Arbeitsgedächtnis bei Kindern: Altersinvarianz der Struktur und Bedeutung für die Entwicklung früher numerischer Kompetenzen

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Einleitung

Zur Vielzahl der Leistungen, die unser Gehirn jeden Tag vollbringt, gehört auch das kurzfristige und aktive Speichern von Information, wie beispielsweise das Memorieren einer Einkaufsliste. Diese kann dabei als Wortsequenz kurzfristig gespeichert werden. Eine Wegbeschreibung hingegen (z.B. zum Supermarkt) lässt sich visuell von einer Karte her einprägen, so dass wir den Weg auf der Karte vor unserem inneren Auge nachvollziehen können. Die visuell aufgenommene Information, zu welcher der Weg auf der Karte gehört, ist aber auch sprachlich umwandelbar („erst links abbiegen, dann rechts, dann die zweite wieder links“). Die Information durchläuft in diesem Fall also einen Transformationsprozess von der visuellen in die phonologische Modalität. Möglicherweise schildert uns jedoch eine andere Person den Weg zum Supermarkt und somit hören wir die Wegbeschreibung lediglich. Da wir gerade noch die Einkaufsliste im Gedächtnis haben, stellen wir uns den Weg lieber auf einer Art inneren Landkarte vor (zusätzlich wiederholen wir vielleicht die Einkaufsliste noch einmal leise). Wir teilen uns die Informationen also in unterschiedliche Modalitäten auf und schaffen so mehr Kapazität für die gesamte Behaltensleistung. Für diese Funktionen des Speicherns, der Transformation und der „Ressourcenverwaltung“ der Speicherkapazitäten ist das Arbeitsgedächtnis zuständig. Aber was versteht man eigentlich unter dem Arbeitsgedächtnis?

Es gibt eine Vielzahl von Definitionen und Modellvorstellungen des Arbeitsgedächtnisses. Diesen ist gemeinsam, dass das Arbeitsgedächtnis als internes kognitives System verstanden wird, welches dafür sorgt, dass mehrere Informationen temporär im Bewusstsein gehalten und dabei miteinander in Beziehung gesetzt werden (Hasselhorn & Schumann-Hengsteler, 2001). Das Arbeitsgedächtnis wird dabei meist funktional definiert und umfasst eine Vielzahl kognitiver Prozesse; so ist es zuständig für das aktive Behalten der Information im Gedächtnis, sowie die Manipulation und Integration dieser Information. Konzeptuell ist das Arbeitsgedächtnis dabei abzugrenzen vom Kurzzeitgedächtnis, welches als passiver Speicher zu verstehen ist.

Der Begriff des Arbeitsgedächtnisses wurde erstmalig von Miller, Galanter und Pribram (1960) in der Zeit des Beginns der kognitiven Wende der akademischen Psychologie gebraucht. Die Ursprünge des Konzepts gehen jedoch bis ins vorvorletzte Jahrhundert zurück. Heutzutage findet sich das Arbeitsgedächtnis in einer Vielzahl von Bereichen der psychologischen Forschung wieder. In ihrer Übersichtsarbeit sprechen Conway, Jarrold, Kane, Miyake und Towse (2007) von mehr als 12 Theorien bzw. Konzeptionen des Arbeitsgedächtnisses, welche in der Forschung aktuell diskutiert werden. Dies spiegelt zum einen die Relevanz dieses Konstrukts und zum anderen auch seine Bandbreite in der Anwendung für unterschiedliche Forschungsbereiche wider. Im entwicklungspsychologisch-pädagogischen Kontext wird die Bedeutung des Arbeitsgedächtnisses unter anderem in seinem Bezug zu unterschiedlichen Bereichen akademischer Leistungen deutlich (z.B. (Baddeley & Logie, 1999; Dehn, 2008; Swanson & Berninger, 1995) wozu vor allem auch die grundlegenden Kulturtechniken Lesen, Schreiben und Rechnen gehören (vgl. Grube & Hasselhorn, 2006; Schuchhardt, Kunze, Grube & Hasselhorn, 2006; Schumann-Hengsteler et al., 2010). Darin grenzt sich das Arbeitsgedächtnis auch vom eingeschränkteren Konzept des Kurzzeitgedächtnisses ab, dessen Indikatoren in geringerem Maße mit schulischen Fertigkeiten zusammenhängen (z.B. Daneman & Merikle, 1996; Jensen & Figueroa, 1975; Perfetti & Goldman, 1976).

Die vorliegende Dissertation setzt sich aus drei in Relation stehenden Arbeiten zusammen. Die erste Veröffentlichung ist ein Buchkapitel (Michalczyk & Hasselhorn, 2010), in welchem eine Einführung zum Arbeitsgedächtnis als Forschungsgegenstand in der Entwicklungspsychologie gegeben wird. Zwei Aspekte des Buchkapitels – die Entwicklung der Arbeitsgedächtnisstruktur und der Zusammenhang des Arbeitsgedächtnisses mit der vorschulischen numerischen Kompetenzentwicklung – werden im Laufe der Arbeit weiter durch die Darstellung des aktuellen Forschungsstandes vertieft. Aus diesen Vertiefungen heraus werden die Fragestellungen entwickelt, welche die Grundlagen für die eigenen empirischen Arbeiten darstellen. Ausgehend von dem Modell der Mehrkomponentenstruktur des Arbeitsgedächtnisses nach Baddeley (1986) prüft die erste eigene empirische Arbeit (Michalczyk, Malstädt, Worgt & Hasselhorn, Einladung zur Resubmission bei European Journal of Psychological Assessment, 22. September 2011), ob es zu entwicklungsbedingten Veränderungen dieser Arbeitsgedächtnisstruktur in der kognitiven Entwicklung von Kindern im Altersbereich von 5 bis 12 Jahren kommt. Ebenfalls auf das Arbeitsgedächtnismodell von Baddeley (1986) zurückgreifend, setzt die zweite eigene empirische Arbeit (Michalczyk, Krajewski & Hasselhorn, Resubmission bei Cognitive Development am 8. September 2011) Subkapazitäten des Arbeitsgedächtnisses in Bezug zur vorschulischen numerischen Kompetenzentwicklung (Krajewski, 2008) bei Kindern im Alter von 5 bis 6 Jahren. Abschließend werden diese eigenen Arbeiten weiterführend erörtert, die Ergebnisse integriert und zusammenfassend diskutiert.

1. Zusammenfassung des Forschungshintergrunds

Das Arbeitsgedächtnis findet sich in vielen Ausrichtungen der Psychologie, wie z.B. der Allgemeinen Psychologie, Klinischen Psychologie, Kognitionspsychologie, sowie der Entwicklungs- und Pädagogischen Psychologie. Als Übersicht über das Arbeitsgedächtnis in der Entwicklungspsychologie beginnt die vorliegende Arbeit mit einem einführenden Buchkapitel (Michalczyk & Hasselhorn, 2010). Den Schwerpunkt dieses Abschnitts bildet die Darstellung unterschiedlicher Konzeptionen des Arbeitsgedächtnisses. Besonders hervorgehoben wird das Mehrkomponentenmodell von Baddeley (1986) mit seinen drei Komponenten phonologische Schleife, visuell-räumlicher Notizblock und zentrale Exekutive, welches eines der prominentesten Modelle in diesem Forschungsfeld ist und die Grundlage für viele aktuelle Konzeptionen und Forschungsarbeiten bildet. Das Kapitel zeigt zudem Ansatzpunkte für weitere Forschung zum Arbeitsgedächtnis auf.

1.1. Das Arbeitsgedächtnis in der Entwicklungspsychologie: Ein Überblick

Working Memory in Developmental Psychology – What's Out There?[1]

Given its various definitions in recent literature, the concept of working memory is very fruitful. According to Conway, Jarrold, Kane, Miyake and Towse (2007), there are basically 12 or more theoretical conceptions competing on the intellectual marketplace. Jarrold and Towse (2006) define working memory as the ability to hold in mind information in the face of potentially interfering distraction in order to guide behaviour. This functional definition demonstrates the importance of working memory for everyday life. Working memory is

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[1] Die Erstellung dieses Beitrags wurde gefördert durch die LOEWE-Initiative der Hessischen Landesregierung im Rahmen des "Center for Individual Development and Adaptive Education of Children at Risk" (IDeA), Frankfurt, Germany.
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pivotal to many real-world activities that imply these demands, such as reading, understanding spoken discourse, problem solving and mental arithmetic (Conway, Jarrold, Kane, Miyake, & Towse, 2007). For instance, in language comprehension, we are required to retain earlier parts of a spoken message in order to integrate them with later parts. Often, for the solution of a mathematical problem, we need to retain partial results to arrive at the final solution. Similarly, in reasoning, we need to somehow store the premises we work upon. Moreover, in the course of various tasks – be it in an experimental design or in everyday life – , new information has to be integrated, information that is no longer relevant has to be updated and interfering information inhibited, processes need to be supervised, attention needs to be shifted and much more. In this chapter we provide a brief overview of different aspects of working memory from a developmental perspective. We start with a description of the development of working memory and/or preceding constructs. Subsequently, we turn to some (but by far not all) theoretical perspectives on working memory in developmental psychology. According to the extent to which these approaches relate to the structural account proposed by Baddeley (1986, see below), we have roughly grouped the approaches into Baddeley-bound and non Baddeley-bound models. This presentation of models is followed by a short distinction of working memory and short-term memory. Finally, we switch to a broader perspective describing working memory in the course of the lifespan, presenting state-of-the-art results considering mainly structure and capacity. This somewhat more general part of the chapter follows the theoretically driven part, for some of the findings seem more comprehensible once the theoretical background has been introduced.

