, there are individual differences from early on (Kyttälä, et al., 2003). Compared to those with better WM skills right at the start of kindergarten, children with poor WM resources have detectable difficulties in following instructions, completing complex tasks, and in situations and tasks that involve simultaneous processing and storing of information (Gathercole, Lamont, & Alloway, 2006).

Working Memory and Early Mathematics

WM is related to children's early counting ability and basic arithmetic skills (Bull & Scerif, 2001; Bull, Espy, & Wiebe, 2008; Noël, 2009). All the WM components seem to be involved (Noël, 2009; Ranghubar et al., 2010) but they have somewhat different roles, depending on used measures and maybe even over different cultures. Number-word-sequence skills of five- to six-year old children were related to their PL capacity (Preßler, Krajewski, & Hasselhorn, 2013). Counting skills and skills to solve simple addition tasks have been observed to be related to both the PL and the CE (Noël, 2009). CE is probably needed in controlling the direction, and phase of counting. On the other hand, Rasmussen and Bisanz (2005) observed that, when simple additions were presented visually using concrete materials, performance in addition tasks was associated with visuospatial WM resources. The

VSSP, in turn, is responsible for the storage of visuospatial information: for example, mental images of digits or manipulation of the mental number-line (Bachot, Gevers, Fias, & Roeyers, 2005; Gunderson, Ramirez, Beilock, & Levine, 2012). Zheng, Swanson, and Marcoulides (2011) suggested that all WM components predict problem solving accuracy among primary school children. Among Italian children, arithmetic word problem solving was mainly related to the CE (Passolunghi & Pazzaglia, 2005). However, Kyttälä, Aunio, Lepola, & Hautamäki (2014) observed that, among Finnish children aged four to seven, VSWM played an important role in word problem solving.

Working Memory and Reading-Related Skills

Based on previous studies, WM is related to both word decoding skills and reading comprehension (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Cain, Oakhill, & Bryant, 2004). Poor decoding skills often lead to difficulties in reading comprehension. However, there are children who have difficulties in only one of these areas (Hulme & Snowling, 2011). Reading comprehension relies on WM in many ways. One has to hold already-read information in WM while trying to continue extracting meaning from upcoming text (Swanson, 1999). Simultaneously, the reader must read the words correctly. Both the CE and PL have been suggested to be necessary for reading comprehension (Baddeley, 1992). PL helps to retain verbal information in WM, and the CE is responsible for guiding the whole reading process, including retrieval of information from long-term memory. The lower the WM capacity, the harder it is for the reader to decode and comprehend. Many of the previous studies have shown that children with reading difficulties have difficulties in both PL tasks (e.g., Ackerman & Dykman, 1993; Mann, Liberman, & Shankweiler, 1980; Roodenrys & Stokes, 2001) and verbal CE tasks (e.g., de Jong, 1998; Swanson, 1999; Swanson & Ashbaker, 2000). This seems natural, since PL is thought to store verbal information for a short time (Baddeley, 1986, 2000) and is closely related to phonological awareness

(Gathercole, Alloway, Willis, & Adams, 2006). In addition, verbal CE tasks are dependent on PL, as well (Duff & Logie, 2001; for a meta-analysis, see Tillman, 2011). On the other hand, depending on the reading task type, visuospatial WM resources also seem to be relevant. In fact, Wang and Gathercole (2013) observed that children with low reading skills had substantial difficulties in both verbal and visuospatial CE tasks.

Current Study

Based on current knowledge, it seems that WM resources form an important basis for learning mathematics and reading. Thus, children with better WM skills at the beginning of formal schooling tend to have better academic achievements in later years. Many studies using cross-sectional data have shown that WM capacity increases rapidly through the childhood years (e.g. Simmering, 2012), and that there are both quantitative and qualitative changes (Koppenol-Gonzalez, Bouwmeester, & Vermunt, 2012). However, few of the previous studies (e.g. Alloway & Alloway, 2010) have concentrated on individual WM progress and individual WM differences with longitudinal data. For educational practices, it should be important to increase the knowledge regarding stability of WM skills – do those children who start behind also stay behind, or are the individual differences observed at kindergarten age mainly developmental differences that decrease or disappear by second grade? In this study, we investigated the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress) and the extent to which WM measured in kindergarten predicts academic performance in second grade in the Finnish educational context.

Compared with many other countries, school starts later in Finland. Finnish children begin pre-primary education in kindergarten in the year they become six, and begin formal schooling in the year they become seven. That is, when they start school, their WM resources should be more developed than those of children who start school earlier. Pre-primary education in Finland is compulsory and free of charge, as is primary education. Even though pre-primary education is based on systematic education and instruction, instruction in Finnish kindergartens is not usually divided into lessons. Instead, small group activities and play-related methods are emphasised. The Finnish educational system is based on the ideology of inclusion, and the focus is on supporting as early as possible (Finnish National Agency for Education, 2018). Despite a slight performance drop in recent years, Finland was still among the best OECD countries in the latest PISA survey (OECD, 2016) in scientific literacy, reading literacy and mathematical literacy, as well as collaborative problem solving.

Twenty-five percent of Finnish children learn to read before formal schooling and before they are formally taught to read (Lerkkanen, Rasku-Puttonen, Aunola, & Nurmi, 2004). In a more recent study, 39% of the Finnish participants could correctly read aloud all the test words at the beginning of the first grade (Soodla, Lerkkanen, Niemi, Kikas, Silinskas, & Nurmi, 2015). Finnish is an orthographically transparent language with simple syllabic structure (Seymour, Aro, & Erskine, 2003), and therefore it should be relatively easy to learn to read. About one-third of the children in each age cohort also have basic arithmetic skills at the beginning of formal schooling (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). After entering school, individual differences in reading skills decrease (Leppänen, Niemi, Aunola, & Nurmi, 2004; Parrila, Aunola,, Leskinen, Nurmi, & Kirby, 2005) while individual differences in mathematics tend to increase (Aunola, et al., 2004).

The following research questions were formulated:

1. To what extent do WM skills measured in kindergarten age predict WM skills at second grade?
2. To what extent do WM skills measured in kindergarten age predict academic skills (mathematical skills, reading skills) at second grade?

Method

Participants

Ninety-four Finnish children (39 girls and 55 boys) from a larger city (population 189 669, Statistics Finland, 2017) on the West coast of Finland participated in this study. The participating children were from nine different kindergartens that volunteered to participate in this study. The number of participating children per kindergarten varied from seven to sixteen (total number of all kindergarten-aged children in each kindergarten varied from eight to twenty). The kindergartens were recruited so that they would represent different types of socio-economic city areas. The kindergartens did not have any specific curricular emphases (e.g. mathematics, science or foreign language) but all followed the national core curriculum as well as the local curriculum based on the national version. All the children in the appropriate age group (including those with special needs and multi-lingual backgrounds) who returned a written parental consent were included in the study. However, to be able to participate, sufficient language skills in Finnish were required. The adequacy of Finnish skills was assessed by kindergarten teachers, and the assessment was based on the teachers' experiences of working with the same children. At the beginning of the study/at the first measurement time point (T_1), the six-to-seven-year-old children were attending their last two months in kindergarten. In Finland, kindergarten starts in August of the year the child becomes six years old, and compulsory schooling one year after that. At the second measurement time point (T_2), the children were attending their last two months of the second year in compulsory schooling. At that point, the children were eight to nine years old, and 77 of them could be reached (32 girls and 46 boys).

Procedure

The children were tested individually in quiet areas of the kindergarten and school, by a trained research assistant. Children participated in two 20- to 30-minute sessions. The tasks were presented in the same fixed order for each participant. At both time points, tests were conducted within a two-week span.

Measures

Working memory. VWM and VSWM were assessed with six subtasks of the Automated Working Memory Assessment (AWMA) (Alloway, 2007) at both timepoints. There is no Finnish version of AWMA. Therefore, only the visuospatial tasks were administered by computerised AWMA (with oral instructions in Finnish). The verbal tasks were adapted in Finnish, based on the original English version of AWMA. This adaptation means that the tasks were administered similarly to the original assessment, but with Finnish translations. Literal translations were used when appropriate. Because of the differences between English and Finnish (words are not necessarily equal in length), in most of the cases, the original words were replaced with another word or expression to ensure that the level of difficulty remained the same as the original assessment.

Each AWMA task is based on a series of blocks of increasing difficulty. Each block includes six trials. The participant proceeds to the next block if he/she responds correctly to four of the six trials, and gets a score of six. The test stops if three or more errors are made within the same block, and the score of the total correct responses is given.

Passive visuospatial storage. In the Dot Matrix task, a sequence of red dots was presented for two seconds in a 4 x 4 grid. After that, the participant’s task was to point to the positions of the dots in the same order that they appeared. In the block recall task, a sequence of cubes was highlighted on a screen among nine randomly located cubes. After that, the child’s task was to point the highlighted cubes in the same order. Test-retest correlations for the Dot Matrix and Block tasks are .85 and .90, respectively (Alloway, 2007).

Active visuospatial processing. In the Odd-One-Out task, children were presented with three shapes in a row. Every row had two shapes that were the same and one that was different. The child's task was to point the odd one out and remember its location. At the end of the task, the child was instructed to recall all the positions of the shapes that had been identified as being different. Test-retest correlation for the odd-One-Out task is .88 (Alloway, 2007).

Passive verbal storage. In the Word Span Forward task, the child's task was to recall word lists in correct order. The words were two-syllable Finnish words. In the Non-word task, the lists included two-syllable non-words. The non-words have previously been used with Finnish children by Laasonen, Virsu, Oinonen, Sandbacka, Salakari, & Service (2012). Test-retest correlations for the Word Span Forward and Non-Word Span tasks in the original AWMA test package are .88 and .69, respectively (Alloway, 2007).

