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Three functional aspects of working memory as strong predictors of early school achievements: The review and illustrative evidence

Abstract: *The paper presents an overview of research on working memory as a predictor of early school achievements. We contrast two main areas of research on the role of working memory in school achievements: the first concerns the structural model of working memory and the second focuses on executive functions. Then, we discuss the facet model of working memory as a promising approach merging the two research branches on working memory tasks as predictors of early school achievements. At the end we present exemplary results of the research conducted on a national sample of six- and seven-year-olds in Poland, which indicates strong relation of working memory functions with the measures of competences in mathematics, reading, and writing. Additionally, the mediation analyses, with parents' education as a covariate, indicate that the influence of age on achievements in math, reading, and writing in six- and seven-year olds is mediated by working memory functions.*

Key words: *working memory, early school achievement, executive functions, 6–7-year olds*

1. Introduction: importance of working memory tasks in educational research

Working memory is typically defined as the maintenance of a small amount of information in a highly accessible form that can be used in execution of demanding cognitive tasks (e.g., Conway, Jarrold, Kane, Miyake, & Towse, 2007; Cowan, 2014; Miyake & Shah, 1999). To a great extent, working memory is associated with basic cognitive factors such as fluid intelligence, and it is an important mediator and moderator in cognitive psychopathology and cognitive aging (Engle, Sedek, von Hecker, & McIntosh, 2005; Sedek & von Hecker, 2004; von Hecker, Sedek, & Brzezicka, 2013). Working memory is necessary to reason effectively, make decisions and function in day-to-day activities (e.g., Carpenter, Just, & Shell, 1990; de Jong & Das-Smaal, 1995; Engle, Kane, & Tucholski, 1999; Schatz, Kramer, Ablin, & Matthay, 2000).

The concept of working memory has been successfully introduced to educational psychology. Popularity and significance of working memory tasks in educational research result from the fact that these tasks enable researchers to separate the cognitive potential of a child (mainly the effectiveness of interplay between memory and executive attention) from the general knowledge already mastered by that child (see reviews: Case, 1985; Cowan, 2014; Gathercole, Pickering, Ambridge, & Wearing, 2004; Halford, Cowan, & Andrews, 2007; Phye & Pickering, 2006; St. Clair-Thompson & Gathercole, 2006).

By and large, the available research suggests that various indicators of working memory are associated with the results of a number of achievement tests, e.g., mathematics, reading, and comprehension abilities (see Unsworth, Heitz, & Engle, 2005 for a review). Capacity

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and functions of working memory are strongly associated with the effectiveness of learning, mental processes of text comprehension and reading (e.g., Baddeley, 1986; Daneman & Carpenter, 1980; Perfetti, 1985), speech production (e.g., Peña & Tirre, 1992; Shute & Kyllonen, 1990; Tirre, 1991; Woltz, 1988), arithmetic word problems (e.g., Swanson & Beebe-Frankenberger, 2004), and computational skills (e.g., Bull & Scerif, 2001).

Much of the educational research examined cognitive functioning by incorporating a broad range of tasks to estimate working memory. A representative example of such research is the study by Gathercole and Pickering (2000) who used a battery of 13 tests to assess working memory among 6–7 year olds. Although we greatly value such research, we also acknowledge its limitations. Testing young children with more than 10 different tasks to assess working memory is very demanding in terms of time and resources.

In this paper, we propose a simplified and short test (its completion takes less than 12 minutes) consisting of 3 tasks to assess functional aspects of working memory and we show that it is both reliable instrument and strong predictor of early school achievement.

1.1. Working memory tasks inspired by the structural model of working memory as predictors of early school achievements

The review of working memory research should begin with Baddeley and Hitch (1974) who proposed a very influential structural model of working memory. The model describes central executive system, associated with controlled processing and attention, which coordinates operations of two subsystems: a phonological loop (a temporary store and a rehearsal mechanism for speech-based material), and a visuospatial sketchpad for visuospatial-based information (Baddeley, 1986). These components are of limited capacity but they are relatively independent. Assessment of sub-systems is usually made by using short-term memory tasks e.g., digit span, word recall, visual-patterns tasks. More recently, this model was extended by adding another component, the episodic buffer, which is responsible for integrating information from different sources of the cognitive system, including long-term memory (Baddeley, 2000; Baddeley & Logie, 1999).