Working Memory Research: History, Milestones and Current Research Directions

More than 100 years ago, span tasks where subjects had to recall a presented series of items in the order of presentation became a well-established part of intelligence test batteries (e.g., Binet & Simon, 1905; Burt, 1909; Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890)(Cattel, 1890). At about the same time, William James made a first distinction between “primary” and “secondary” memory, with the first corresponding to what would later be called immediate memory. In 1956, Miller called out the magical number “7” (+/- 2) as a general limit to cognitive capacity. Cowan (2005), however, reports that Miller mentions in an autobiographic article that he did not really mean “7”. Cowan corrects this view to 3 to 4 items. Nowadays various views exist in contemporary research with respect to capacity. They take different aspects of working memory capacity into consideration, such as the number of items, the number of chunks, chunks and associated information, binding limits and others that can be held in mind by an individual. The first reference to “working memory“ as a term can be found in Miller, Galanter, and Pribram’s (1960) book “Plans and the Structure of Behaviour” that had a great impact on modern cognitive psychology. In 1974, Baddeley and Hitch introduced their widely known multicomponent model (see below). In 1980, Daneman and Carpenter were the first to publish data that were based on complex span procedures. In 1986, Baddeley laid out his model in more detail and in 2000, he introduced the episodic buffer as a further component.

Most of the early theories on “working memory” (or similar constructs, such as short-term memory, see below) can be classified as capacity-theories, because they refer to the amount of information to be actively held in mind. Other working memory theories can be labelled as time-based or interference-based accounts. However, different classifications of theories on working memory can be drawn, depending on research methods (e.g., experimental or correlational) or conceptions (e.g., process-oriented vs. structural). From a methodological perspective, traditionally both correlational psychology and experimental psychology address this field of research. Both traditions lead to the development of paradigms and theories by using a great variety of techniques to assess processes, such as statistical approaches of latent variable analysis (Alloway, Gathercole, Willis, & Adams, 2004; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Miyake et al., 2000), EEG and functional neuroimaging-techniques (e.g., Braver et al., 1997; Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998) as well as experimental and quasi-experimental designs (e.g., Grube & Hasselhorn, 2006; Hitch & McAuley, 1991; Schuchardt, Roick, Mähler, & Hasselhorn, 2008; Swanson, Ashbaker, & Lee, 1996; Swanson & Berninger, 1995). Correlational approaches typically test the predictive validity of working memory tasks and in developmental psychology the predictive power of working memory is often focussed on school relevant achievement (e.g., (Alloway et al., 2005; Krajewski & Schneider, 2009a). Structural equation modelling is of particular importance because it allows for the extraction of latent variables from a combination of manifest variables which leads to less task-bound conceptions (see Bollen, 2002).

Assessment of Working Memory

Working memory relates to very basic processes. As Klatzky (1980) put it, working memory is the "workbench of cognition". Working memory tasks are often very simple in nature and easy to understand for participants at different points of the lifespan and at different levels of intellectual ability. Thus, working memory tasks are very economic: Usually their administration does not take a lot of time and even if they represent only a small part of behaviour, they are strong predictors of higher cognitive abilities and skills such as reasoning and fluid intelligence that likely play a role in high-level cognitive tasks (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990). However, one has to be aware that working memory performance does not only vary strongly between individuals at a given age, but also over the life span – which is especially important from a developmental perspective and makes it a most interesting construct. Generally speaking, many tasks have been constructed for the assessment of different aspects of working memory for different groups of participants across the lifespan, and it would be impossible to list them all within this chapter. However, in the most typical approach subjects are required to maintain a list of to-be-remembered items while performing additional processing operations on other stimulus material, for instance, counting and/or speaking out loud whether a presented object is edible or not. These tasks are often referred to as complex span tasks (e.g., Daneman, Carpenter, & Just, 1982). An often used alternative is the n-back task. This paradigm requires the participant to hear (or watch) a running sequence of items. Whenever a presented item is identical to a previously presented item, the participant is instructed to react, for example, to press a button. However, even though such tasks are well-established, they only grasp certain aspects of working memory. Beyond that, attempts have been made in order to assess working memory performance in individuals through a battery of tasks (which may include the aforementioned tasks). Often these batteries rely on a certain theoretical concept of working memory according to which the tasks are grouped and/or developed. In the context of developmental psychology, the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) and the German Working Memory Test Battery for ages 5-12 (AGTB 5-12, (Hasselhorn et al., in prep.) are particularly noteworthy. In general, many other fruitful and influential approaches to the working memory concept exist, and to describe them all would go far beyond the scope of this chapter, which emphasizes an overview of the different approaches to working memory that are relevant in a developmental context.

Component-based Theories of Working Memory

Baddeley & Hitch: A Multicomponent Model of Working Memory

A first description of this model was offered by Baddeley and Hitch in 1974. In 1986, Baddeley introduced a more formalized model, presenting a domain-general approach to working memory, consisting of three components: The central executive, the phonological loop, and the visuospatial sketchpad. The basic idea of this approach was to consider working memory as more than just a system of retention. In their tripartite model, the central executive operates as a flexible master unit that controls and allocates resources. Additionally, it monitors information processing across informational domains (see Baddeley, Emslie, Kolodny, & Duncan, 1998; Baddeley & Hitch, 1974). Moreover, the central executive retrieves information from long-term memory and controls attention. The phonological loop and the visuospatial sketchpad work as domain-specific slave units. The phonological loop stores verbal information temporarily, and the visuospatial sketchpad specializes in visual and spatial representations. A large amount of evidence has been gained from studies of children (e.g., Alloway, Gathercole, Willis, & Adams, 2004; Roebers & Zoelch, 2005), adults, and neuroimaging investigations. From a developmental perspective, Alloway, Gathercole, and Pickering (2006) concluded that all working memory components are in place by four years of age and they showed that its structure is consistent across childhood years. In Germany, Roebers and Zoelch (2005) showed that in four-year-olds, the phonological and the visual-spatial subsystem can be separated. Schuchardt, Roick, Mähler and Hasselhorn (2008) found that the tripartite structure of working memory applies to children with and without a learning disorder from the first to the fourth grade of elementary school. Findings from Grube and Hasselhorn (2006) show that working memory is important for acquiring reading, writing, and arithmetic skills. The impact of Baddeley's model was tremendous and it is on-going. A lot of research on working memory is and was inspired by the model which is still under development. In 2000, Baddeley introduced a new component into his model, the episodic buffer. This component serves for the integration of components from working memory (and long-term memory) into unitary episodic representations. Thereby, it uses multidimensional codes and gives direct input into episodic long-term memory.

Towse & Hitch: A Task-switching Model?

The account by Towse and Hitch (Towse & Hitch, 1995, 2007) is closely connected to Baddeley's model. Working memory is again conceptualized as a multicomponent, limited-capacity system that retains and transforms fragile representations. It is composed of the central executive, the phonological loop, the visual sketchpad and possibly the episodic buffer. In this account, the domain-specific components of working memory span each have two orthogonal dimensions: modality of information and information content. Modality refers to whether information is verbal or visuospatial. Content refers to the knowledge domain the information relates to, for instance, reading or arithmetic. Furthermore, they claim that the interaction of processing and storage is crucial to the understanding of the limitations of working memory capacity. In terms of task selection, their research focuses mainly on the working memory span. According to them, in working memory, information processing and storage interact through task-switching. Their account is different from others in that it disagrees with the usual assumption of limited resource sharing. Instead, task switching represents a general feature of working memory and depicts a limiting factor; its balance with other limiting factors varies across individuals and over time. Moreover, Towse and Hitch (2007) apply the multicomponent model to children, focussing on working memory span tasks. As they point out, it is important to note that memories perish and delaying the point of recall can lead to a decrease of recall. Therefore, working memory is not only determined by task-processing time. In contrast, retention delay seems to be important for working memory performance, which might be the case especially in children. However, they found only little experimental evidence supporting the (common) explanation of span as a limit to the capacity for resource sharing (Towse & Hitch, 1995). Furthermore, they argue that the retention duration of stimuli affects both children and adults. Yet, there is a qualitative difference between adults and children, because on-line processing speed in pre-school children is related to individual differences in working memory span, whereas this is not the case in differences in adults' working memory span. However, they emphasize that further analyses of children's and adults' profiles might reveal different patterns of working memory performance across age-groups. Their main conclusion is that working memory is constrained by temporal dynamic. In this view, working memory does not only resolve the competition of task requirements, but requires their integration as such. Despite qualitative differences, they claim that working memory has the same structure in children and adults and serves similar functions in both.