Active verbal processing. In the listening recall task, the participants heard orally presented sentences. The child was supposed to judge whether a sentence was true or false, and to remember the final word of the sentence. Test-retest correlation for the Listening Recall task in the original AWMA package is .88 (Alloway, 2007).

Mathematics Skills.The tests for the construct 'Mathematics Skills' comprise basic arithmetic and word problem skills. Both were measured at second grade.

Basic arithmetic. Basic arithmetic skills at P_2 were measured with basic addition and subtraction fluency tasks, mental arithmetic, and paper and pencil calculation tasks from the Math Assessment second grade task battery (Koponen, Salminen, Aunio, & Polet, 2011). Cronbach's alpha for this task battery is .94 (Koponen, et al., 2011). There were 20 *basic addition fluency* tasks containing numbers from one to ten. The child's task was to solve as many addition tasks as he or she could during a one-minute-timeslot. One point was given for each correct answer, and the total score was then divided by two, according to the instruction manual. Thus, the maximum score for basic addition fluency tasks was 20/2 = 10.

There were 20 *basic subtraction fluency* tasks containing numbers from one to 15. The child's task was to solve as many subtraction tasks as he or she could during a one-minute timeslot. One point was given for each correct answer, and the maximum total score was 20/2 = 10. In addition, the task battery included eight *mental arithmetic* tasks (four addition tasks, and four subtraction tasks) with two-digit numbers (e.g., 30 + 24, 54 – 13), and eight *paper and pencil calculation* tasks with two-digit numbers. One point was given for each correct answer. The maximum total score of mental arithmetic and paper and pencil calculations was 16. The maximum total score of basic arithmetic was 36 (10 + 10 + 16).

Word problem skills. Word problem solving skills at P_2 were measured with the K-version of the MATTE –test (Kajamies, Vauras, Kinnunen, & Iiskala, 2003). It includes six tasks. The time limit in the K-version is 30 minutes. One point is given for each correctly solved task, with the maximum score being six. The tasks in the MATTE-test differ from traditional word problem tasks often used in school math books. They may contain information that is irrelevant for solving the task. Thus, using a superficial solving strategy may not provide the best outcome. The split-half reliability for this task was .83.

Reading Skills. The construct 'Reading Skills' comprises tests on word decoding and reading comprehension. These tests were performed by children in the second grade.

Word decoding skills. Word decoding skills at P_2 were measured using the word recognition subtest of the nationally normed reading test battery ALLU (Lindeman, 2000). In the word recognition subtest the words are written together in sets of two to four words, and the participant's task is to separate those words by marking lines between them (e.g., manynowearthwinter should become many/now/earth/winter). There are six practice items and 78 test items. Test time is limited to three minutes and 30 seconds. One point is given for each correctly separated word with the maximum score being 214. KR-20 for this subtest is .97 (Lindeman, 2000).

Reading comprehension. Reading comprehension at P_2 was measured using two pragmatic texts (with themes of judo and gymnastics instruction) from the nationally normed reading test battery ALLU (Lindeman, 2000). The child's task was to read the text and answer 12 questions, selecting answers from four alternatives. One point was given for each correct answer. The maximum score for one text was 12, and maximum score for both texts was 24. KR-20 for this subtest is .80 (Lindeman, 2000).

Analysis Strategy

Firstly, descriptive statistics were calculated for WM tasks at T_1 and T_2 (Table 1). Secondly, using CFA, we started by testing whether similar theoretical WM model would fit the data at both time points. Thirdly, based on the tested theoretical model, combined scores for two factors, VSWM (Dot Matrix, Block Task, Odd-One-Out) and VWM (Word Span Forward; Non-Word Task, Listening Recall), at two time points were computed based on z-scores. Fourthly, to answer the first research question on to what extent do WM skills measured at kindergarten age predict WM skills at second grade, a three-step procedure was conducted. In the first step, to confirm that the WM skills developed at this age phase in this data, we investigated whether the children's WM performance changed over time by comparing the means of performance levels in WM tasks at two time points, by using repeated measures ANOVA-tests. In the second step, we examined whether the WM measured at kindergarten was related to WM measured at second grade by calculating the correlations between measures of WM task performance at both time points. In the third step, a set of multiple regression analyses was carried out to predict WM performance in second grade by WM performance in kindergarten. Finally, in the fourth step, the stability of differences in WM skills was investigated by comparing how the participating children ranked in skill groups at two different time points.

To answer the second research question (whether WM measured in kindergarten predicts academic skills), we first calculated correlations between VWM, VSWM, and academic skills at both time points. Both basic arithmetical skills and word problem skills, as well as word decoding skills and reading comprehension, were inspected. In the second step, a set of multiple regression analyses was carried out to predict academic skills in second grade. For each analysis, only those WM variables that correlated with given second grade academic skills were chosen as potential predictors. In the third step, we tested whether the participants in different WM skill groups at kindergarten age differed in their later academic skills in second grade, by calculating a series of one-way ANOVAs.

Results

The Stability of WM Skills from Kindergarten to Second Grade

Descriptive statistics for WM tasks at T_1 and T_2 are presented in Table 1. Next, we tested whether similar theoretical WM models would fit the data at both time points. Three models of the WM structure were tested. We began by testing the two-construct measurement model for modality-specific WM, as suggested by Cornoldi & Vecchi (2003), at both time points (Figure 1). The loading of one indicator for VSWM was constrained to one. The loading of one indicator for VWM was constrained to one. In T_1, the fit of the model to the data was excellent ($\chi^2(8) = 7.46$, $p = .488$; CFI = 1.00, RMSEA=.00). Thus, the result of the confirmatory factor analysis supports the two-factor model including verbal and visuospatial WM factors at kindergarten age. In T_2, the fit of the model was nearly acceptable ($\chi^2(8) = 13.98$, $p = .082$; CFI = 0.93, RMSEA=.09). The modification indices suggested that we should let the two CE tasks correlate. After that, the fit of the model was excellent ($\chi^2(7) = 6.48$, $p = .484$; CFI = 1.00, RMSEA=.00).

Figure 1 about here

The law of parsimony suggests that it is best to present the simplest model (Bollen, 1989). Thus, a single-factor model for WM (suggested e.g. by Wiebe et al., 2008 & Bull et al., 2011) was tested at both time points, as well. The fit of the single-factor model was poor in both T_1 ($\chi^2(9) = 31.51$, p =.000; CFI =.92, RMSEA=.16) and T_2 ($\chi^2(9) = 38.72$, p =.000; CFI =.67, RMSEA=.18).

In the third step, we tested the original three-factor model of Baddeley & Hitch (1974) with three factors representing the CE (Listening Span, Odd-One-Out), VSSP (Dot Span, Block Task), and PL (Word Span, Non-word Span). In T_1, this three-factor model provided a nearly acceptable fit ($\chi^2(6) = 11.26$, p =.080; CFI =.98, RMSEA=.09). However, the fit of the two-factor model was better in this age group. This three-factor model did not provide satisfactory fit to the data in T_2 ($\chi^2(6) = 19.94$, p =.003; CFI =.85, RMSEA=.15). Thus, the two-factor WM model fit the data best at both time points. Based on this model, combined scores for two factors, VSWM (Dot Matrix, Block Task, Odd-One-Out) and VWM (Word Span Forward; Non-Word Task, Listening Recall), at two time points were computed based on z-scores, and used in subsequent analysis.

Repeated measures ANOVA-tests showed that WM capacity significantly increased between the two time points. There were no time*gender interactions except for the odd-one-out task ($F(1,60) = 4.27$; $p<.05$; partial $\eta 2 = .07$) where the girls gained more than the boys from kindergarten to second grade. In the second step, correlations between WM task performance at T_1 (kindergarten) and T_2 (second grade) were calculated (Table 2). All the WM tasks measured at kindergarten age, except for the Block task, correlated with the corresponding WM measures in second grade. The correlations were statistically significant, but were mostly quite low or moderate (r =.29-.69). The strongest correlation was between Listening Span measured in kindergarten and measured again in second grade (r=.69; p<.001).

Table 1

Table 2

Next, a set of multiple regression analyses was carried out to predict WM performance in second grade by WM performance in kindergarten (Table 3). The combined scores for VSWM and VWM were constructed based on a two-factor WM measurement model. In Model One, $VSWM_2$ was predicted by $VSWM_1$ and VWM_1. The results showed that $VSWM_1$ and VWM_1 predicted 13.6% of the variance in $VSWM_2$ but the only statistically significant predictor was $VSWM_1$. In Model Two, VWM_2 was predicted by VWM_1 and $VSWM_1$. The results showed that VWM_1 and $VSWM_1$ predicted 41.6% of the variance in VWM2 but the only significant predictor was VWM_1. Because $VSWM_1$ and VWM_1 correlated significantly with each other (r=.56***), there was a possibility of multicollinearity between independent variables. Therefore, alternate regression analysis was conducted. First, $VSWM_2$ was predicted by VWM_1 and $VSWM_1$ so that VWM_1 was forced first into the equation. VWM_1 did not predict performance in $VSWM_2$, even though it was forced as first into the equation ($F = 2.04$; $R^2 =.03$; $\beta =.181$, $t = 1.43$). The same result appeared when VWM_2 was predicted by $VSWM_1$ and VWM_1. $VSWM_1$ did not predict VWM_2 even though it was forced as first into the equation ($F = 3.33$; $R^2 =.05$; $\beta =.229$, $t = 1.83$).