The first measure of central executive was reading span proposed by Daneman and Carpenter in 1980. In the reading or listening recall task a child was to read/listen to a number of short sentences and indicate whether they were true or false. After the last sentence, the task was to recall the last words of all sentences in the order they originally appeared. The span score is the number of correctly recalled words. With the increasing popularity of working memory, a wide variety of other working memory measures became available all of which to some extent require processing and storage of information at the same time (e.g., Kyllonen & Christal, 1990; Oberauer, Süß, Schulze, Wilhelm, & Wittman, 2000; Pickering & Gathercole, 2001).

In the context of educational studies, Gathercole and collaborators is one of the leading research teams verifying predictive validity of working memory tasks within the framework of Baddeley's structural model. For example, Gathercole and Pickering (2000) examined associations between school achievements of 6 and-7-year-old children and measures verifying the structural model of working memory. The battery included 13 tasks: six phonological loop, four visuospatial memory, and three central executive measures. Performance on phonological loop tasks and central executive tasks was highly correlated; however, central executive measures had a broader predictive value. Central executive measures were related to literacy and arithmetic achievements even a year after the testing, whereas phonological tests were uniquely related to vocabulary performance. The study provided little evidence that visuospatial tasks, at least for the sample of 6–7 year olds, shared a unique variability with the attainment tasks. Gathercole and Pickering (2000) suggested that the central executive has housekeeping duties within the working memory system; therefore tasks measuring its capacity are also tapping functions of phonological loop and visuospatial sketchpad.

In a different study, Gathercole, Pickering, Knight, and Stegmann (2004) demonstrated that based on scores of central executive tasks it was possible to correctly differentiate between different levels of school abilities. The authors administered two central executive tests (backward digit recall, listening recall) and two phonological loop measures (digit recall and word list matching) from Working Memory Battery for Children (Pickering & Gathercole, 2001) to assess the capacity of working memory. However, they did not include visuospatial tasks. School performance measures included language, mathematics, and science achievement scores. In line with expectations, children with low, medium, and high performance on achievement tests differed significantly in average performance on central executive tasks. What is even more important, based on the working memory scores, over 80% of children were correctly classified into ability groups, discriminating children with low ability from the rest of the sample. For the older children, more specific relations were observed. Only mathematics and science achievements were strongly related with working memory scores, with task scores significantly differing between ability groups. On the other hand, the associations with language performance and working memory tests were low and not discriminative. Overall, the findings clearly pointed at dominative predictive value of central executive tasks and suggested that working memory capacity puts constrains on academic performance.

In a longitudinal study, Alloway & Alloway (2010) reported that working memory at the age of 5 was a more powerful predictor of academic achievement 6 years later than crystallized intelligence. Working memory was assessed using listening recall, while verbal short-term memory was assessed using digit recall and word recall. Working memory skills were uniquely related to learning outcomes at the age of 11. The results demonstrated that working memory cannot be reduced to intelligence but it rather represents a dissociable cognitive ability with unique contributions to learning.

1.2. Measures of working memory as the part of broader executive function tests

The crucial role of central executive tasks in predicting cognitive functioning shifted attention of scientists toward functional aspects of this working memory system. Baddeley (1998) suggested coordination of multiple tasks, shifting between tasks, and selectivity of attention as the main functions of central executive system. These aspects of central executive map three executive functions proposed by Miyake, Friedman, Emerson, Witzki, and Howerter (2000), which are shifting, updating, and inhibiting. A more recent focus on functional aspects of central executive system (Baddeley 1996; Miyake et al., 2000) tends to put measures of central executive under the umbrella of executive functions tasks. In fact in developmental psychology, working memory measures are quite often classified as executive functions tasks (e.g., Carlson, 2005; Roebers, Röthlisberger, Cimeli, Michel, & Neuenschwander, 2011; Röthlisberger, Neuenschwander, Cimeli, Michel, & Roebers, 2012).