Jarrold & Bayliss: Executive Control & Content-bound Organisation of the Subsystems

Jarrold and Bayliss (Jarrold & Bayliss, 2007) are guided by Baddeley's (1986) work, too. They emphasize that in the domain-specific short-term storage (verbal and visuospatial) the distinction between these two components is bound to content rather than process. They emphasize the possible role of executive control in complex span tasks, and argue that often traditional working memory tasks do not tap on executive processes. However, they disagree with the resource sharing approach of working memory variation, and find support for separable influences of processing efficiency. Given the assumption that the reactivation of items from memory takes place during pauses between processing, their model of complex span performance is consistent with a resource-switching account. Considering individual differences, they postulate that individuals may vary in the rate of forgetting information during processing activities. With respect to development, they argue that changes in working memory in the aging process might be mediated by a common mechanism of working memory rather than domain-specific change. Jarrold and Bayliss (2007) take a closer look at the complex span task and its constraints. They try to explain both individual and developmental constrictions of working memory, arguing that storage capacity and processing are separable. Furthermore, a third component that is potentially executive in nature is needed in order to combine these two demands of the complex span task.

Hale, Myerson, Emery, Lawrence, and Dufault: Storage, Inhibition and Switching Functions

One of the central assumptions of the account by Hale and colleagues (Hale, Myerson, Emery, Lawrence, & Dufault, 2007) is that mental processing speed explains large part of developmental variation. Here, the development of faster processing speed results in a greater capacity of working memory. In terms of structure, the working memory model by Hale and colleagues (2007) also relies on the conception of working memory according to Baddeley (1986) and their results principally show the same structure. However, they report differences, especially with respect to interference. When presenting a primary memory task, they find secondary memory to interfere with working memory span only if the latter taps on the same subsystem as the primary memory task – as opposed to the occurrence of interference whenever the secondary task interferes with domain-independent (i.e., the central executive) facets of working memory. Furthermore, Hale et al.'s (2007) research focuses on the role of processing speed and storage, inhibition and switching functions. They argue that differences in performance across the lifespan cannot be completely accounted for by processing speed and storage. However, they reject the importance of inhibition and switching back and forth between tasks (i.e., older adults are less flexible and have difficulties in "blocking/sorting out" irrelevant information). Instead, they emphasize the role of interference as described above: In cognitively healthy people aged 10 to 80, interference in memory span only seems to occur when the tasks tap on the same neural system. In children younger than 10 years, the subsystems (verbal and visuospatial) are not fully independent. From the age of 10 onwards, working memory performance improves mostly quantitatively, with general improvements in late childhood and adolescence. However, in older adults, working memory performance is generally lower with an accelerated decrease of performance in the visuospatial domain. Nevertheless, Hale et al. (2007) point out that chronological age is only a rough indicator for the neurobiological changes that take place in the aging process.

Reuter-Lorenz and Jonides: Neural Mechanisms, Executive Functions, and Attentional Control

The approach by Reuter-Lorenz and Jonides (Reuter-Lorenz & Jonides, 2007) is guided by the search for underlying neural mechanisms of working memory performance. They claim that the identification of neural evidence may help to clarify the nature of psychological constructs, especially with regard to a more fine-grained determination of central executive processes. In contrast to other lines of research, they place strong emphasis on executive functions and on attentional control in particular. They claim that especially in those tasks that tap "short-term" memory as opposed to "working memory" (for the distinction of these two terms, see below), the involvement of executive functions is underestimated. This is especially the case in poor-performing young adults and in older participants. In their view, attentional control is crucial to performance in working memory and performance of tasks will be hindered once high levels of attentional control are required, for the availability of control processes will decrease. The two main predictors for the availability of control (individual-difference variables) are age and fluid intelligence. Reuter-Lorenz' and Jonides' research aims at revealing variation in neural activation patterns, and tries to identify cognitive operations that underlie the presented tasks. Indeed, with respect to development their research shows that the same level of performance in younger and older adults involves different neural circuitry.

Non-Baddeley-bound Models of Working Memory

There are a variety of approaches in working memory research that are less or not at all structurally similar to the approach by Baddeley (1986). However, not all of these approaches relate specifically to developmental issues; therefore, we only describe three approaches as examples for non-Baddeley-bound models of working memory that deal with developmental issues.

Munakata, Morton and O'Reilly: A Biologically Oriented Computational Model

Munakata, Morton, and O'Reilly (2007) provide a biologically oriented computational model that accounts for the development of working memory and cognitive control in young children. Hereby, their work underpins the importance of two complementary processes, that is, maintenance and updating as the computational mechanisms underlying components of working memory. In their account, these relatively simple processes provide an explanatory basis for a range of phenomena that relate to working memory. Their research focuses on types of representations and learning mechanisms. These allow different brain systems such as the prefrontal cortex and basal ganglia to specialize in these two aspects of working memory. They assume a controlled attentional system, in which variation in capacity is due to variation in executive attention and control. According to them, working memory representations provide a controlled attentional system in order to activate task-relevant information. Variability in development serves for assessing the basic components of working memory. If, for instance, children of a certain age group fail consistently on certain tasks, the same tasks might allow for a more fine-grained analysis of working memory performance in adults. Munakata and colleagues (2007) argue that an investigation of underlying mechanisms leads to different conclusions with respect to cognitive constructs such as activation and inhibition.

Braver, Gray, and Burgess: The Dual Mechanisms of Control Account

Braver, Gray, and Burgess (2007) link psychological constructs of working memory to neural computational mechanisms: To them, working memory is a phenomenon that results from the interaction of various mechanisms such as active context representation, dynamic updating, conflict detection, and binding. They propose a dual-mechanism theory. In their conception, there are two modes of cognitive control, the proactive and the reactive mode. According to Braver et al. (2007) most cognitive tasks tap a mixture of both modes. Individual differences, however, depend on the extent to which (1) subjects are able to engage proactive control and (2) on their ability to move from one mode of control to another. Their model extends to non-cognitive factors such as, for instance, the BIS and BAS-system (Gray, 1994). Braver et al. (2007) do not explicitly propose a developmental model. However, they point out that the developmental maturation of the cognitive system and related neural changes serve as important sources of variation. Moreover, such neural changes might serve as a useful tool for exploring the causal mechanisms that underlie cognitive developmental variability (similar to Munakata et al., 2007). In addition, they hypothesize that the dual mechanisms of control account (DMC) might provide a way of better understanding cognitive control in children. They also argue that developmental changes in the efficiency of working memory are possibly related to the developmental trajectory of the dopaminergic (DA) function (cf. Diamond, 2002).

Hasher, Lustig, and Zacks: A General Theory of Cognition Including Working Memory

Hasher, Lustig, and Zacks (2007) propose a general theory of cognition (Hasher, Zacks, & May, 1999) taking into consideration data from younger and older adults. The basic idea of this theory is that people perform best on a variety of tasks when the contents of consciousness are narrowly focused on goal-relevant cognition. For this narrowing, inhibition is crucial rather than capacity or resources: Given the individual's massive activation through the internal and external context (i.e., environment, recent past, near-future tasks and "subsidiary" goals), the resulting activation needs to be tuned through inhibitory processes. Inhibition, in turn, depends on circadian arousal pattern throughout the day. Tuning is managed by means of (at least) three control processes: Access, deletion, and restraint. Working memory as the content of consciousness is largely determined by these three processes and goals. Inhibitory control varies with age as well as with an individual's circadian arousal pattern and the time of testing. However, the question as to whether these mechanisms are independent or partially overlapping still remains unresolved. Especially important from a developmental perspective, it is yet unclear if the pattern of dependence or independence remains the same throughout the developmental process. For example, the work by Friedman and Miyake (2004) points to access and deletion being the same mechanism whereas restraint seems to be a separable process.

Short-Term Memory Conceptions

The development of a theory of short-term memory took place in the 1960s. At the time, it provided the explanatory power of the new cognitive approach. One of the most influential formulations of that theory was provided by Waugh and Norman (Waugh & Norman, 1965) and was integrated into a broader theory of memory by Atkinson and Shiffrin (1968). Although this theory was of great influence, it is nowadays no longer accepted. In more recent literature, the terms "working memory" and "short-term memory" are often used interchangeably (Jarrold & Towse, 2006). Furthermore, the use of the term "short-term memory" in everyday life and in the public contributes to confusion: here, this term often refers to what a person did or did not remember as to what happened the last days or weeks, as opposed to what happened in the last few seconds (Moulin & Gathercole, 2008). However, by definition "short-term memory" refers to an individual's ability to store and/or maintain information over a limited period of time; thus, the focus is set on time. In contrast, working memory is the broader construct and refers to the ability of an individual to hold information in mind while manipulating and integrating other information with regard to a cognitive goal (e.g., Kane & Engle, 2002; Roberts & Pennington, 1996). Of course, a certain overlap remains that, at a first glance, might seem confusing to readers who are new to the field. Moreover, typical tasks to assess working memory and short-term memory are rooted in different research traditions. Working memory tasks are often developed from an individual differences approach (Jarrold & Towse, 2006). In contrast, short-term memory classically stems from the field of general psychology, and is put into practice through variants of simple span tasks. Hereby, the focus lies on the disruptional effects of secondary tasks (e.g., Baddeley, Lewis, & Vallar, 1984). Baddeley (1986, 2000) offered a model where short-term memory components are considered a part of working memory, with other systems responsible for coordinating and processing representations of the (stimulus) material. Therefore, tasks for the assessment of working memory are not necessarily tasks for short-term memory and vice versa. Typical tasks for the assessment of short-term memory are span tasks like digit span forward; some authors also assign Corsi-block tasks to short-term memory. However, short-term memory tasks have in common that they require individuals to repeat verbal or visuospatial material in the presented order. Such tasks focus on the correct reproduction and do not aim at processing or manipulating the stimulus material. These tasks are often referred to as “simple span tasks”. In a meta-analysis of 77 published studies, Daneman and Merikle (1996) were able to show that the complex span correlated significantly higher with standardized indices of reading and vocabulary tests (r = .42) than measures of short-term memory that reached a correlation to the same measures of .28.