Table 3

Finally, the stability of differences in WM skills was investigated by comparing how participating children ranked in skill groups at two different time points (Table 4). The participating children were divided into three groups based on their combined score in all WM tasks at two time points (Group One (good) ≥ 75 percentile; 75 percentile > Group Two (moderate) ≥ 25 percentile; Group Three (poor) < 25 percentile). Based on crosstabs (Table 2), 57% of the participants (35/61) fell into the same category at both time points. All the transitions between categories were one-step transitions. That is, none of the participants who fell into Group One at T_1 fell into Group Three at T_2, or vice versa. Eight of the 61 participants (13%) fell into Group Three at both time points. Eight out of nine participants (89%) who were placed in Group Three in kindergarten were placed in the same group two years later. Eight out of 61 participants (13%) were placed in Group One at both time points. Eight out of 15 participants (53%) who were placed in Group One when in kindergarten were in the same group two years later. The same comparison was also carried out separately for boys and girls. Five out of 36 boys (14%) fell into Group Three (poor performance) at both time points. Four of the nine boys who were placed into Group Three in kindergarten were placed into Group Two in second grade. Three out of 36 boys (8%) were placed into Group One at both time points. Five girls out of 25 (20%) were in Group Three at both time points. The same number of girls (5/25, or 20%) were ranked in Group One at both time points.

Table 4

To What Extent Do WM Skills Measured at Kindergarten Predict Counting Skills, Basic Arithmetic Skills, and Word Problem Solving Skills at Second Grade?

In the first step, correlations between VWM and VSWM at both time points and both basic arithmetical skills and word problem skills, as well as word decoding skills and reading comprehension, were inspected (Table 5). From the WM tasks measured at kindergarten age, both VWM_1 (r =.40**) and $VSWM_1$ (r =.32*) correlated with math word problems. $VSWM_1$ correlated with word decoding in second grade (r =.29*), and VWM_1 with reading comprehension in second grade (r =.28*). At the second-grade level, VWM_2 correlated with both arithmetic (r =.30*) and math word problems (r =.37**), as well as word decoding (r =.42**) and reading comprehension (r =.45***). $VSWM_2$ correlated with arithmetic (r =.31*), word decoding, (r =.54***), and reading comprehension (r =.32*).

Table 5

In the second step, a set of multiple regression analyses was carried out to predict academic skills in second grade (Table 3). For each analysis, only those WM variables that correlated with given second grade academic skills were chosen as potential predictors. The regression models of two different time points were analysed separately. $VSWM_2$ and VWM_2 predicted 14% of the variance in basic arithmetic tasks (Model Three). However, probably due to a significant correlation (r =.32**) between these two predictors, neither of these appeared to be a significant predictor when included in the same model. When these variables were alternately forced first into the equation, both $VSWM_2$ (R^2 =.10; F = 6.20*; β =.308, t = 2.49*) and VWM_2 (R^2 =.09; F = 5.71*; β =.297, t = 2.39*) predicted basic arithmetic skills significantly. This may mean that the relationship between WM_2 resources and arithmetic skills has more to do with general CE resources, common to both VSWM and VWM tasks, and less with modality-specific visuospatial or verbal storage resources.

Math word problems (Model Four) were predicted by $VSWM_1$ and VWM_1. They predicted 18% of the variance in math word problem tasks, but the only significant predictor was VWM_1. Two alternate models, when $VSWM_1$ and VWM_1 were forced as first into the equation, were calculated. When forced as first, $VSWM_1$ predicted 10 % (R^2 =.10; F = 5.29* β =.318, t = 2.30*) of the variance in word problem tasks. When forced as first, VWM_1 predicted 14 % of the variance in math word problems (R^2 =.16; F = 9.00** β =.401, t = 3.00**). In the second grade, only VWM_2 correlated with math word problems. It predicted 14 % of the variance in word problem tasks. Even though both $VSWM_1$ and VWM_1 correlated with word decoding, they did not predict word decoding skills significantly (R^2 =.08; F = 2.89; p =.063). The same WM resources, two years later (Model Five), predicted 36 % of the variance in the word decoding test, and both $VSWM_2$ and VWM_2 were significant predictors. When forced first, $VSWM_2$ predicted 29% of the variance in word decoding (R^2 =.29; F = 23.82*** β =.540, t = 4.88***).and VWM_2 18% (R^2 =.18; F = 12.69** β =.424, t =

3.56**). $VSWM_2$ and VWM_2 predicted 23% of the variance in reading comprehension, with only VWM_2 being a significant predictor. When forced as first into the equation, $VSWM_2$ predicted 10% of the variance in reading comprehension (R^2 =.10; F = 6.95*; β =.322, *t* = 2.64*), and VWM_2 20% (R^2 =.20; F = 15.20*** β =.450, *t* = 3.90***).

Finally, we tested whether the participants in different WM skill groups at kindergarten age differed in their later academic skills in second grade. The results of one-way ANOVAs showed that the there was a statistically significant difference in academic performance based on children's WM performance in kindergarten (*F* (4, 112) = 2.93, *p* <.01; partial η^2 =.22). The three WM skill groups showed statistically significant differences in math word problems, word decoding, and reading comprehension (Table 6). Post hoc Scheffe tests showed that, in math word problems, Group One (good performance) differed from Groups Two and Three. Group Two (moderate performance) did not differ from Group Three (poor performance) statistically significantly. In word decoding, Group Three (poor performance) differed statistically significantly from the other groups that did not differ from another. In reading comprehension, Group One (good performance) and Group Three (poor performance) differed from one another.

Table 6

Discussion

The aim of this longitudinal study was to investigate the extent to which WM measured in kindergarten predicts WM skills measured in second grade (stability of individual WM progress), and to what extent these kindergarten WM skills predict later academic skills in second grade. Our results show that WM skills significantly increase during this time span from Finnish kindergarten (6- to 7-year-olds) to second grade (8- to 9-year-olds) which corresponds to previous results (e.g., Gathercole, et al., 2004; Wilson, Scott,

& Power, 1987). As suggested earlier (Alloway & Alloway, 2010), individual differences seem to show some stability. Sixty-two percent of the participants were ranked in the same skill group at two time points. Sixteen percent of all the participants were classified in the poor performance group at both time points. All the WM tasks, except for the Block Task, correlated with the same measures two years later, which suggests that these tasks predict performance in the same tasks two years later. However, it must be noted that the correlation coefficients were mostly quite low or moderate in high. The most stable predictor at this age phase seems to be Listening Span, which is used to measure verbal CE.

As suggested before (Gathercole, Pickering, Ambridge, & Wearing, 2004), verbal and visuospatial WM resources seem to develop quite independently. VSWM resources measured at kindergarten age predicted VSWM resources in second grade but not VWM resources at the same age, and vice versa. In general, VWM skills seem to show more stability at this age phase than VSWM skills. This stability does not mean that the VWM skills would not have developed as, at first, ANOVA showed that VWM skills did increase between the two measurement time points. Instead, it means that the development of VWM is more straightforward and predictable based on kindergarten performance. This finding is notable, considering that between the ages of seven and eleven, children begin to prioritise VWM resources (Andersson & Lyxell, 2007; McKenzie, Bull, & Gray, 2003; Rasmussen & Bisanz, 2005). Thus, VWM resources become a more important information processing tool or resource in this age phase.

The same modality-specific WM model seems to fit to the data at both time points. This does not necessarily mean that a two-factor solution would be the best to theoretically model WM functions. It only means that it is empirically, on a WM task level, almost impossible to separate CE functions from short-term storage functions as previously suggested by Duff & Logie, (2001). Thus, CE tasks are almost inevitably dependent on either verbal or visuospatial storage resources. It seems that, at least in this age phase, CE tasks are quite dependent on storage resources. However, it is important to note that, based on our data, WM models that separate WM resources modality-specifically into visuospatial and verbal ones, such as Baddeley's (1986, 2000) or Cornoldi and Vecchi's (2003), seem to be an important starting point when furthering our understanding of children's WM skills and their significance in learning, for instance.

Our second research question addressed the extent to which WM measured at kindergarten predicts academic performance at second grade in the Finnish educational context. In Finland, school starts later than in many other countries. Finnish children begin kindergarten in the year they turn six, and formal schooling in the year they turn seven. That is, when they start school and begin to participate in formal reading and mathematics instruction, their WM resources should be more developed than those of children who start their school earlier. As observed before (Passolunghi, et al., 2008; Östergren, & Träff 2013), WM resources measured just before the start of school predicted later academic performance to some extent in our data, as well. Even though the only significant association between WM and subsequent academic skills in regression analysis was between VWM and math word problems, our results also show that children from various WM skills groups in kindergarten perform differently in math word problems, word decoding, and reading comprehension two years later. In math word problems, the group with good WM performance performed significantly better than the groups with moderate or poor performance. In decoding, the group with poor performance differed significantly from the other two groups. Thus, it seems that good overall WM skills at kindergarten age predict good math word problem solving skills two years later. Further, poor overall WM skills at kindergarten age predict poor decoding skills two years later. In second grade, both VSWM and VWM skills seem to be an important factor behind decoding performance, since they predict 36% of its variation. This is in line with previous studies (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Cain, Oakhill, & Bryant, 2004), showing that WM resources are needed in decoding. It is possible that this relationship is even more visible in the second school grade when *most* of the Finnish children are able to read accurately (see Aro, 2006).