Definitions of executive functions largely overlap with functional definitions of working memory and these functions are generally referred to as different higher-order cognitive processes in the service of changing demands of various and multiple tasks. Under the umbrella term of executive functions, scientists enumerate inhibition of attention and behavioral responses (Diamond, Carlson, & Beck, 2005), cognitive flexibility (i.e., attentional switching; Miyake et al., 2000), and updating which is closely related to Baddeley's concept of working memory.

Replicated findings have shown that working memory tests supplemented by a variety of executive functions components (such as shifting, inhibiting, updating, interference control, or cognitive flexibility) are important factors predicting development of school competences in early childhood. Such measures account for substantial variance in assessing school readiness (Blair, 2002; Garon, Bryson, & Smith, 2008; Welsh, Nix, Blair, Bierman, & Nelson, 2010) and school achievements (Bialystok & Craik, 2006; Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Clark, Pritchard, & Woodward, 2010). Below we describe representative recent research in this field.

For example, St. Clair-Thompson and Gathercole (2006) included executive functions and capacity measures of working memory to investigate whether updating, shifting, and inhibition underline performance on working memory span tasks, as well as to assess the unique contribution of executive functions in predicting academic achievement. Eleven- and twelve-year-old children performed six executive tasks (two for each function: shifting, updating, and inhibition), and four working memory span tasks (two for each: verbal and visuospatial memory). Standardized tests in language, mathematics, and science were used as indices of school achievement. As a result of factor analysis, updating and working memory tasks were averaged to constitute one factor, separate from inhibition, and shifting tasks were excluded from further analyses. The results of partial correlations indicated that after controlling for working memory, inhibition was related to language, mathematics, and science performance, whereas working memory related to language and mathematics after inhibition was partialled out. In the domain specific working memory, visuospatial tasks showed stronger relationships with scholastic attainment than verbal tasks, which related only to language performance.

Bull and colleagues (2008) examined the role of working memory, executive functions, and short-term memory among preschoolers in explaining later school achievement level. The authors used the Shape School and Tower of London tasks as central executive measure, Corsi Blocks and Digit Span tasks as measures of short-term and working memory respectively. Children's academic achievement level of basic phonics, number, and reading skills were predicted. The authors reported that higher scores of executive functions and working memory were associated with better math and reading achievement scores for three consecutive school years. Working memory and visual short-term memory predicted mathematics performance at each level, whereas executive functions predicted general learning abilities.

In another study, Roebers et al. (2011) investigated developmental changes in updating, inhibition, and cognitive flexibility and verified contribution of the executive functions to pre-academic achievement among 5–7 year old children. The authors used the fruit Stroop task (Archibald & Kerns, 1999) as the measure of inhibition, the backwards color recall task (Schmid, Zoelch, & Roebers, 2008) for updating defined as working memory function, and a measure of cognitive flexibility (Zimmermann, Gondan, & Fimm 2004). Performance on all three functions improved over a year and the study demonstrated that inhibition and updating contributed significantly to the prediction of early academic performance.

Finally, Röthlisberger and collaborators (2012) in their intervention study on 5- and 6-year-olds focused on working memory, interference control, and cognitive flexibility. The intervention program included nineteen tasks based on executive function measures, such as Stroop task (Stroop, 1935), listening recall task, mazes memory task (Pickering & Gathercole, 2001), dimensional card sorting (Carlson, 2005), and trail making test (Reitan, 1958). The authors used the flanker and span tasks (Roebers & Kauer, 2009) as the pre-test and post-test measures. The research indicated improvement followed by the intervention program: 5-year-olds improved their working memory and cognitive flexibility functions, while improvement of interference control was found among 6-year-old children.