Working Memory and Development Across the Lifespan

From a developmental perspective, it seems promising to take a closer look at changes in different aspects of working memory. In order to address this issue, the following part provides a description of results from working memory research in children to older adults mainly with respect to structure, capacity, and related constructs. We take a developmental perspective and focus on change, thus our emphasis in the next paragraph lies on both ends of the lifespan and less on younger adults.

Working Memory in Children: Structure

Recent findings corroborate the view that from the age of 4 years on, working memory is best to be described as a system composed of several components. However, several questions arise concerning the number of components, their nature and their interdependencies. For example, Gathercole, Pickering, Ambridge, and Wearing (2004) suggest that a model consisting of three distinct but correlated factors best describes working memory performance over a variety of tasks in 6-year-olds and possibly in even younger children. Analysing data from 4- to 15-year-olds, they found that each component undergoes expansion. Roebers and Zoelch (2005) showed that already at the age of 4 years, a clear distinction of the phonological and the visuospatial subsystem is observable. Alloway, Gathercole and Pickering (2006) looked into the structure of verbal and visuospatial short-term memory and working memory in children at the age of 4 years in order to identify the different cognitive processes that underlie working memory. They found that storage aspects are best described in domain-specific verbal and visuospatial subsystems while processing components were supported by a common resource pool. Their findings showed that this model was consistent over the developmental period from 4 to 11 years. However, they report that in the age group of the 4- to 6-year-olds, the domain specific visuospatial construct and the domain-general construct were more strongly associated than in the other age groups. Other researchers report on finding a strong association of the phonological loop with central executive (domain-general) mechanisms. In sum, the findings by Alloway, Gathercole, and Pickering (2006) indicate that all working components suggested by the Baddeley conception (1986) are in place at the age of 4 years.

Working Memory in Children: Capacity

It is important to note, as Alloway, Gathercole, and Pickering (2006) point out, that even at a certain age, working memory capacity varies strongly. They analysed data from a sample of

709 children between four and eleven years of age. They estimate that within an average class of 30 children (that are roughly about the same age) variation in working memory covers the range of five years of normal development. This strong variance in children is linked to academic achievement. The perspective by Hale et al. (2007, see above) argues that differences in working memory across the lifespan are bound to cognitive processing speed. One of the basic assumptions of this line of research is that cognitive development and aging are related to remarkable changes in reaction times (see review by Cerella & Hale, 1994). The basic idea is that processing speed changes over a lifetime and represents an age-related source of variation in working memory. This conception is somewhat hierarchical with cognitive processing speed underlying working memory that, in turn, influences higher-order cognitive processes (Hale et al., 2007). For instance, under the assumption that there is limited time for processing, slower processing of memory items might decrease encoding efficiency. In addition, slower processing of non-memory information (e.g., paying attention to and concentrating on a task demand in older adults), might subtract time (and resources) from processing memory information. Subsequently, this is hypothesized to lead to inadequate encoding of items and/or forgetting. However, Hale et al. (2007) claim that processing speed and age do not account for all the age-related variance in complex memory span. Several explanations are possible here. One hypothesis refers to the role of executive functions in children's complex memory span: Hale et al. (2007) reject both the role of (1) inhibiting irrelevant information and (2) the ability to switch back and forth between tasks. Instead, Hale et al. (2007) argue that (for most of the life span) interference occurs when primary and secondary tasks operate on the same domain-specific neural system. They argue that before the age of ten, the verbal and the visuospatial subsystems are not completely independent but changes from the age of 10 onwards are mainly quantitative in nature. In late childhood and adolescence these changes go along with general improvements; in older adults a general decline is commonly observable. This decline, however, is exacerbated in the visuospatial

domain. Nevertheless, they point out that chronological age is only a proxy that gives an indication of neurobiological changes. Here, the role of white matter is especially important because it affects the cognitive processing speed. Generally spoken, changes of memory capacity due to cognitive processing speed are of special importance at both ends of the lifespan; however, as described further below, the changes that occur during senescence do not seem to be equal to those during maturation.

Working Memory in Children: Strategies

In addition to capacity variations, strategy use in children contributes to changes in memory among primary school children (Cerella & Hale, 1994). As far as working memory is concerned, strategy use seems less important than in long-term memory, since working memory tasks often tap capacity directly. Nevertheless, in most children, the automation of rehearsal processes in the phonological loop takes place between 5 and 6 years of age (see Gathercole & Hitch, 1993).

Working memory in children: Relations to other Constructs

Working memory is an important predictor for a variety of skills in children. In children, working memory is associated with performance in the areas of reading (e.g., De Jong, 1998, Swanson, 1994) mathematics (e.g., Bull & Scerif, 2001; Mayringer & Wimmer, 2000; Siegal & Ryan, 1989) and language comprehension (e.g., Nation, Adams, Bowyer-Crane, & Snowling, 1999; Seigneuric, Ehrlich, Oakhill, & Yuill, 2000). Bayliss, Jarrold, Gunn, and Baddeley (2003) showed that the ability to coordinate the processing and storage aspects of working memory tasks, that is central executive parts of working memory, has predictive power for both reading and mathematical achievement. Findings by Alloway, Brown, and Pickering (2003) indicated that working memory at school entry is a strong predictor of children’s success in assessments of academic performance within a three-year follow-up.

According to Alloway (2009), there is evidence that working memory capacity, and especially the central executive, constrains children’s academic achievement. Similar findings come from Grube and Hasselhorn (2006), who were able to show that working memory is important for the acquisition of reading, writing and arithmetic in German speaking children. In addition, recent research from Alloway (2009) in children with learning difficulties shows that working memory, not IQ, predicts subsequent learning.

Working Memory in Older Adults

People generally assume that the older the person is, the worse her or his memory will be. The “Use it or lose it”-theory (e.g., Hultsch, Hertzog, Small, & Dixon, 1999) suggests that the massive changes in social and cognitive activities in older adults may contribute to memory loss. Also, cultural influences might exist with respect to general memory theory and/or findings. In Chinese cultures, where aging is less negatively connotated than in Western cultures, older adults do not show the same memory difficulties as their Western controls (Levy & Langer, 1994). However, we can overall state that memory performance declines in older adults. As a neurological correlate, disproportionate cell loss is reported from a certain age on. Moulin and Gathercole (2008) point out that memory loss in older adults is a common finding and this decrease is an inevitable part of healthy aging. In contrast, Alzheimer’s disease and dementia are pathological conditions that are related to the aging process. Several theoretical accounts of working memory deal with aging and/or can at least be referred to aging. These include Baddeley´s (1986) working memory model, frontal-lobe aging theories (Moscovitch & Winocur, 1995; West, 2000) and the inhibition-deficit framework (Hasher & Zacks, 1988; Zacks, Radvansky, & Hasher, 1996). Others reported that in older adults a decrease in visuospatial memory seems to be associated with a more general decline in the efficiency of visuospatial processing (Jenkins, Myerson, Joerding, & Hale, 2000; Myerson, Emery, White, & Hale, 2003). For instance, in research with healthy older adults, one model that explains this decrease is the model of memory ageing in terms of frontal lobe dysfunction. The model refers to different findings: (1) In older adults, cell atrophy takes place in the frontal cortex (e.g., Ivy, MacLeod, Petit, & Markus, 1992). (2) In batteries of cognitive tasks, older adults show deficits on tasks that tap cognitive functions (e.g., Parkin & Java, 1999). (3) Patterns of performance across experimental tasks between older adults and frontal patients seem to be similar (e.g., Perfect, 1997). With respect to executive functions (at least when measured with switching paradigms), a decline seems to be associated with normal aging. Accordingly, not only children below 10 years of age, but also older adults perform worse than young adults with regard to the visuospatial domain. However, different explanations for this finding may account for each age group. As mentioned above, children show lower performance in the visuospatial domain, but show same-domain interference by secondary tasks in task switching designs. Older adults, however, show a visuospatial decrease without lower performance in (same domain) task-switching. According to Hasher et al. (2007) both (1) differences in verbal and visuospatial memory and (2) differences in the functional independence of these two domains possibly reflect two separate developmental phenomena (as opposed to task switching accounting for both children and older adults). Regardless of the task, older adults are outperformed by younger adults especially in visuospatial working memory tasks.