Certain limitations should be noted. First, our sample size was quite small. A larger sample size would have enabled us to use more sophisticated analysis methods, like SEM, in predicting later academic skills. Second, the number of WM indicators was limited. Even though the measures used in our study have previously been found to be good indicators of WM (Alloway, 2007), using additional measures of WM components (e.g. more AWMA subtasks) would provide an even more reliable and versatile assessment of WM skills, considering that the relationship between WM and academic skills has previously varied as a function of WM subskill/measure (see, e.g. Peng, Namkung, Barnes, & Sun, 2015)

Conclusions

In conclusion, our results show that WM skills significantly increase during the time span from Finnish kindergarten (six- to seven-year-olds) to second grade (eight- to nine-year-olds), verbal and visuospatial WM resources seem to develop quite independently, and individual progress seem to show some stability. WM resources measured just before school start predicted later academic performance, and VWM seems to be a more powerful predictor than VSWM resources. This probably has to do with the fact that they seem to develop with more stability in this age phase. It is obvious, based on our study that many children who have weaker WM skills than their age-mates in kindergarten also lag behind later in school. Based on this study and on previous studies (e.g. Pham & Hasson, 2014; Toll et al., 2011), it seems obvious that poor WM skills restrain learning of (basic) academic skills. This has at least three potential educational implications: first, WM difficulties should be identified as early as possible. Thus, teachers and other professionals working with preschool and kindergarten age children should have the skills to assess students' skills. Second, individual or group-based intervention directed towards enhancing children's WM skills would be most important when provided before the start of school; and, third, since the effects of intervention programmes and methods are proven to be controversial (Melby-Lervåg & Hulme, 2013; Shipstead et al., 2012), poor WM skills should be given attention from an early age when planning the learning environment. The problems that result from poor WM are problems mostly because of our methods of teaching and that the learning environment does not support all individuals. In future studies, how the learning environment can support WM should be systematically investigated.

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Table 1. Descriptive statistics for WM measures and academic skills at two time points

	Kindergarten (N=94)		2nd Grade (N=77)			
Measure	M	SD	M	SD	F	η_p^2
Dot Matrix	16.92	4.79	22.60	4.39	66.78***	.52
Block Task	16.77	5.26	21.42	4.10	39.01***	.39
Odd-One-Out	14.81	4.25	20.05	4.46	66.13***	.52
Word Span	18.60	3.32	21.74	2.56	57.23***	.48
Nonword Span	11.02	3.72	18.40	2.96	234.87***	.79
Listening Span	6.60	3.17	12.06	2.78	333.14***	.85
Arithmetics	-	-	25.35	6.51	-	-
Word Problems	-	-	2.63	1.36	-	-
Word Decoding	-	-	52.21	33.74	-	-
Reading comprehension	-	-	18.53	3.59	-	-

Note. ***p<.001.

Table 2. Correlations between WM measures at two time points

	2nd Grade					
Kindergarten	1	2	3	4	5	6
1 Dot Matrix	**.29***	.28*	.26*	.11	.12	.10
2 Block Task	.23	**.24**	.28*	.13	.17	.32*
3 Odd-One-Out	.18	.36**	**.32***	.18	.18	.19
4 Word Span	.02	-.16	-.04	**.40****	.36**	.30*
5 Nonword Span	.11	.10	-.06	.44***	**.37****	.18
6 Listening Span	.45***	.16	.45***	.37**	.45***	**.69*****

Note. N = 77. ***p<.001, **p<.01, *p<.05.

Table 3. Summary of Hierarchical Regression Analysis for Variables Predicting WM performance and academic skills in second grade

Variable		β	t
Model 1	VSWM$_2$		
VSWM$_1$		.375	2.65*
VWM$_1$		-.012	-.08
F = 4.65*; R^2 = .14			
Model 2	VWM$_2$		
VSWM$_1$		-.133	-1.15
VWM$_1$		.704	6.06***
F = 21.04***; R^2 = .42			
Model 3	Basic Arithmetics		
VSWM$_2$		.238	1.85
VWM$_2$		.222	1.73
F = 4.69*; R^2 = .14			
Model 4	Math Word Problems		
VSWM$_1$		.150	.96
VWM$_1$		.323	2.06*
F = 4.95*; R^2 = .18			
Model 5	Word Decoding		
VSWM$_2$		.450	4.03***
VWM$_2$		.280	2.51*
F = 16.14***; R^2 = .36			
Model 6	Reading Comprehension		
VSWM$_2$		.191	1.58
VWM$_2$		.384	3.17**
F = 9.03***; R^2 = .23			

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

Table 4. The stability of WM skills at two time points

	2nd grade			
		Good	Moderate	Low
X^2=24.74***		*M*=22.24; *SD*=1.46	*M*=19.47; *SD*=.71	*M*=16.88; *SD*=1.67
Kindergarten	Good *M*=17.06; *SD*=1.21	8	7	0
	Moderate *M*=13.98; *SD*=1.06	7	19	11
	Low *M*=10.54; *SD*=2.37	0	1	8

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

Table 5. Correlations between WM performance and academic skills

	$VSWM_1$	VWM_1	$VSWM_2$	VWM_2
Basic arithmetics	.18	.20	.31*	.30*
Word problem	.32*	.40**	.20	.37**
Word decoding	.23*	.25*	.53***	.43***
Reading comprehension	.14	.15	.32*	.45***

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

Table 6. Later academic performance of different WM kindergarten skill groups

	Good		Moderate		Low			
Measure	*M*	*Sd*	*M*	*Sd*	*M*	*Sd*	*F*	η_p^2
Basic arithmetics	28.92	1.51	26.96	1.05	23.29	2.06	2.44	.10
Word problems	3.85	0.32	2.48	0.22	1.57	0.43	10.31***	.32
Word decoding	82.62	8.01	59.15	5.56	34.86	10.92	6.53**	.23
Reading comprehension	20.69	0.83	18.78	0.58	17.00	1.13	3.70*	.14

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

Working memory resources in children: Stability and relation to subsequent academic skills

Abstract

This study aimed to investigate the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress), and the extent to which WM measured at kindergarten predicts academic performance at second grade (N = 94). The results showed that WM skills significantly increase during the time span from Finnish kindergarten to second grade. Verbal (VWM) and visuospatial WM (VSWM) resources seem to develop quite independently, whereas individual progress showed some stability. WM resources measured just before the start of formal school predicted later academic performance, and VWM acted as more powerful predictor than VSWM resources. The results have two important educational implications: first, individual or group-based intervention designed to enhance children's WM skills would be most important even before the start of school, and second, poor WM skills should be addressed when planning the learning environment beginning in kindergarten.

Key words: Working memory, mathematical skills, reading skills, longitudinal study

Introduction

Working memory (WM) is an important and impassable information processing system behind learning. It stores and processes information for a short period of time during a range of cognitive tasks, and has a limited capacity. Several studies have shown that WM skills are related to academic skills both at preschool (Fuhs, Nesbitt, Farran, & Dong, 2014; Kroesbergen, Van Luit, Naglieri, Franchi, & Taddei, 2010; Kyttälä, Aunio, & Hautamäki, 2010; Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003) and school years (Alloway, et al., 2005; De Weerdt, Desoete, & Roeyers, 2012; Gathercole, Tiffany, Briscoe, Thorn & ALSPAC team, 2005; Reuhkala, 2001; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011; Passolunghi, Vercelloni, & Schadee, 2007). Previous studies have also shown that, based on WM resources measured before school start, it is even possible to predict future WM resources (Alloway, & Alloway, 2010), and academic performance at school (Passolunghi, Mammarella, & Altoè, 2008; Stipek, & Valentino, 2015; Toll, Kroesbergen, & Van Luit, 2016; Östergren & Träff, 2013). In the current study, we investigate the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress) and the extent to which WM measured in kindergarten predicts academic performance in second grade in the Finnish educational context.

There are various theoretical frameworks that address WM organisation (e.g., Barrouillet, Bernardin, & Camos, 2004; Cowan, 2005; Engle, Kane, & Tuholski, 1999). One common view is Baddeley's multicomponent WM model (1986, 2000) which includes a passive storage system (short-term memory) and an active processing system (working memory). According to that model, separate WM subcomponents are specialised to different functions. While the phonological loop (PL) stores verbal information for a short time, the visuospatial sketchpad (VSSP) is responsible for the temporal storage of visuospatial information. The central executive (CE) is the coordinator responsible for information processing, inhibitory control, and cognitive flexibility. The episodic buffer (EB) integrates information from subcomponents and from long-term memory in the WM.

Even though Baddeley's three-component model is widely used in research related to WM and academic skills, and although it clearly has its advantages in separating the passive storage and active processing functions, it also has some problems in operationalising the framework. Although the CE is presented as a single component in the original model, it has been stated that the CE might not, in fact, be a unitary component (Baddeley, 1996). Some researchers have even suggested that there might be separate CE units for verbal and visuospatial information (e.g., Shah & Miyake, 1996). In fact, previous results show that verbal and visuospatial CE tasks are related to different academic skills (Jarvis & Gathercole, 2003). However, rather than proving that there are modality-specific CE units, these results may reflect the fact that most of the typical CE tasks also depend on short-term storages (PL or VSSP) (Duff & Logie, 2001; for a meta-analysis, see Tillman, 2011). Because of these difficulties in separating pure CE functioning from short-term modality-specific storing, we rather adopted the continuity model proposed by Cornoldi and Vecchi (2003) in this study. They divide WM functions into modality-specific continuums, and these modality-specific WM functions are more or less dependent on storage or processing. Following this idea of continuity between passive storing and active processing, we did not try to separate the passive storage and active processing functions. Instead, we divided the WM function modality (specifically, into visuospatial and verbal functions) in order to investigate whether these two contribute differently to later academic skills. We refer to these horizontal dimensions as the verbal working memory (VWM) and the visuospatial working memory (VSWM).

During childhood years, WM capacity increases rapidly (Gathercole, 1999; Pickering, 2001). It has been suggested that the adult level of WM capacity is reached at approximately

15 to 16 years of age (Gathercole, Pickering, Ambridge, & Wearing, 2004). Even after that, WM resources continue developing, but are more related to growing expertise that helps to process information more efficiently than just to simple developmental factors. It has also been suggested that there is a developmental shift from visuospatial WM resources to verbal WM resources. Young children rely mostly on visuospatial resources because they are unable to use verbal rehearsal strategies (McKenzie, Bull, & Gray, 2003). At about seven to eleven years of age, when they first learn to read and then begin to use language efficiently, they begin to prioritise verbal WM resources (Andersson & Lyxell, 2007; McKenzie, et al., 2003; Rasmussen & Bisanz, 2005). Even though WM resources rapidly develop during childhood years, there are individual differences from early on (Kyttälä, et al., 2003). Compared to those with better WM skills right at the start of kindergarten, children with poor WM resources have detectable difficulties in following instructions, completing complex tasks, and in situations and tasks that involve simultaneous processing and storing of information (Gathercole, Lamont, & Alloway, 2006).