The common feature of these and other working memory studies is a complex procedure including multitude of tasks. With the overwhelming variety of different measures, working memory score is built on averaged score across several tasks whose configuration often changes.

Although in the discussed studies, the overall pattern of results is similar, working memory as a composite measure positively relates to school achievement, various nuances which are task dependent emerge e.g., visuospatial tasks are or are not effective predictors, updating is or is not a part of working memory model. Nevertheless, central executive tasks consistently relate to academic performance and also share variance with a broader concept of executive functions.

Tasks which refer to working memory differ in the source of variance which can explain differences in the correlations between ability tests and various measures of working memory. Therefore, we would like to present data in support of a theoretical framework, which unifies working memory and executive functions approaches under the facet model of working memory, developed by Klaus Oberauer and his associates (Oberauer et al., 2000; Oberauer, Süß, Wilhelm, & Wittman, 2003).

2. Functional facets of working memory

Working memory in the facet model is understood more broadly, as a set of factors that limit execution of complex cognitive tasks (Oberauer et al., 2003). Oberauer postulated that in order to measure aspects of working memory, it is extremely important to select complementing tasks to render the functional complexity of the construct of working memory (Kane et al., 2004; Oberauer et al., 2003). On the basis of the factor analysis results, Oberauer et al. (2003) distinguished a set of three mutually related cognitive functions: simultaneous storage and processing, supervision, and coordination (recently renamed to relational integration: Lewandowsky, Oberauer, Yang, & Ecker, 2010; Oberauer, Süß, Wilhelm, & Wittman, 2008).

Simultaneous storage and processing refers directly to the leading definition of working memory (e.g., Daneman & Carpenter, 1980; Kyllonen & Christal, 1990; Salthouse, 1991). Processing is understood here as transforming information which is new or retrieved from long-term memory; this in turn may lead to creating a new content. Storage, on the other hand, is keeping available briefly presented new information over a period of time.

The function of supervision is responsible for monitoring and control of running cognitive operations by means of selective activation of relevant content and procedures, as well as inhibition of the insignificant ones. This understanding of the supervision function is conceptually most similar to the central executive system, in accordance with the Baddeley's model (1986).

Relational integration of elements into structures (Lewandowsky et al., 2010; Oberauer et al., 2008) is the third of the functional aspects of working memory. This is an ability to create higher order structures from available elements, new connections between already stored information and content presented at a given moment. During the course of creating a mental structure, simultaneous activation of its individual parts takes place.

When combined into a unitary composite variable, these three functions constitute a measure of working memory, which includes features of central executive system and executive functions. In the study on a representative sample of 1376 children in Poland, we verified the predictive value of this unitary construct of working memory composed of three tasks best representing the three working memory functions (detailed empirical report, Sedek, Krejtz, Rycielski, Kaczan & Rydzewska, 2015).

Selecting tasks for measuring individual functions of working memory of 6–7-year-olds we adapted tasks from the battery of experimental procedures used by Klaus Oberauer et al. (2000, 2003) that on one hand are possibly precise measures of a given function of working memory and on the other – are realistic to be completed by a typical child, aged 6–7.

Tasks that refer to working memory are very cognitively demanding – they require high and concurrent mobilization of attentional and memory systems; consequently, they could quickly become exhausting and wearisome for children aged 6 and 7. Therefore, we have attempted to make these tasks very short in duration and visually more attractive (see Table 1 for selected descriptive statistics). We aimed at the tasks not to be taking excessive amount of time to be explained and executed, and at the number of tasks themselves not being excessively large either (hence, limitation of the number of tasks to three), so that the Functional Aspects of Working Memory Test (FAWMT) could be effectively included in a more general educational research. The ultimate goal was to select one most effective task for each of the three working memory functions. Below we present short description of the three tasks included in FAWMT.