Summary and Perspective

Working memory research in developmental psychology includes a wide theoretical variety and different paradigms and conceptions at the task level. It has been proven as a valid construct that is related to a number of abilities and phenomena across the lifespan, like cognitive processing speed, intelligence and academic achievement. Ever since “working memory” was first coined as a term in 1956, working memory research has blossomed, especially in the past decades. Today, more than a dozen theoretical accounts exist in the developmental research field. In the context of working memory in the area of developmental psychology, the approach by Baddeley (1986, 2000) is particularly important, for many research accounts go back to or are inspired by this model of working memory. The tripartite structure of working memory according to Baddeley (1986) is composed of the central executive, the phonological loop and the visuospatial sketchpad. Baddeley (2000) adds a fourth component, the episodic buffer. Many other research groups that deal with developmental aspects rely on this conception; however, their research in many cases puts a stronger emphasis on different aspects of working memory and potentially underlying mechanisms. For instance, the conception by Towse and Hitch (2007) highlights the importance of task switching as a general feature of working memory. As a counterweight to the usual assumption of a limit on resource sharing, their account claims that the limiting factor of working memory lies in the fragility of representations. Jarrold and Bayliss (2007), who are also guided by the Baddeley model, argue, however, that the distinction between the visual and visuospatial subsystem might represent a distinction in content rather than process. In addition, changes in these subsystems in the course of development may be mediated by a common mechanism and they emphasize the importance of executive cognitive control. Hale, Myerson, Emery, Lawrence, & Dufault (2007) also employ the Baddeley model in their research. They claim that interference of secondary tasks occurs only under engagement of the same domain-specific subsystem as does the primary task. Furthermore, they argue that changes in working memory performance in children and older adults, even though similar on the surface level, might be due to different maturation processes. Reuter-Lorenz and Jonides (2007) agree with the Baddeley model in general, but put a strong emphasis on executive functions, particularly attentional control, and underline the importance of neural evidence for working memory research in order to better understand the nature of psychological constructs. It is moreover noteworthy that different accounts of working memory also exist in the developmental field. One of these is the biologically oriented computational model by

Munakata, Morton, and O'Reilly (2007) that focuses on active maintenance of information and updating as two computational mechanisms that supposedly underlie working memory. Similarly, the approach by Braver, Gray, and Burgess (2007) also searches for neural and computational mechanisms that underlie working memory tasks. Herein, working memory is conceived of as an interaction of multiple mechanisms. Hasher, Lustig, and Zacks (2007) provide a general theory of cognition in which working memory is integrated with inhibition as a pivotal factor. Beyond working memory theorizing, this chapter discusses the terms "working memory" and "short-term memory". The main differences between these two constructs are that (1) short-term memory is restricted to (short) time and that (2) working memory encompasses a greater variety of cognitive processes that are more active in character. Furthermore, we take a closer look at the development of working memory with respect to both structure and capacity, focussing on both ends of the lifespan, that is, children and older adults. Here, different theoretical approaches as well as concrete findings are taken into consideration.

Of course, working memory research meets the usual problems that can be found in other areas of developmental psychology. One particular problem of working memory research, however, is that many models of working memory are very task-dependent. Thus, a challenge for future research will be the creation of less task-dependent models of working memory (Jarrold & Towse, 2006). This creates the need to develop new tasks of working memory and indeed, further measures of working memory are under way (e.g., Hasselhorn et al., in prep.; Lépine, Barrouillet, & Camos, 2005; Towse, Hitch, Hamilton, Peacock, & Hutton, 2005). Further issues are, for instance, the nature of domain-general processes, the potential appearance of patterns in working memory in different subgroups (e.g., children with learning disorders), the development of such patterns, the correlates of working memory across the lifespan and many more.

2. Vertiefung 1: Die Struktur des Arbeitsgedächtnisses

Die im vorherigen Kapitel dargestellte Übersicht (Michalczyk & Hasselhorn, 2010) stellt einen Einstieg in den Themenbereich des Arbeitsgedächtnisses als Forschungsgegenstand in der Entwicklungspsychologie dar. Hierbei konnten einige Aspekte lediglich ansatzweise beschrieben werden, wozu auch die funktionale Differenzierung des Baddeley'schen Modells (1986) im Kindes- und Jugendalter gehört. Einige Arbeiten der letzten Jahre legen die Gültigkeit der Arbeitsgedächtnisstruktur nach Baddeley (1986) bereits im Vorschulalter nahe (z.B. Alloway et al., 2006; Gathercole et al., 2004; Roebers & Zoelch, 2005). Diese Annahme bedarf jedoch weiterer Klärung und soll daher in der folgenden Vertiefung zum Forschungsgegenstand gemacht werden. Im weiteren Sinne umfasst dabei die Frage der Struktur nicht nur die Qualität der Komponenten (z.B. phonologisch, visuell-räumlich, zentral-exekutiv) sondern auch ihr Verhältnis zueinander und dessen Veränderung oder Nicht-Veränderung im Laufe der Entwicklung. Somit ist auch die Varianz oder Invarianz der funktionalen Interdependenz der Arbeitsgedächtniskomponenten in der kognitiven Entwicklung von Kindern ein zentrales Anliegen der nachfolgenden Betrachtungen.

2.1 Die funktionale Differenzierung des Baddeley'schen Modells im Kindesalter

Baddeley (1986) beschrieb das Arbeitsgedächtnis als komplexes Systemgefüge mit den drei Hauptkomponenten zentrale Exekutive, phonologische Schleife und visuell-räumlicher Notizblock. Ein wesentliches Kennzeichen dieses Modells ist seine Struktur. Die Annahme eines dreigliedrigen Systems wird von einer Vielzahl von Befunden aus Erwachsenenpopulationen gestützt (Baddeley, 2003). Diese stammen aus unterschiedlichen methodischen Ansätzen der Psychologie, wie zum Beispiel aus dem korrelativen Ansatz interindividueller Differenzen (Jarrold & Towse, 2006), oder aber auch Studien experimenteller, neuropsychologischer und bildgebender Verfahren (Baddeley, 1986; Baddeley & Logie, 1999; Engle, Tuholski, Laughlin & Conway, 1999; Henson, 2001; Vallar

& Papagno, 2002). In der Baddeley'schen Modellauffassung wird postuliert, dass die zentrale Exekutive unter anderem eine ressourcenverwaltende Funktion für die Subsysteme phonologische Schleife und visuell-räumlicher Notizblock einnimmt (Baddeley, 1986). Die Subsysteme sind dabei unabhängig voneinander, während die zentrale Exekutive in größerem funktionalem Zusammenhang zu jedem dieser beiden Subsysteme steht. Diese Modellvorstellung lässt sich auch als „Hierarchie“ der Komponenten des Arbeitsgedächtnisses bezeichnen. Zusätzlich zum Verhältnis der einzelnen Arbeitsgedächtniskomponenten zueinander ist auch die Zusammensetzung bzw. Binnendifferenzierung der einzelnen Komponenten möglich und wichtig für das Verständnis der beteiligten kognitiven Prozesse. Daher beschreibt der nachfolgende Abschnitt Binnendifferenzierungen der Komponenten des Arbeitsgedächtnismodells nach Baddeley (1986). Bei der phonologischen Schleife lassen sich der phonetische Speicher und der subvokale Kontrollprozess unterscheiden (vgl. Hasselhorn, Grube & Mähler, 2000). Auditorisch-verbale Informationen verbleiben für 1,5 bis 2 Sekunden im phonetischen Speicher, während der subvokale Kontrollprozess durch eine Art „inneres Sprechen“ oder „inneres Wiederholen“ ermöglicht, dass Informationen auch jenseits dieses Zeitfensters im Zugriffsbereich der bewussten Verarbeitung bleiben. Die noch fehlende Automatisierung des subvokalen Kontrollprozesses ist dabei eine Erklärungsmöglichkeit für das Nicht-Auftreten des Wortlängeneffekts weder bei Kindern im Vorschulalter (Gathercole & Hitch, 1993) noch bei lernbehinderten Grundschulkindern (Mähler & Hasselhorn, 2003). Hasselhorn et al. (2000) nehmen eine weitere Unterteilung sowohl des phonetischen Speichers als auch des subvokalen artikulatorischen Kontrollprozesses der phonologischen Schleife vor. Sie differenzieren beim phonetischen Speicher zwischen Größe und Verarbeitungspräzision, beim subvokalen Kontrollprozess hingegen zwischen der Geschwindigkeit und dem Automatisierungsgrad seiner Aktivierung. Auch die visuell-räumliche Komponente kann weiter unterteilt werden. Logie (1995) beschreibt einen visuellen Speicher und einen