Working Memory and Early Mathematics

WM is related to children's early counting ability and basic arithmetic skills (Bull & Scerif, 2001; Bull, Espy, & Wiebe, 2008; Noël, 2009). All the WM components seem to be involved (Noël, 2009; Ranghubar et al., 2010) but they have somewhat different roles, depending on used measures and maybe even over different cultures. Number-word-sequence skills of five- to six-year old children were related to their PL capacity (Preßler, Krajewski, & Hasselhorn, 2013). Counting skills and skills to solve simple addition tasks have been observed to be related to both the PL and the CE (Noël, 2009). CE is probably needed in controlling the direction, and phase of counting. On the other hand, Rasmussen and Bisanz (2005) observed that, when simple additions were presented visually using concrete materials, performance in addition tasks was associated with visuospatial WM resources. The

VSSP, in turn, is responsible for the storage of visuospatial information: for example, mental images of digits or manipulation of the mental number-line (Bachot, Gevers, Fias, & Roeyers, 2005; Gunderson, Ramirez, Beilock, & Levine, 2012). Zheng, Swanson, and Marcoulides (2011) suggested that all WM components predict problem solving accuracy among primary school children. Among Italian children, arithmetic word problem solving was mainly related to the CE (Passolunghi & Pazzaglia, 2005). However, Kyttälä, Aunio, Lepola, & Hautamäki (2014) observed that, among Finnish children aged four to seven, VSWM played an important role in word problem solving.

Working Memory and Reading-Related Skills

Based on previous studies, WM is related to both word decoding skills and reading comprehension (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Cain, Oakhill, & Bryant, 2004). Poor decoding skills often lead to difficulties in reading comprehension. However, there are children who have difficulties in only one of these areas (Hulme & Snowling, 2011). Reading comprehension relies on WM in many ways. One has to hold already-read information in WM while trying to continue extracting meaning from upcoming text (Swanson, 1999). Simultaneously, the reader must read the words correctly. Both the CE and PL have been suggested to be necessary for reading comprehension (Baddeley, 1992). PL helps to retain verbal information in WM, and the CE is responsible for guiding the whole reading process, including retrieval of information from long-term memory. The lower the WM capacity, the harder it is for the reader to decode and comprehend. Many of the previous studies have shown that children with reading difficulties have difficulties in both PL tasks (e.g., Ackerman & Dykman, 1993; Mann, Liberman, & Shankweiler, 1980; Roodenrys & Stokes, 2001) and verbal CE tasks (e.g., de Jong, 1998; Swanson, 1999; Swanson & Ashbaker, 2000). This seems natural, since PL is thought to store verbal information for a short time (Baddeley, 1986, 2000) and is closely related to phonological awareness

(Gathercole, Alloway, Willis, & Adams, 2006). In addition, verbal CE tasks are dependent on PL, as well (Duff & Logie, 2001; for a meta-analysis, see Tillman, 2011). On the other hand, depending on the reading task type, visuospatial WM resources also seem to be relevant. In fact, Wang and Gathercole (2013) observed that children with low reading skills had substantial difficulties in both verbal and visuospatial CE tasks.

Current Study

Based on current knowledge, it seems that WM resources form an important basis for learning mathematics and reading. Thus, children with better WM skills at the beginning of formal schooling tend to have better academic achievements in later years. Many studies using cross-sectional data have shown that WM capacity increases rapidly through the childhood years (e.g. Simmering, 2012), and that there are both quantitative and qualitative changes (Koppenol-Gonzalez, Bouwmeester, & Vermunt, 2012). However, few of the previous studies (e.g. Alloway & Alloway, 2010) have concentrated on individual WM progress and individual WM differences with longitudinal data. For educational practices, it should be important to increase the knowledge regarding stability of WM skills – do those children who start behind also stay behind, or are the individual differences observed at kindergarten age mainly developmental differences that decrease or disappear by second grade? In this study, we investigated the extent to which WM measured in kindergarten predicts WM measured in second grade (stability of individual WM progress) and the extent to which WM measured in kindergarten predicts academic performance in second grade in the Finnish educational context.

Compared with many other countries, school starts later in Finland. Finnish children begin pre-primary education in kindergarten in the year they become six, and begin formal schooling in the year they become seven. That is, when they start school, their WM resources should be more developed than those of children who start school earlier. Pre-primary education in Finland is compulsory and free of charge, as is primary education. Even though pre-primary education is based on systematic education and instruction, instruction in Finnish kindergartens is not usually divided into lessons. Instead, small group activities and play-related methods are emphasised. The Finnish educational system is based on the ideology of inclusion, and the focus is on supporting as early as possible (Finnish National Agency for Education, 2018). Despite a slight performance drop in recent years, Finland was still among the best OECD countries in the latest PISA survey (OECD, 2016) in scientific literacy, reading literacy and mathematical literacy, as well as collaborative problem solving.

Twenty-five percent of Finnish children learn to read before formal schooling and before they are formally taught to read (Lerkkanen, Rasku-Puttonen, Aunola, & Nurmi, 2004). In a more recent study, 39% of the Finnish participants could correctly read aloud all the test words at the beginning of the first grade (Soodla, Lerkkanen, Niemi, Kikas, Silinskas, & Nurmi, 2015). Finnish is an orthographically transparent language with simple syllabic structure (Seymour, Aro, & Erskine, 2003), and therefore it should be relatively easy to learn to read. About one-third of the children in each age cohort also have basic arithmetic skills at the beginning of formal schooling (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). After entering school, individual differences in reading skills decrease (Leppänen, Niemi, Aunola, & Nurmi, 2004; Parrila, Aunola,, Leskinen, Nurmi, & Kirby, 2005) while individual differences in mathematics tend to increase (Aunola, et al., 2004).

The following research questions were formulated:

1. To what extent do WM skills measured in kindergarten age predict WM skills at second grade?
2. To what extent do WM skills measured in kindergarten age predict academic skills (mathematical skills, reading skills) at second grade?

Method

Participants

Ninety-four Finnish children (39 girls and 55 boys) from a larger city (population 189 669, Statistics Finland, 2017) on the West coast of Finland participated in this study. The participating children were from nine different kindergartens that volunteered to participate in this study. The number of participating children per kindergarten varied from seven to sixteen (total number of all kindergarten-aged children in each kindergarten varied from eight to twenty). The kindergartens were recruited so that they would represent different types of socio-economic city areas. The kindergartens did not have any specific curricular emphases (e.g. mathematics, science or foreign language) but all followed the national core curriculum as well as the local curriculum based on the national version. All the children in the appropriate age group (including those with special needs and multi-lingual backgrounds) who returned a written parental consent were included in the study. However, to be able to participate, sufficient language skills in Finnish were required. The adequacy of Finnish skills was assessed by kindergarten teachers, and the assessment was based on the teachers' experiences of working with the same children. At the beginning of the study/at the first measurement time point (T_1), the six-to-seven-year-old children were attending their last two months in kindergarten. In Finland, kindergarten starts in August of the year the child becomes six years old, and compulsory schooling one year after that. At the second measurement time point (T_2), the children were attending their last two months of the second year in compulsory schooling. At that point, the children were eight to nine years old, and 77 of them could be reached (32 girls and 46 boys).

Procedure

The children were tested individually in quiet areas of the kindergarten and school, by a trained research assistant. Children participated in two 20- to 30-minute sessions. The tasks were presented in the same fixed order for each participant. At both time points, tests were conducted within a two-week span.

Measures

Working memory. VWM and VSWM were assessed with six subtasks of the Automated Working Memory Assessment (AWMA) (Alloway, 2007) at both timepoints. There is no Finnish version of AWMA. Therefore, only the visuospatial tasks were administered by computerised AWMA (with oral instructions in Finnish). The verbal tasks were adapted in Finnish, based on the original English version of AWMA. This adaptation means that the tasks were administered similarly to the original assessment, but with Finnish translations. Literal translations were used when appropriate. Because of the differences between English and Finnish (words are not necessarily equal in length), in most of the cases, the original words were replaced with another word or expression to ensure that the level of difficulty remained the same as the original assessment.

Each AWMA task is based on a series of blocks of increasing difficulty. Each block includes six trials. The participant proceeds to the next block if he/she responds correctly to four of the six trials, and gets a score of six. The test stops if three or more errors are made within the same block, and the score of the total correct responses is given.

Passive visuospatial storage. In the Dot Matrix task, a sequence of red dots was presented for two seconds in a 4 x 4 grid. After that, the participant’s task was to point to the positions of the dots in the same order that they appeared. In the block recall task, a sequence of cubes was highlighted on a screen among nine randomly located cubes. After that, the child’s task was to point the highlighted cubes in the same order. Test-retest correlations for the Dot Matrix and Block tasks are .85 and .90, respectively (Alloway, 2007).

Active visuospatial processing. In the Odd-One-Out task, children were presented with three shapes in a row. Every row had two shapes that were the same and one that was different. The child's task was to point the odd one out and remember its location. At the end of the task, the child was instructed to recall all the positions of the shapes that had been identified as being different. Test-retest correlation for the odd-One-Out task is .88 (Alloway, 2007).

Passive verbal storage. In the Word Span Forward task, the child's task was to recall word lists in correct order. The words were two-syllable Finnish words. In the Non-word task, the lists included two-syllable non-words. The non-words have previously been used with Finnish children by Laasonen, Virsu, Oinonen, Sandbacka, Salakari, & Service (2012). Test-retest correlations for the Word Span Forward and Non-Word Span tasks in the original AWMA test package are .88 and .69, respectively (Alloway, 2007).