Table 1. Descriptive statistics of FAWMT (Functional Aspects of Working Memory Test): Number of trials, total duration time, and Cronbach's alpha

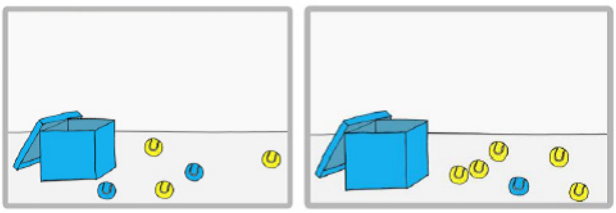
Functional Aspect of Working memory	Number of trials	Total time (in minutes)	Cronbach's alpha
Simultaneous storage and processing (counting span)	14	4.62	.754
Supervising (set switching task 2x2)	48	4.55	.911
Relational integration (spatial location memory task)	28	2.56	.753

Note: The descriptive statistics based on national random sample (N = 1376) of Polish 6–7 years old children.

2.1. Simultaneous storage and processing function of working memory

After Oberauer et al. (2000), we operationalized simultaneous storage and processing function with an adaptation of counting span task which is the most frequently used measure of children's working memory capacity (detailed reviews: Case, Kurland, & Goldberg, 1982; Conway et al., 2005; Cowan et al., 2003). In this version of the counting span (see Figure 1), a child's task is to count balls of the color of the box, and ignore the balls of a different color but the same size, then remember the number; subsequently, count balls of a specific color (ignore others), and remember their number from the next chart. The number of charts grows up to 5. At the end, the child is to recall the number of relevant balls in the order of occurrence from all presented charts. We can see the specificity of the working memory task: it is not enough to just remember information. Concurrently, inhibition of unnecessary information is taking place as well as attentional coordination of information which is supposed to be remembered for each given chart. Additionally, the task itself does not require any specific knowledge; elements such as balls and boxes are well known, and counting to five is also a well-mastered activity. What constitutes proper completion of this task is not an appropriate knowledge level, but an appropriate level of the ability to remember specific elements while processing in the midst of competing operations. A proportion of properly remembered elements in their appropriate order is a basic measure of completing this task.

Figure 1. Counting span task (simultaneous storage and processing function of working memory)



2.2. Supervision function of working memory

While operationalizing the supervision function, we adapted the set switching task 2 x 2 (Rogers & Monsell, 1995). This task is strongly associated with switching, one of the executive functions distinguished by Miyake et al. (2000). The task requires inhibition of an active operating scheme in order for another script to be initiated (see Figure 2). Children are presented with images of a boy and a girl who are either happy or sad. The faces are shown sequentially in a clockwise direction. Depending on the auditorily presented question: "is the face happy?" or "is it a boy?", a child needs to switch between types of categorization. While studying the elements of the task, it is worth to pay attention to its specific requirements. Alternately, we are dealing here with continuous classification of an image on the basis of a given category and switch in categorization (e.g., determining gender on the basis of facial expression). The basic measure in this task is mean proportion of proper classifications (though in the more advanced analyses more attention is paid to the so-called switching costs – an increase in the amount of time needed to properly react to categorization switch).

2.3. Relational integration function of working memory

Tasks that measure the third function of working memory, relational integration, correlate quite strongly with simultaneous storage and processing tasks (Oberauer et al., 2000). However, simultaneous access, activation of all elements does not necessarily assume that these elements undergo manipulation. It is not just an ability to remember a limited number of elements, but to discover the relation in which they are with respect to each other. As Oberauer highlights, relational integration is an attentional function of working memory.

We used spatial location memory task as an indicator of the relational integration function designed by Oberauer et al., (1993, 2008), although we operationalized it in a much more simplified (matrix 6 x 6) and visually more attractive form (see Figure 3). The task is to remember the position of ladybugs appearing sequentially on the matrix. It is worth to note that while studying the elements of the tasks that refer to spatial capacity, there is a number of processes involved in it. First of all, elements to be remembered (ladybugs) do not appear on a 6x6 matrix simultaneously, but sequentially; hence it is important to integrate their location, especially when sequences become longer (between 2 and 5 elements), as well as to remember their respective location (see Figure 3). The overall measure is the mean accuracy of the remembered structure understood here as the distance between presented elements. The better the memory of distances between presented elements, the higher the value of accuracy index.