Mechanismus für die Aufnahme räumlicher Abfolgen oder Bewegungssequenzen. In diesem Zusammenhang wird oft auch von der statischen vs. der dynamischen Komponente des visuell-räumlichen Arbeitsgedächtnisses berichtet (vgl. Raghubar et al., 2010). Bei Baddeley (1986) wird die zentrale Exekutive als ein System zur Supervision und Kontrolle der eigenen Aufmerksamkeit aufgefasst. Der zentralen Exekutive kommen dabei folgende Aufgaben zu: Überwachung der in den Hilfssystemen aktivierten Inhalte, Bewusstmachen von Information bzw. Transformierung der Information für weitere Verarbeitungsschritte, Entwerfen von Verarbeitungs- und Handlungsplänen, sowie Umsetzung, Planung, Kontrolle und Modifikation dieser Pläne. In Hinsicht auf eine weitere Differenzierung der zentralen Exekutive schlug Baddeley (1996) vier voneinander abzugrenzende zentral-exekutive Funktionen vor. Drei dieser Kapazitäten werden von Aufmerksamkeitskontrollsystemen gebraucht (vgl. Baddeley, 2003) und umfassen (1) die Koordination bei der gleichzeitigen Bearbeitung von Aufgaben, (2) die Flexibilität beim Wechsel von Abrufstrategien und (3) die selektive Fokussierung beim Ausblenden irrelevanter Information. Schließlich kommt noch die selektive Aktivierung von Wissensinhalten aus dem Langzeitgedächtnis hinzu, welches eine Verbindung zwischen Arbeitsgedächtnis und Langzeitgedächtnis herstellt. Wie auch andere Versuche zur Erstellung von Taxonomien der zentral-exekutiven Funktionen zeigen (z.B. Miyake et al., 2000), gestaltet sich die einheitliche Systematisierung zentral-exekutiver Funktionen als schwierig und entwickelt sich stetig fort. Auch ist es möglich, dass diejenigen Funktionen, welche unter dem Begriff der zentral-exekutiven Funktionen subsumiert werden, nicht zusammenhängende und stark spezialisierte kognitive Mechanismen sind (vgl. Towse & Houston-Price, 2001).Vor diesem Hintergrund wird in der vorliegenden Arbeit der Begriff der zentralen Exekutive aus Gründen der sprachlichen Einfachheit beibehalten, jedoch in dem Verständnis, dass die zentrale Exekutive ein sehr heterogenes Konstrukt und eine weniger klar umrissene Komponente als beispielsweise die phonologische Schleife ist.

Wie in der vorhergehenden Übersichtsarbeit (Abschnitt 1.1) skizziert, deuten neuere Befunde auch in Richtung der Gültigkeit einer mehrgliedrigen Arbeitsgedächtnisstruktur bei Jugendlichen und Schulkindern (Alloway et al., 2006; Alloway et al., 2004; Bayliss, Jarrold, Gunn & Baddeley, 2003; Gathercole et al., 2004; Mammarella, Pazzaglia & Cornoldi, 2008). Bei Schulkindern sprechen Befunde aus dem englischen Sprachraum für eine Gültigkeit des Baddeley'schen Modells (1986). Bayliss, Gunn, Jarrold und Baddeley (2003) belegten bei 8- bis 9-Jährigen eine Arbeitsgedächtnisstruktur mit einem generellen Verarbeitungsfaktor, einem verbalen, sowie einem visuell-räumlichen Speicherfaktor. Gathercole, Ambridge, Pickering und Wearing (2004) zeigten, dass ein Dreikomponentenmodell des Arbeitsgedächtnisses bei Kindern im Alter von 6 bis 15 beschrieben werden kann. In ihrer Untersuchung war der Zusammenhang der zentralen Exekutive mit den beiden Subsystemen höher als der Zusammenhang der beiden Subsysteme, was für eine hierarchische Struktur der Komponenten spricht. Mammarella et al. (2008) fanden ebenfalls Belege für ein Mehrkomponentenmodell bei 8- bis 9-Jährigen, wobei sie den visuell-räumlichen Notizblock in drei weitere Komponenten unterteilten, sowie zwei phonologische Komponenten unterschieden: eine verbale und eine verbal-aktive Komponente. Eine separate zentral-exekutive Komponente enthielt das Modell nicht. Allgemein zeigen die Befunde wie sehr die Arbeitsgedächtnismodelle von der Aufgabenauswahl bedingt werden. Sie verdeutlichen aber auch, wie sehr die Modellentwicklung einzelner Komponenten, vornehmlich des visuell-räumlichen Notizblocks und der zentralen Exekutive, noch in der Entwicklung begriffen ist. Dies wirft die Frage auf, ob im Kindesalter – und wenn ja, wie früh? – tatsächlich von der für Erwachsenen angenommenen dreigliedrigen Struktur ausgegangen werden kann.

In jüngeren, vorschulischen Altersbereichen sind die Befunde zur Struktur des Arbeitsgedächtnisses eher dürftig. Die bei Erwachsenen gefundene neuroanatomische Basis durch in unterschiedlichen Loci verorteten und auf Verhaltensebene funktionell trennbaren Arbeitsgedächtniskomponenten spricht für die mögliche Validität funktional trennbarer

Arbeitsgedächtniskomponenten auch schon im frühen Kindesalter. Natürlich ist es hierbei möglich, dass sich die unterschiedlichen Subsysteme des Arbeitsgedächtnisses im Laufe der Entwicklung weiter ausdifferenzieren, insbesondere die im Frontallappen verortete zentrale Exekutive, da dessen Entwicklung bis in frühe Erwachsenenalter voranschreitet (Nelson, 1995). Bisher gibt es erste Befunde, welche für die Gültigkeit der Dreikomponentenstruktur des Arbeitsgedächtnisses sensu Baddeley (1986) auch schon im früheren Kindesalter sprechen. Ausgehend von Befunden bei 6-Jährigen Kindern, mutmaßen Gathercole et al. (2004), dass die Dreikomponentenstruktur des Arbeitsgedächtnisses (Baddeley, 1986) auch für Kinder unter 6 Jahren gelten könnte. Allerdings konnten Gathercole und Pickering (2000) bei 6- und 7-Jährigen Kindern zwar eine phonologische Schleife sowie eine zentrale Exekutive, aber keinen separaten visuell-räumlichen Notizblock bilden. Alloway et al. (2004) zeigten bei 4- bis 6-Jährigen, dass die zentrale Exekutive, die phonologische Schleife und der episodische Puffer voneinander trennbar sind, sie berücksichtigten jedoch kein visuell-räumliches Maß der Arbeitsgedächtnisleistung. Die Arbeit von Roebers und Zoelch (2005) hingegen deutet darauf hin, dass die Messung subsystemspezifischer Arbeitsgedächtniskapazitäten, also der phonologischen Schleife und des visuell-räumlichen Notizblocks, schon bei Kindern bei 4- bis 5-jährigen Kindern möglich ist. Erst Alloway, Gathercole und Pickering (2006) belegten, dass das Dreikomponenten-Modell (Baddeley, 1986) bei Kindern von 4 bis 6 Jahren Gültigkeit besitzt. Diese Studie scheint die erste Arbeit im Altersbereich unter 6 Jahren zu sein, welche die dreigliedrige Struktur im Sinne des Baddeley-Modells (1986) mit der phonologischen Schleife, dem visuell-räumlichen Notizblock und der zentralen Exekutive erfasst und bestätigt.

Zur Struktur des Arbeitsgedächtnisses sensu Baddeley (1986) lässt sich also festhalten, dass trotz erster Fortschritte betreffs der Validierung dieses Modells im Kindesalter eine Diskrepanz zwischen der Anzahl der Befunde aus Erwachsenenpopulationen und Jugendlichen, Schulkindern und Vorschulkindern besteht. Insbesondere ist dies der Fall für

Kinder unterhalb von 7 Jahren. Insgesamt scheint die bisherige Befundlage für die Trennbarkeit einzelner Komponenten zu sprechen. Im Vorschul- und Grundschulter besteht in Hinsicht auf die Validität aller drei Komponenten und insbesondere auf die Validierung der zentralen Exekutive noch erheblicher Forschungsbedarf.