Active verbal processing. In the listening recall task, the participants heard orally presented sentences. The child was supposed to judge whether a sentence was true or false, and to remember the final word of the sentence. Test-retest correlation for the Listening Recall task in the original AWMA package is .88 (Alloway, 2007).

Mathematics Skills.The tests for the construct 'Mathematics Skills' comprise basic arithmetic and word problem skills. Both were measured at second grade.

Basic arithmetic. Basic arithmetic skills at P_2 were measured with basic addition and subtraction fluency tasks, mental arithmetic, and paper and pencil calculation tasks from the Math Assessment second grade task battery (Koponen, Salminen, Aunio, & Polet, 2011). Cronbach's alpha for this task battery is .94 (Koponen, et al., 2011). There were 20 *basic addition fluency* tasks containing numbers from one to ten. The child's task was to solve as many addition tasks as he or she could during a one-minute-timeslot. One point was given for each correct answer, and the total score was then divided by two, according to the instruction manual. Thus, the maximum score for basic addition fluency tasks was 20/2 = 10.

There were 20 *basic subtraction fluency* tasks containing numbers from one to 15. The child's task was to solve as many subtraction tasks as he or she could during a one-minute timeslot. One point was given for each correct answer, and the maximum total score was 20/2 = 10. In addition, the task battery included eight *mental arithmetic* tasks (four addition tasks, and four subtraction tasks) with two-digit numbers (e.g., 30 + 24, 54 – 13), and eight *paper and pencil calculation* tasks with two-digit numbers. One point was given for each correct answer. The maximum total score of mental arithmetic and paper and pencil calculations was 16. The maximum total score of basic arithmetic was 36 (10 + 10 + 16).

Word problem skills. Word problem solving skills at P_2 were measured with the K-version of the MATTE –test (Kajamies, Vauras, Kinnunen, & Iiskala, 2003). It includes six tasks. The time limit in the K-version is 30 minutes. One point is given for each correctly solved task, with the maximum score being six. The tasks in the MATTE-test differ from traditional word problem tasks often used in school math books. They may contain information that is irrelevant for solving the task. Thus, using a superficial solving strategy may not provide the best outcome. The split-half reliability for this task was .83.

Reading Skills. The construct 'Reading Skills' comprises tests on word decoding and reading comprehension. These tests were performed by children in the second grade.

Word decoding skills. Word decoding skills at P_2 were measured using the word recognition subtest of the nationally normed reading test battery ALLU (Lindeman, 2000). In the word recognition subtest the words are written together in sets of two to four words, and the participant's task is to separate those words by marking lines between them (e.g., manynowearthwinter should become many/now/earth/winter). There are six practice items and 78 test items. Test time is limited to three minutes and 30 seconds. One point is given for each correctly separated word with the maximum score being 214. KR-20 for this subtest is .97 (Lindeman, 2000).

Reading comprehension. Reading comprehension at P_2 was measured using two pragmatic texts (with themes of judo and gymnastics instruction) from the nationally normed reading test battery ALLU (Lindeman, 2000). The child's task was to read the text and answer 12 questions, selecting answers from four alternatives. One point was given for each correct answer. The maximum score for one text was 12, and maximum score for both texts was 24. KR-20 for this subtest is .80 (Lindeman, 2000).

Analysis Strategy

Firstly, descriptive statistics were calculated for WM tasks at T_1 and T_2 (Table 1). Secondly, using CFA, we started by testing whether similar theoretical WM model would fit the data at both time points. Thirdly, based on the tested theoretical model, combined scores for two factors, VSWM (Dot Matrix, Block Task, Odd-One-Out) and VWM (Word Span Forward; Non-Word Task, Listening Recall), at two time points were computed based on z-scores. Fourthly, to answer the first research question on to what extent do WM skills measured at kindergarten age predict WM skills at second grade, a three-step procedure was conducted. In the first step, to confirm that the WM skills developed at this age phase in this data, we investigated whether the children's WM performance changed over time by comparing the means of performance levels in WM tasks at two time points, by using repeated measures ANOVA-tests. In the second step, we examined whether the WM measured at kindergarten was related to WM measured at second grade by calculating the correlations between measures of WM task performance at both time points. In the third step, a set of multiple regression analyses was carried out to predict WM performance in second grade by WM performance in kindergarten. Finally, in the fourth step, the stability of differences in WM skills was investigated by comparing how the participating children ranked in skill groups at two different time points.

To answer the second research question (whether WM measured in kindergarten predicts academic skills), we first calculated correlations between VWM, VSWM, and academic skills at both time points. Both basic arithmetical skills and word problem skills, as well as word decoding skills and reading comprehension, were inspected. In the second step, a set of multiple regression analyses was carried out to predict academic skills in second grade. For each analysis, only those WM variables that correlated with given second grade academic skills were chosen as potential predictors. In the third step, we tested whether the participants in different WM skill groups at kindergarten age differed in their later academic skills in second grade, by calculating a series of one-way ANOVAs.

Results

The Stability of WM Skills from Kindergarten to Second Grade

Descriptive statistics for WM tasks at T_1 and T_2 are presented in Table 1. Next, we tested whether similar theoretical WM models would fit the data at both time points. Three models of the WM structure were tested. We began by testing the two-construct measurement model for modality-specific WM, as suggested by Cornoldi & Vecchi (2003), at both time points (Figure 1). The loading of one indicator for VSWM was constrained to one. The loading of one indicator for VWM was constrained to one. In T_1, the fit of the model to the data was excellent ($\chi^2(8) = 7.46$, $p = .488$; CFI = 1.00, RMSEA=.00). Thus, the result of the confirmatory factor analysis supports the two-factor model including verbal and visuospatial WM factors at kindergarten age. In T_2, the fit of the model was nearly acceptable ($\chi^2(8) = 13.98$, $p = .082$; CFI = 0.93, RMSEA=.09). The modification indices suggested that we should let the two CE tasks correlate. After that, the fit of the model was excellent ($\chi^2(7) = 6.48$, $p = .484$; CFI = 1.00, RMSEA=.00).

Figure 1 about here

The law of parsimony suggests that it is best to present the simplest model (Bollen, 1989). Thus, a single-factor model for WM (suggested e.g. by Wiebe et al., 2008 & Bull et al., 2011) was tested at both time points, as well. The fit of the single-factor model was poor in both T_1 ($\chi^2(9) = 31.51$, p =.000; CFI =.92, RMSEA=.16) and T_2 ($\chi^2(9) = 38.72$, p =.000; CFI =.67, RMSEA=.18).

In the third step, we tested the original three-factor model of Baddeley & Hitch (1974) with three factors representing the CE (Listening Span, Odd-One-Out), VSSP (Dot Span, Block Task), and PL (Word Span, Non-word Span). In T_1, this three-factor model provided a nearly acceptable fit ($\chi^2(6) = 11.26$, p =.080; CFI =.98, RMSEA=.09). However, the fit of the two-factor model was better in this age group. This three-factor model did not provide satisfactory fit to the data in T_2 ($\chi^2(6) = 19.94$, p =.003; CFI =.85, RMSEA=.15). Thus, the two-factor WM model fit the data best at both time points. Based on this model, combined scores for two factors, VSWM (Dot Matrix, Block Task, Odd-One-Out) and VWM (Word Span Forward; Non-Word Task, Listening Recall), at two time points were computed based on z-scores, and used in subsequent analysis.

Repeated measures ANOVA-tests showed that WM capacity significantly increased between the two time points. There were no time*gender interactions except for the odd-one-out task ($F(1,60) = 4.27$; $p<.05$; partial $\eta 2 = .07$) where the girls gained more than the boys from kindergarten to second grade. In the second step, correlations between WM task performance at T_1 (kindergarten) and T_2 (second grade) were calculated (Table 2). All the WM tasks measured at kindergarten age, except for the Block task, correlated with the corresponding WM measures in second grade. The correlations were statistically significant, but were mostly quite low or moderate (r =.29-.69). The strongest correlation was between Listening Span measured in kindergarten and measured again in second grade (r=.69; p<.001).

Table 1

Table 2

Next, a set of multiple regression analyses was carried out to predict WM performance in second grade by WM performance in kindergarten (Table 3). The combined scores for VSWM and VWM were constructed based on a two-factor WM measurement model. In Model One, $VSWM_2$ was predicted by $VSWM_1$ and VWM_1. The results showed that $VSWM_1$ and VWM_1 predicted 13.6% of the variance in $VSWM_2$ but the only statistically significant predictor was $VSWM_1$. In Model Two, VWM_2 was predicted by VWM_1 and $VSWM_1$. The results showed that VWM_1 and $VSWM_1$ predicted 41.6% of the variance in VWM2 but the only significant predictor was VWM_1. Because $VSWM_1$ and VWM_1 correlated significantly with each other (r=.56***), there was a possibility of multicollinearity between independent variables. Therefore, alternate regression analysis was conducted. First, $VSWM_2$ was predicted by VWM_1 and $VSWM_1$ so that VWM_1 was forced first into the equation. VWM_1 did not predict performance in $VSWM_2$, even though it was forced as first into the equation ($F = 2.04$; $R^2 = .03$; $\beta = .181$, $t = 1.43$). The same result appeared when VWM_2 was predicted by $VSWM_1$ and VWM_1. $VSWM_1$ did not predict VWM_2 even though it was forced as first into the equation ($F = 3.33$; $R^2 = .05$; $\beta = .229$, $t = 1.83$).