Figure 2. Set switching task 2x2 (supervising function of working memory)

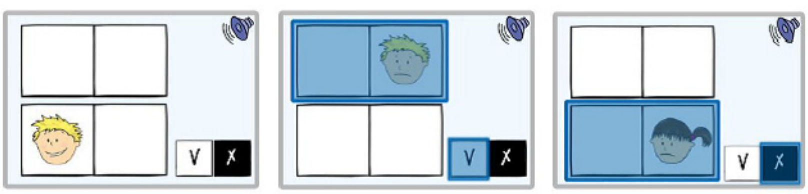
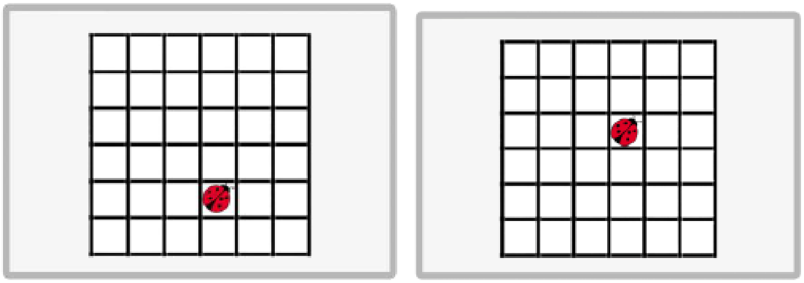


Figure 3. Spatial location memory task (relational integration function of working memory)



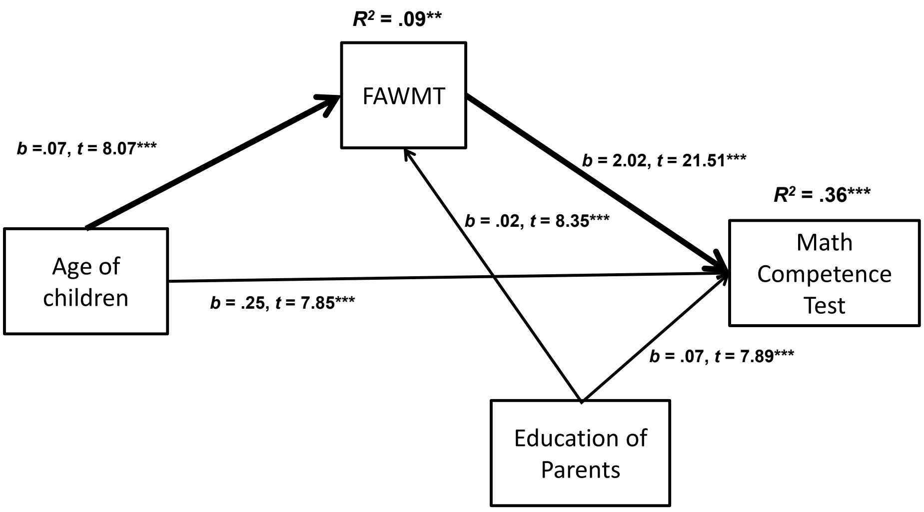
3. The Functional Aspects of Working Memory Test as predictors of early school achievement

As we illustrate below, the functional facets approach was very effective in our research and we supported the significant role of working memory as an important mediator of the relationship between age and school competence with the use of the IRT (item response theory) methodology.