Zusätzlich zur Art der Komponenten stellt sich auch die Frage ob und in welchem Maße eine Struktur des Arbeitsgedächtnisses vom Vorschul- bis zum Ende des Grundschulalters entwicklungsbezogenen Veränderungen unterworfen ist. Insbesondere aus der entwicklungspsychologischen Perspektive scheint die Betrachtung der Veränderung der Arbeitsgedächtniskomponenten zueinander im Entwicklungsverlauf aufschlussreich. Zum einen bietet dies einen Zugang zum tieferen Verständnis der Veränderung oder Nicht-Veränderung kognitiver Prozesse und ihres Zusammenwirkens, was wiederum Einfluss nimmt auf die Theorieentwicklung kognitiver Informationsverarbeitung im Sinne des Arbeitsgedächtnisses. Zum anderen ermöglicht die Dokumentation von Strukturvarianz oder -invarianz die Interpretation des Zusammenhangs von Arbeitsgedächtniskomponenten mit weiteren Variablen der kognitiven Leistungsfähigkeit. Letzteres wiederum hat auch praktische Implikationen, wie zum Beispiel in der Diagnostik. Beispielsweise belegen Studien aus jüngerer Zeit mehr und mehr die Bedeutung des Arbeitsgedächtnisses als mögliches diagnostisches Merkmal für die leistungsbezogene schulische Entwicklung von Kindern (vgl. Gaup, 2003; Schuchhardt, Mähler & Hasselhorn, 2008). Das Baddeley’sche Modell postuliert jedoch eine komplexe Struktur. Wäre diese starken Veränderungen im kognitiven Entwicklungsverlauf von Kindern unterworfen, so hätte dies erhebliche Konsequenzen für die Betrachtung und Interpretation der Zusammenhänge und gegebenenfalls für die Prädiktion anderer Leistungsmerkmale (z.B. der Leseleistung), welche ihrerseits in entwicklungsbedingter Veränderung stehen. Ist zum Beispiel die Funktionstüchtigkeit der phonologischen Schleife diagnostischer Indikator einer Teilleistungsstörung wie der Dyslexie in einer bestimmten Altersgruppe, hängt der Erklärungswert dieser

Arbeitsgedächtniskomponente für andere (z.B. jüngere) Altersgruppen, von der Nachweisbarkeit dieser Komponente in der entsprechenden (z.B. jüngeren) Altersgruppe ab. Im Sinne der Konstruktvalidität und der diskriminanten Validität der einzelnen Arbeitsgedächtniskomponenten schließt dies auch die Trennbarkeit dieser Komponente von anderen Komponenten (wie zum Beispiel der zentralen Exekutive) ein. Die Trennbarkeit der Arbeitsgedächtniskomponenten sollte im Entwicklungsverlauf natürlich bestehen bleiben, oder eine Veränderung des Zusammenhangs gegebenenfalls entsprechend dokumentiert werden. Bis dato scheint es lediglich zwei Arbeiten zu geben, deren Ergebnisse für die Invarianz der Struktur über mehrere Altersgruppen im Kindes- und Jugendalter hinweg sprechen (Alloway et al., 2006; Gathercole et al., 2004). Gathercole et al. (2004) untersuchten den Altersbereich von 4 bis 15 Jahren und fanden, dass sich die dreigliedrige Struktur ab dem 6. Lebensjahr bereits nachweisen lässt und das Verhältnis der drei Komponenten zudem relativ altersinvariant ist. Die Ergebnisse von Alloway et al. (2006) zur Arbeitsgedächtnisstruktur in einer Stichprobe im Alter von 4 bis 11 Jahren sprechen ebenfalls für eine altersinvariante Struktur des Arbeitsgedächtnisses nach Baddeley (1986). Beim Vergleich dieser beiden Studien innerhalb einander entsprechender Altersgruppen zeigt sich, dass die Höhe der Interkorrelationen der latenten Faktoren unterschiedlich groß ausfällt. Beispielsweise war der Zusammenhang zwischen den beiden Subsystemen bei Gathercole et al. (2004) auf latenter Faktorebene .32 bei 8- bis 9-Jährigen, bei Alloway et al. (2006) hingegen bei .55 bei 7- bis 8-Jährigen. Hinsichtlich der möglichen entwicklungsbezogenen Veränderungen der Arbeitsgedächtnisstruktur berichten beide Studien (Alloway, 2006; Gathercole, 2004) stabile Zusammenhänge der Arbeitsgedächtniskomponenten über unterschiedliche Altersgruppen hinweg. Wenn auch nicht signifikant (vgl. Gathercole et al., 2004) zeigten sich jedoch gewisse Schwankungen in der Höhe der Zusammenhänge dieser Komponenten im Vergleich unterschiedlicher Alterskohorten von Kindern. Diese Schwankungen betreffen sowohl die Höhe der Zusammenhänge innerhalb der einzelnen

Studien im Laufe der Entwicklung, als auch das Ausmaß der Veränderung dieser Zusammenhänge im Laufe der Entwicklung zwischen den beiden Studien. Bei Gathercole et al. (2004) stieg beispielsweise der Zusammenhang der phonologischen Schleife zur zentralen Exekutive von .73 bei 6- bis 7-Jährigen auf .92 bei 10- bis 12-Jährigen. Bei Alloway et al. (2006) stieg dieser Zusammenhang von .32 bei 4- bis 6-Jährigen auf über .51 bei 7- bis 8-Jährigen und sank auf schließlich .43 bei 9- bis 11-Jährigen. Wie bereits erwähnt sind diese Zusammenhangsunterschiede nicht signifikant (vgl. Gathercole et al., 2004), bzw. die Prüfung der entwicklungsbezogenen Schwankungen innerhalb des Modells wird nicht berichtet (Alloway et al., 2006). In ersterem Fall lässt sich argumentieren, dass diese Schwankungen rein zufällig und auf Messfehler zurückzuführen sind. Vor dem Hintergrund der bisher wenigen Studien zur Strukturinvarianz des Arbeitsgedächtnisses bei Kindern sowie der Nicht-Überprüfung der Varianz einzelner Faktorinterkorrelationen bei Alloway et al. (2006) sind daher weitere Studien zur Überprüfung der Invarianz der Baddeley'schen Modellannahme (1986) notwendig.

2.2 Zusammenfassung der Forschungsfragen 1

Zusammenfassend lassen sich zwei Hauptforschungsfragen aus den dargelegten Überlegungen ableiten. Diese werden als Grundlage der ersten eigenen empirischen Arbeit (Michalczyk et al., Einladung zur Resubmission bei European Journal of Psychological Assessment, 22. September 2011) daher im Folgenden kurz dargestellt. Die erste Hauptforschungsfrage betrifft die Struktur des Arbeitsgedächtnisses bei Kindern. Wie in der Übersichtsarbeit (Michalczyk & Hasselhorn, 2010) dargelegt wurde, existiert eine Vielzahl methodischer Ansätze und daraus resultierender Modellvorstellungen zum Arbeitsgedächtnis. Dabei scheint das Arbeitsgedächtnismodell von Baddeley (1986) besonders geeignet für weitere entwicklungspsychologische Forschung, da die meisten bisherigen Befunde auf diesem Modell aufbauen und in Richtung seiner Gültigkeit im schulischen und auch vorschulischen Altersbereich deuten (Alloway et al., 2006; Alloway et al., 2004; Gathercole et al., 2004; Roebers & Zoelch, 2005). Aufbauend auf diesen, vorwiegend dem korrelativen Forschungsansatz zugehörigen, Befunden und an diese weiter anknüpfend, stellt sich die Frage, ob die dreigliedrige Struktur des Arbeitsgedächtnisses nach Baddeley (1986) schon ab dem fünften Lebensjahr bei Kindern zu finden ist. Hierzu gehören die Frage nach der Anzahl der Komponenten, die Zusammensetzung derselben sowie ihr Verhältnis zueinander, was ihre Trennbarkeit und hierarchische Ordnung mit einschließt. Die zweite Forschungsfrage betrifft die möglichen Veränderungen dieser Arbeitsgedächtnisstruktur im Laufe der Entwicklung, also die Varianz oder Invarianz der funktionalen Interdependenz der phonologischen Schleife, des visuell-räumlichen Notizblocks und der zentralen Exekutive.

2.3. Untersuchung 1: Age Differences and Invariances of Working Memory Functioning in Children[2]

Baddeley's model (1986) represents one of the most prominent approaches in working memory research (e.g., Conway, Jarrold, Kane, Miyake, & Towse, 2007; Jarrold & Towse, 2006; Michalczyk & Hasselhorn, 2010). It consists of a central executive and two subsystems: the phonological loop and the visual-spatial sketchpad. The central executive works as a flexible master unit that controls and allocates resources and monitors information processing across informational domains (see Baddeley, Emslie, Kolodny, & Duncan, 1998; Baddeley & Hitch, 1974). The phonological loop stores verbal information temporarily, whereas the visual-spatial sketchpad is specialized in processing visual and spatial information. In adult

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[2] Die Erstellung dieses Beitrags wurde gefördert durch die LOEWE-Initiative der Hessischen Landesregierung im Rahmen des "Center for Individual Development and Adaptive Education of Children at Risk" (IDeA), Frankfurt, Germany. Das Manuskript wurde am 22.September 2011 bei European Journal of Psychological Assessment zur Resubmission eingeladen.