Table 3

Finally, the stability of differences in WM skills was investigated by comparing how participating children ranked in skill groups at two different time points (Table 4). The participating children were divided into three groups based on their combined score in all WM tasks at two time points (Group One (good) ≥ 75 percentile; 75 percentile > Group Two (moderate) ≥ 25 percentile; Group Three (poor) < 25 percentile). Based on crosstabs (Table 2), 57% of the participants (35/61) fell into the same category at both time points. All the transitions between categories were one-step transitions. That is, none of the participants who fell into Group One at T_1 fell into Group Three at T_2, or vice versa. Eight of the 61 participants (13%) fell into Group Three at both time points. Eight out of nine participants (89%) who were placed in Group Three in kindergarten were placed in the same group two years later. Eight out of 61 participants (13%) were placed in Group One at both time points. Eight out of 15 participants (53%) who were placed in Group One when in kindergarten were in the same group two years later. The same comparison was also carried out separately for boys and girls. Five out of 36 boys (14%) fell into Group Three (poor performance) at both time points. Four of the nine boys who were placed into Group Three in kindergarten were placed into Group Two in second grade. Three out of 36 boys (8%) were placed into Group One at both time points. Five girls out of 25 (20%) were in Group Three at both time points. The same number of girls (5/25, or 20%) were ranked in Group One at both time points.

Table 4

To What Extent Do WM Skills Measured at Kindergarten Predict Counting Skills, Basic Arithmetic Skills, and Word Problem Solving Skills at Second Grade?

In the first step, correlations between VWM and VSWM at both time points and both basic arithmetical skills and word problem skills, as well as word decoding skills and reading comprehension, were inspected (Table 5). From the WM tasks measured at kindergarten age, both VWM_1 (r =.40**) and $VSWM_1$ (r =.32*) correlated with math word problems. $VSWM_1$ correlated with word decoding in second grade (r =.29*), and VWM_1 with reading comprehension in second grade (r =.28*). At the second-grade level, VWM_2 correlated with both arithmetic (r =.30*) and math word problems (r =.37**), as well as word decoding (r =.42**) and reading comprehension (r =.45***). $VSWM_2$ correlated with arithmetic (r =.31*), word decoding, (r =.54***), and reading comprehension (r =.32*).

Table 5

In the second step, a set of multiple regression analyses was carried out to predict academic skills in second grade (Table 3). For each analysis, only those WM variables that correlated with given second grade academic skills were chosen as potential predictors. The regression models of two different time points were analysed separately. $VSWM_2$ and VWM_2 predicted 14% of the variance in basic arithmetic tasks (Model Three). However, probably due to a significant correlation (r =.32**) between these two predictors, neither of these appeared to be a significant predictor when included in the same model. When these variables were alternately forced first into the equation, both $VSWM_2$ (R^2 =.10; F = 6.20*; β =.308, t = 2.49*) and VWM_2 (R^2 =.09; F = 5.71*; β =.297, t = 2.39*) predicted basic arithmetic skills significantly. This may mean that the relationship between WM_2 resources and arithmetic skills has more to do with general CE resources, common to both VSWM and VWM tasks, and less with modality-specific visuospatial or verbal storage resources.

Math word problems (Model Four) were predicted by $VSWM_1$ and VWM_1. They predicted 18% of the variance in math word problem tasks, but the only significant predictor was VWM_1. Two alternate models, when $VSWM_1$ and VWM_1 were forced as first into the equation, were calculated. When forced as first, $VSWM_1$ predicted 10 % (R^2 =.10; F = 5.29* β =.318, t = 2.30*) of the variance in word problem tasks. When forced as first, VWM_1 predicted 14 % of the variance in math word problems (R^2 =.16; F = 9.00** β =.401, t = 3.00**). In the second grade, only VWM_2 correlated with math word problems. It predicted 14 % of the variance in word problem tasks. Even though both $VSWM_1$ and VWM_1 correlated with word decoding, they did not predict word decoding skills significantly (R^2 =.08; F = 2.89; p =.063). The same WM resources, two years later (Model Five), predicted 36 % of the variance in the word decoding test, and both $VSWM_2$ and VWM_2 were significant predictors. When forced first, $VSWM_2$ predicted 29% of the variance in word decoding (R^2 =.29; F = 23.82*** β =.540, t = 4.88***).and VWM_2 18% (R^2 =.18; F = 12.69** β =.424, t =

3.56**). $VSWM_2$ and VWM_2 predicted 23% of the variance in reading comprehension, with only VWM_2 being a significant predictor. When forced as first into the equation, $VSWM_2$ predicted 10% of the variance in reading comprehension (R^2 =.10; F = 6.95*; β =.322, t = 2.64*), and VWM_2 20% (R^2 =.20; F = 15.20*** β =.450, t = 3.90***).

Finally, we tested whether the participants in different WM skill groups at kindergarten age differed in their later academic skills in second grade. The results of one-way ANOVAs showed that the there was a statistically significant difference in academic performance based on children's WM performance in kindergarten (F (4, 112) = 2.93, p <.01; partial η^2 =.22). The three WM skill groups showed statistically significant differences in math word problems, word decoding, and reading comprehension (Table 6). Post hoc Scheffe tests showed that, in math word problems, Group One (good performance) differed from Groups Two and Three. Group Two (moderate performance) did not differ from Group Three (poor performance) statistically significantly. In word decoding, Group Three (poor performance) differed statistically significantly from the other groups that did not differ from another. In reading comprehension, Group One (good performance) and Group Three (poor performance) differed from one another.

Table 6

Discussion

The aim of this longitudinal study was to investigate the extent to which WM measured in kindergarten predicts WM skills measured in second grade (stability of individual WM progress), and to what extent these kindergarten WM skills predict later academic skills in second grade. Our results show that WM skills significantly increase during this time span from Finnish kindergarten (6- to 7-year-olds) to second grade (8- to 9-year-olds) which corresponds to previous results (e.g., Gathercole, et al., 2004; Wilson, Scott,

& Power, 1987). As suggested earlier (Alloway & Alloway, 2010), individual differences seem to show some stability. Sixty-two percent of the participants were ranked in the same skill group at two time points. Sixteen percent of all the participants were classified in the poor performance group at both time points. All the WM tasks, except for the Block Task, correlated with the same measures two years later, which suggests that these tasks predict performance in the same tasks two years later. However, it must be noted that the correlation coefficients were mostly quite low or moderate in high. The most stable predictor at this age phase seems to be Listening Span, which is used to measure verbal CE.

As suggested before (Gathercole, Pickering, Ambridge, & Wearing, 2004), verbal and visuospatial WM resources seem to develop quite independently. VSWM resources measured at kindergarten age predicted VSWM resources in second grade but not VWM resources at the same age, and vice versa. In general, VWM skills seem to show more stability at this age phase than VSWM skills. This stability does not mean that the VWM skills would not have developed as, at first, ANOVA showed that VWM skills did increase between the two measurement time points. Instead, it means that the development of VWM is more straightforward and predictable based on kindergarten performance. This finding is notable, considering that between the ages of seven and eleven, children begin to prioritise VWM resources (Andersson & Lyxell, 2007; McKenzie, Bull, & Gray, 2003; Rasmussen & Bisanz, 2005). Thus, VWM resources become a more important information processing tool or resource in this age phase.

The same modality-specific WM model seems to fit to the data at both time points. This does not necessarily mean that a two-factor solution would be the best to theoretically model WM functions. It only means that it is empirically, on a WM task level, almost impossible to separate CE functions from short-term storage functions as previously suggested by Duff & Logie, (2001). Thus, CE tasks are almost inevitably dependent on either verbal or visuospatial storage resources. It seems that, at least in this age phase, CE tasks are quite dependent on storage resources. However, it is important to note that, based on our data, WM models that separate WM resources modality-specifically into visuospatial and verbal ones, such as Baddeley's (1986, 2000) or Cornoldi and Vecchi's (2003), seem to be an important starting point when furthering our understanding of children's WM skills and their significance in learning, for instance.

Our second research question addressed the extent to which WM measured at kindergarten predicts academic performance at second grade in the Finnish educational context. In Finland, school starts later than in many other countries. Finnish children begin kindergarten in the year they turn six, and formal schooling in the year they turn seven. That is, when they start school and begin to participate in formal reading and mathematics instruction, their WM resources should be more developed than those of children who start their school earlier. As observed before (Passolunghi, et al., 2008; Östergren, & Träff 2013), WM resources measured just before the start of school predicted later academic performance to some extent in our data, as well. Even though the only significant association between WM and subsequent academic skills in regression analysis was between VWM and math word problems, our results also show that children from various WM skills groups in kindergarten perform differently in math word problems, word decoding, and reading comprehension two years later. In math word problems, the group with good WM performance performed significantly better than the groups with moderate or poor performance. In decoding, the group with poor performance differed significantly from the other two groups. Thus, it seems that good overall WM skills at kindergarten age predict good math word problem solving skills two years later. Further, poor overall WM skills at kindergarten age predict poor decoding skills two years later. In second grade, both VSWM and VWM skills seem to be an important factor behind decoding performance, since they predict 36% of its variation. This is in line with previous studies (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Cain, Oakhill, & Bryant, 2004), showing that WM resources are needed in decoding. It is possible that this relationship is even more visible in the second school grade when *most* of the Finnish children are able to read accurately (see Aro, 2006).