The competency test consisted of tasks in each of the three domains: mathematics, reading, and writing. For each task, a child chose one out of four possible responses, and was assigned 1 point for the correct answer. The tasks were selected from the TUNSS (*Ability Test at the Start of School*; Karwowski & Dziedziewicz, 2012), using the educational domains which most strongly diversify children aged 6–7, while statistics were based on the item response theory (IRT; Hambleton & Jones, 1993; Hulin, Drasgow, & Parsons, 1983; Walker & Beretvas, 2003). On the basis of scaling the task parameters on the sample of N = 5,000 children, we determined the parameters of each of the TUNSS tasks. Based on these characteristics (difficulty and discrimination), the TUNSS application for each examined child calculates the level of abilities in a given area. That is the reason the mediation models presented below show more advanced indicators of children's abilities (thetas) which refer to mathematics, reading, and writing competences, instead of simple sums of points for each test we used.

The exemplary findings are based on the random national sample (Sedek et al., 2015). The sample is representative on the national level for population of 6 and 7 year olds in Poland. For the sampling frame we used the national ID number registry – in Poland, such number is given at birth (obligatory) and the registry is managed by the Ministry of Internal Affairs. We also used information from the Polish Nomenclature of Territorial Units for Statistics registry (NUTS). We decided for the multistage cluster design, with Hartley-Rao solution conducted in SPSS Power Sample and Complex Sample software (Lehtonen & Pahkinen, 2004). In the first step we created a Probability Proportional to Size sample of NUTS. In the second step, in the selected counties we sampled subjects according to age and educational level.

Figure 4. FAWMT (Functional Aspects of Working Memory Test – mean of standardized values of three functions) as a mediator of the relationship between age and math competence in six- and seven-year old children, with parents' education as a covariate. National random sample (N = 1376) of Polish 6–7 years old children

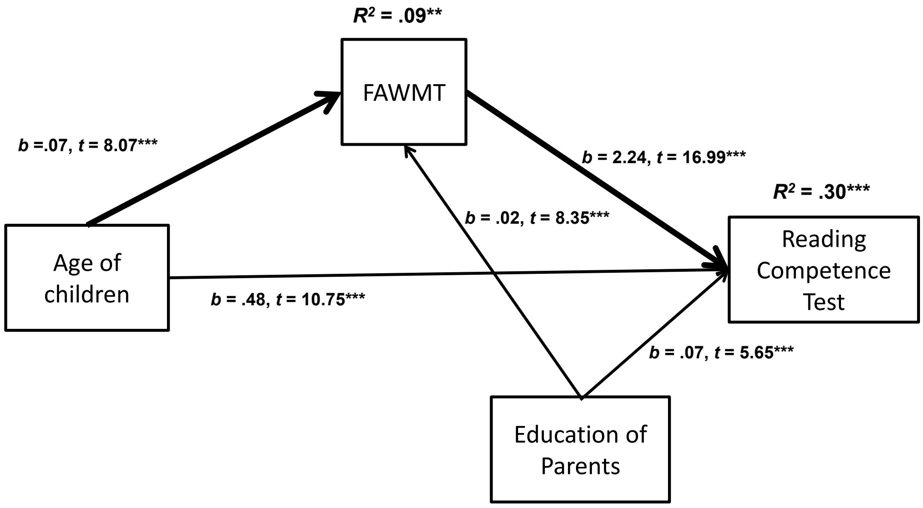


Note: * $p < .05$; ** $p < .01$; *** $p < .001$

We report here three exemplary mediation analyses on the relationship between age and educational achievements based on the modern boot-strapping direct and indirect process analyses developed by Hayes (2013) on the national sample of Polish 6 and 7-year-old children (detailed report, Sedek et al., 2015). In all analyses (see Figure 4, Figure 5, and Figure 6) the composite measure of FAWMT (mean of the three standardized scores of the functional aspects of working memory) was applied as the mediator, while the important measure of SES (social economic status), namely the mean education of parents, was used as a covariate variable.

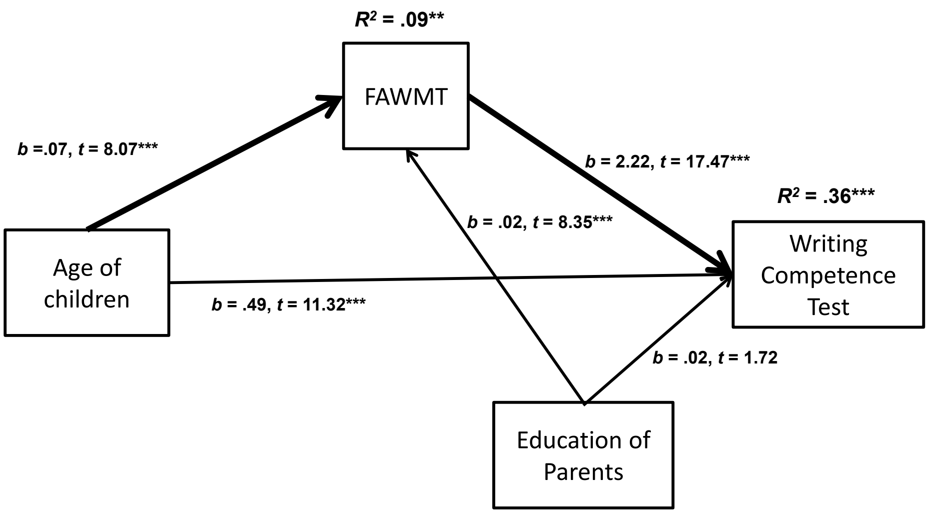
Generally these analyses showed that FAWMT is a very strong predictor of early school achievement in all examined education domains: math, reading, and writing. Interestingly, the mediation analyses showed that in the case of math, reading, and writing competences the indirect effect (via composite measure of FAWMT) of age on pre-school achievements was similarly strong as the direct effect (see Figures 4, 5, and 6). Education of parents was significantly related to working memory and to both math and reading competences. In the case of writing abilities, education of parents was significantly related to working memory but not to writing achievements. The conservative Sobel tests

Figure 5. FAWMT (Functional Aspects of Working Memory Test – mean of standardized values of three functions) as a mediator of the relationship between age and reading competence in six- and seven-year old children, with parents' education as a covariate. National random sample (N = 1376) of Polish 6–7 years old children



Note: * $p < .05$; ** $p < .01$; *** $p < .001$

Figure 6. FAWMT (Functional Aspects of Working Memory Test – mean of standardized values of three functions) as a mediator of the relationship between age and writing competence in six- and seven-year old children, with parents' education as a covariate. National random sample (N = 1376) of Polish 6–7 years old children



Note: * $p < .05$; ** $p < .01$; *** $p < .001$

of mediation were highly significant ($z > 7$; $p < .001$) in all three mediation analyses (without covariate of parents' education). However, there are clear limitations to these mediational analyses: due to data being cross-sectional, the causal developmental interpretation of these findings is not warranted.

4. Summary

The aim of this article was to briefly review the main available research programs on the role of working memory as predictor of early school achievements. We described in some details findings stemming from the Baddeley's structural model of working memory and from broad executive functions research in which working memory measures were included among many other cognitive tests. Next, we showed that the facet model of working memory (e.g., Lewandowsky et al., 2010; Oberauer et al., 2008; Oberauer et al., 2003, von Bastain & Oberauer, 2013) is very promising in dealing with sometimes overwhelming multitude of different tasks, by merging working memory and executive functions into one composite measure applied to assess child potential in early education. We presented exemplary findings based on national random sample (N = 1376) of Polish 6–7 years old children that proved FAWMT (Functional Aspects of Working Memory Test) to be a very strong predictor of early school achievement and showed that the influence of age on educational achievements is partially explained by the improvement in FAWMT, especially in the domains of math, reading, and writing.

Moreover, these findings present scientific evidence for the importance of further development of special training programs dedicated to preschoolers and based on the functional aspects of working memory (for review of the effective training programs, see: Diamond, Barnett, Thomas, & Munro, 2007; Diamond & Lee, 2011; Thorell et al., 2009).

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