Certain limitations should be noted. First, our sample size was quite small. A larger sample size would have enabled us to use more sophisticated analysis methods, like SEM, in predicting later academic skills. Second, the number of WM indicators was limited. Even though the measures used in our study have previously been found to be good indicators of WM (Alloway, 2007), using additional measures of WM components (e.g. more AWMA subtasks) would provide an even more reliable and versatile assessment of WM skills, considering that the relationship between WM and academic skills has previously varied as a function of WM subskill/measure (see, e.g. Peng, Namkung, Barnes, & Sun, 2015)

Conclusions

In conclusion, our results show that WM skills significantly increase during the time span from Finnish kindergarten (six- to seven-year-olds) to second grade (eight- to nine-year-olds), verbal and visuospatial WM resources seem to develop quite independently, and individual progress seem to show some stability. WM resources measured just before school start predicted later academic performance, and VWM seems to be a more powerful predictor than VSWM resources. This probably has to do with the fact that they seem to develop with more stability in this age phase. It is obvious, based on our study that many children who have weaker WM skills than their age-mates in kindergarten also lag behind later in school. Based on this study and on previous studies (e.g. Pham & Hasson, 2014; Toll et al., 2011), it seems obvious that poor WM skills restrain learning of (basic) academic skills. This has at least three potential educational implications: first, WM difficulties should be identified as early as possible. Thus, teachers and other professionals working with preschool and kindergarten age children should have the skills to assess students' skills. Second, individual or group-based intervention directed towards enhancing children's WM skills would be most important when provided before the start of school; and, third, since the effects of intervention programmes and methods are proven to be controversial (Melby-Lervåg & Hulme, 2013; Shipstead et al., 2012), poor WM skills should be given attention from an early age when planning the learning environment. The problems that result from poor WM are problems mostly because of our methods of teaching and that the learning environment does not support all individuals. In future studies, how the learning environment can support WM should be systematically investigated.

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Table 1. Descriptive statistics for WM measures and academic skills at two time points

	Kindergarten (N=94)		2nd Grade (N=77)			
Measure	M	SD	M	SD	F	η_p^2
Dot Matrix	16.92	4.79	22.60	4.39	66.78***	.52
Block Task	16.77	5.26	21.42	4.10	39.01***	.39
Odd-One-Out	14.81	4.25	20.05	4.46	66.13***	.52
Word Span	18.60	3.32	21.74	2.56	57.23***	.48
Nonword Span	11.02	3.72	18.40	2.96	234.87***	.79
Listening Span	6.60	3.17	12.06	2.78	333.14***	.85
Arithmetics	-	-	25.35	6.51	-	-
Word Problems	-	-	2.63	1.36	-	-
Word Decoding	-	-	52.21	33.74	-	-
Reading comprehension	-	-	18.53	3.59	-	-

Note. ***p<.001.

Table 2. Correlations between WM measures at two time points

	2nd Grade					
Kindergarten	1	2	3	4	5	6
1 Dot Matrix	**.29***	.28*	.26*	.11	.12	.10
2 Block Task	.23	**.24**	.28*	.13	.17	.32*
3 Odd-One-Out	.18	.36**	**.32***	.18	.18	.19
4 Word Span	.02	-.16	-.04	**.40****	.36**	.30*
5 Nonword Span	.11	.10	-.06	.44***	**.37****	.18
6 Listening Span	.45***	.16	.45***	.37**	.45***	**.69*****

Note. N = 77. ***p<.001, **p<.01, *p<.05.

Table 3. Summary of Hierarchical Regression Analysis for Variables Predicting WM performance and academic skills in second grade

Variable		β	t
Model 1	VSWM$_2$		
VSWM$_1$		.375	2.65*
VWM$_1$		-.012	-.08
F = 4.65*; R^2 = .14			
Model 2	VWM$_2$		
VSWM$_1$		-.133	-1.15
VWM$_1$		.704	6.06***
F = 21.04***; R^2 = .42			
Model 3	Basic Arithmetics		
VSWM$_2$		.238	1.85
VWM$_2$		.222	1.73
F = 4.69*; R^2 = .14			
Model 4	Math Word Problems		
VSWM$_1$		.150	.96
VWM$_1$		.323	2.06*
F = 4.95*; R^2 = .18			
Model 5	Word Decoding		
VSWM$_2$		.450	4.03***
VWM$_2$		.280	2.51*
F = 16.14***; R^2 = .36			
Model 6	Reading Comprehension		
VSWM$_2$		.191	1.58
VWM$_2$		.384	3.17**
F = 9.03***; R^2 = .23			

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

Table 4. The stability of WM skills at two time points

	2nd grade			
		Good	Moderate	Low
X^2=24.74***		*M*=22.24; *SD*=1.46	*M*=19.47; *SD*=.71	*M*=16.88; *SD*=1.67
Kindergarten	Good *M*=17.06; *SD*=1.21	8	7	0
	Moderate *M*=13.98; *SD*=1.06	7	19	11
	Low *M*=10.54; *SD*=2.37	0	1	8

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

Table 5. Correlations between WM performance and academic skills

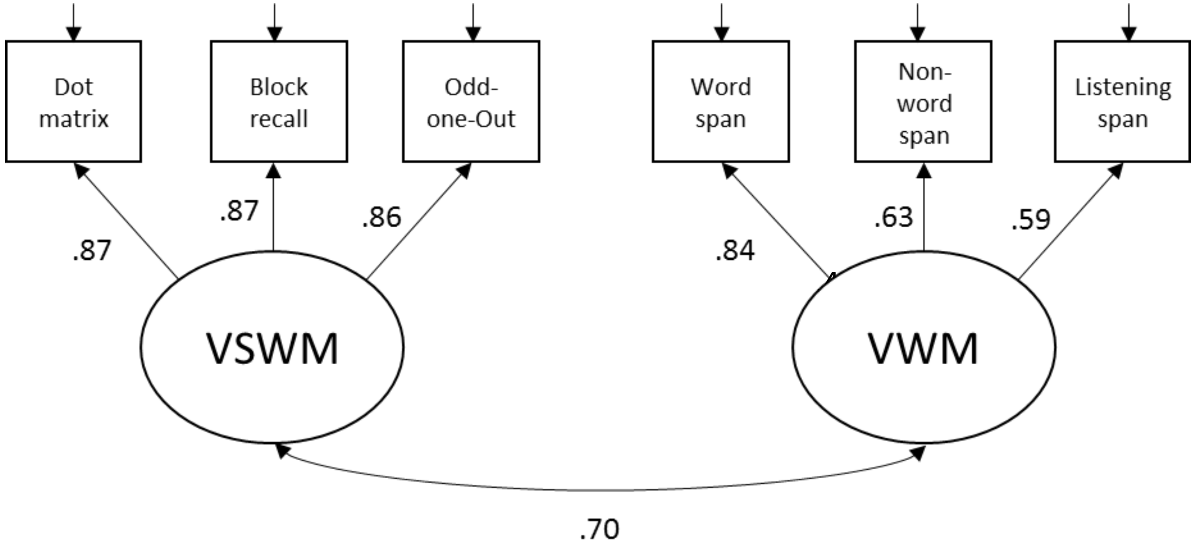
	$VSWM_1$	VWM_1	$VSWM_2$	VWM_2
Basic arithmetics	.18	.20	.31*	.30*
Word problem	.32*	.40**	.20	.37**
Word decoding	.23*	.25*	.53***	.43***
Reading comprehension	.14	.15	.32*	.45***

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

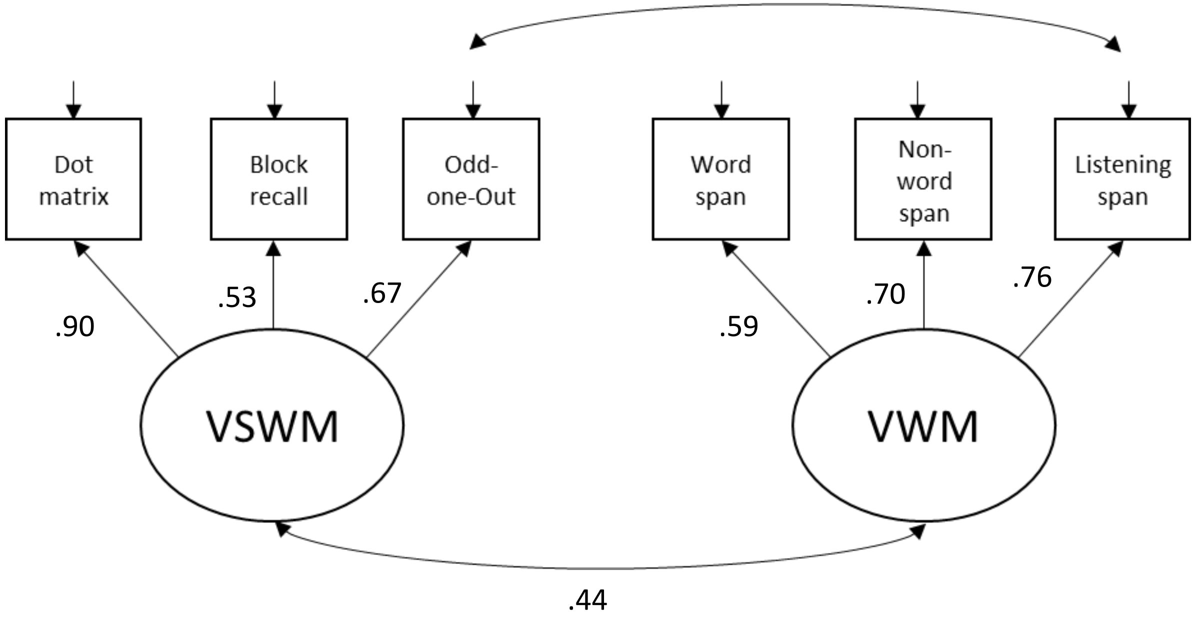
Table 6. Later academic performance of different WM kindergarten skill groups

	Good		Moderate		Low			
Measure	*M*	*Sd*	*M*	*Sd*	*M*	*Sd*	*F*	η_p^2
Basic arithmetics	28.92	1.51	26.96	1.05	23.29	2.06	2.44	.10
Word problems	3.85	0.32	2.48	0.22	1.57	0.43	10.31***	.32
Word decoding	82.62	8.01	59.15	5.56	34.86	10.92	6.53**	.23
Reading comprehension	20.69	0.83	18.78	0.58	17.00	1.13	3.70*	.14

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



Kindergarten



Second grade

Figure 1