populations, this working memory model has been validated by a great number of findings such as experimental and neuropsychological studies (cf., Baddeley & Logie, 1999), neuroimaging and neuropsychological studies (e.g., Henson, 2001; Vallar & Papagno, 2002), and the individual differences approach (for a review, see Jarrold & Towse, 2006). In children, however, evidence is sparser, but does suggest the separability of these working memory components. The visual-spatial sketchpad and the phonological loop seem to be independent in 5- to 8-year olds (Pickering, Gathercole, & Peaker, 1998), in 5-year olds (Roebers & Zoelch, 2005), and 11- and 14-year olds (Jarvis & Gathercole, 2003). In the latter age group, this dissociation was also reported in complex-span memory tasks. So far, some first findings suggest a tripartite working memory structure in young children, that is, from 6 years on and possibly earlier (Gathercole et al., 2004) and in 4- to 6-year-olds (Alloway et al., 2006). However, contradictory findings exist. For instance, in six and seven-year-olds (Gathercole & Pickering, 2000) the visual-spatial sketchpad was not clearly dissociable from the central executive. Otherwise, first findings seem to point to the invariance of the tripartite working memory structure in children. However, findings are few and come from English speaking countries only (Alloway, Gathercole, & Pickering, 2006; Gathercole et al., 2004). In sum, Baddeley's model (1986) remains to be further validated in children. First, it is unclear how many components working memory in children is composed of, and furthermore, how these are organized in relation to one another. Second, working memory structure might change over childhood. These questions are especially important with regard to a broad conception of the central executive in young children, which has been conceptualized very differently in the above named studies. In particular, our hypotheses are as follows: We expect to find the tripartite structure of working memory as described in the model by (Baddeley, 1986) in all age groups ranging from 5 to 12 years. Assuming a hierarchical structure across all age groups, we expect the phonological loop to be only moderately related to the visual sketchpad. However, the central executive should relate stronger to both subsystems. Furthermore, we expect both the structure and the functional interrelations of the respective components to be invariant throughout development. The relation of the central executive and the phonological loop should be weaker in the youngest age group only. This should be the case because spontaneous rehearsal is moderated by the central executive but does not reliably occur from the age of 7 years onwards (cf., Gathercole & Hitch, 1993).

Method

Sample/Participants

1669 children (856 boys and 813 girls) from kindergartens, primary and secondary schools in Frankfurt/M., Göttingen, and Eichstätt and surrounding areas in Germany participated in this study. Parental consent had been obtained for testing of each child. The sample consisted of 134 5-year olds (68 boys and 66 girls), 150 6-year olds (73 boys and 77 girls), 228 7-year olds (123 boys and 105 girls), 237 8-year olds (116 boys and 121 girls), 225 9-year olds (127 boys and 98 girls), 214 10-year olds (109 boys and 105 girls), 278 11-year olds (135 boys and 143 girls), 203 12-year olds (105 boys and 98 girls). However, in data analysis, data were grouped into three age bands: 5 to 6, 7 to 9, and 10 to 12 (see below).

Procedure

Subjects performed on twelve tests from the German Working Memory Test Battery for Children, 5 to 12 years (AGTB 5-12; Hasselhorn et al., in press.). In the presence of an experimenter, the child receives standardized instructions and interacts with the program via a child-friendly interface. Practice trials precede each recorded testing, prior to actual testing. Instructions and task presentation were computer based. Children were tested individually in a quiet area of the kindergarten or the school and a break was given after six tasks, which resulted in a testing time of approximately 2 x 30 minutes.

Working Memory Measures

Four of the working memory subtests assess the phonological loop's efficiency (word span forward one/three syllable, digit span forward, nonword repetition), two address the visual-spatial working memory system (matrix, Corsi-block), and six subtests measure different central executive working memory functions (digit span backward, colour span, complex span, counting span, stroop, and go/no-go). In addition, some of these subtests are adaptive, that is, successful recall of a presented item sequence leads to an increase of the number of items a child has to recall. Respectively, repetitive poor performance leads to a decrease of task difficulty. The adaptive subtests were: word span forward one/three syllables, digit span forward, matrix span, Corsi-block, digit span backward, colour span, complex span, and counting span. All adaptive subtests and nonword repetition started with a pre-set level of difficulty (i.e., number of items to recall) according to the child's age. For example, in the word span forward (one syllable) task a 5-year old starts with two words, whereas a 7-year old starts with three words in the first trial. In the consecutive trial, the number of correctly recalled items determines the number of presented items to recall. For instance, if a child repeats the presented three words correctly in the word span forward task and the three next words in the subsequent trial again, then the following trial requires the child to recall four words. If the child fails to reproduce three words correctly in two consecutive trials, the child is then presented with a sequence of only two words. Table 2 shows the retest-reliabilities for children from 5 to 8 and 9 to 12 years (AGTB 5-12; Hasselhorn et al., in press).

Efficiency of the phonological loop

In the *word span forward (one syllable)* task, the child is asked to recall a sequence of one-syllable words in the presented order. Each set starts with an acoustic signal and the words are presented every 1.5 seconds. The test encompasses ten trials. The *word span forward (three syllables)* task works analogically to the word span forward (one syllable) task, each presented word being composed of three syllables. In the *digit span forward* task, the child is required to recall a series of digits (two to nine digits per trial at maximum) in the same way as described before. In every sequence each numeral occurs only once.

In the *nonword repetition* task, the child hears a wordlike sound that does not belong to the German language and has no meaning in the German language (e.g., “limparett”). The nonwords are presented by the computer and the child is required to repeat each nonword immediately. The child’s answer is recorded by the experimenter as “right” or “wrong”. After a break of 1.5s, the next nonword is presented. The number of syllables in the task varies from 2 to 6. Three lists of varying difficulty exist and are presented according to the child’s age: Children aged between 5;0 and 6;11 receive two to four syllable words. Children aged between 7;0 and 9;11 received 3-5-syllable words and children aged 10;0 to 12;11 receive four to six syllable words. Within each session, half of the words are presented in a modulated manner, that is, the sound of the word is contorted. In the nonword repetition task the number of correctly repeated items out of 24 trials is scored.

Visual-spatial working memory

Visual working memory is assessed by a *matrix span* task, in which an increasing number of black squares are presented in a 4x4 matrix. Over ten trials, the number of black squares increases adaptively as a function of the child’s performance in recalling the black squares in the white 4x4 matrix (two to eight black squares at maximum). After the matrix disappears, a mask (100ms) is presented in order to prevent afterimages. The child is required to indicate on the touchscreen where she or he had seen the squares in the previously presented matrix. Presentation time of a single matrix depends on how many squares it included. For each square, presentation time increased by 1.2 seconds. Thus, a three square matrix was presented for 3.6 seconds.

In the *Corsi-block task*, the child is presented with a grey surface containing nine empty blocks, randomly scattered across the screen. A yellow smiley appears serially in the blocks, with 950ms per block with an interstimulus interval of 50ms. Subsequent to the presentation the child is required to indicate on the touchscreen in the serial order of the blocks where the smiley has previously appeared.

Central-executive functioning

Six tasks are administered to assess the efficiency of central executive working memory functioning. In the *digit span backward* task, the child is required to recall verbally presented numbers in the reverse order. Each set starts with an acoustic signal and the numerals are presented every 1.5 seconds. Same as in the digit span forward task, in each sequence each numeral occurred only once.

In the *colour span backward* task, differently coloured dots (i.e., starting with a blue circle, followed by a red circle) are serially presented to the child on the screen. Each coloured dot was presented for 1,900 milliseconds. In order to prevent an afterimage, a mask occurred (300ms) in between the different colours. After the last presented coloured dot, a circle composed of eight coloured dots is presented. This circle includes all of the coloured dots that were previously presented in the task. Then, the child is required to identify the presented colours in the reverse order by indicating the respective dots on the touchscreen. The location of the coloured dots within the circle changed in each sequence in order to prevent spatial encoding.

In the *complex span* task, the child is presented a series of (two-syllable) objects. After each object, the child is required to declare whether the object is edible or non-edible. The child is allowed 2,000 milliseconds to answer, and the answer is recorded by the experimenter. Once the last stimulus of the series has been presented and is classified by the child, a sound and a question mark appear, indicating that the child can now start to recall the objects in the presented order.

In the *counting span* task, the child is presented a series of pictures, each of which consists of blue squares and circles, varying from 1 to 9 circles. After the presentation of the picture, the child is asked to count the number of circles and say it aloud (e.g., “four”). The test then goes on to the next picture (e.g., “nine”). At the end of the task, the child is required to recall the number she or he had has spoken aloud (e.g., “four, nine”).

In the *go/no-go* task, the child is asked to press a key on the touchscreen whenever she or he sees a specified item, like, for example, a yellow balloon. In a no-go trial, the item is similar but distinct (e.g., a red balloon). In the course of the task, the items requiring the child to press the key increase in number and complexity. The test score is the number of correct reactions or reaction inhibitions in a series of 24 presented trials. Signal detection theory applies to the go/no-go task; hence, we calculated the ability to discriminate (d') over 24 trials according to the procedure described in (Stanislaw & Todorov, 1999).

The *stroop* task measures the inhibition of irrelevant information: A stylized picture of a man or woman is therefore presented on the touchscreen. Simultaneously, the child is given a verbal stimulus which says “man” or “woman”. The verbal stimulus can be either congruent or incongruent with the visual stimulus. The child is required only to react to the visual stimulus and tap on the touchscreen while ignoring the verbal stimulus. The task encompasses 24 trials and the number of correctly repeated congruent trials is scored.

Scoring. In all adaptive tasks, the mean of the ten trials was scored for each child. The number of points given for a child answering correctly equalled the length of the correctly reproduced series. For instance, in the word span forward task, the correct repetition of four words results in four points. If a child fails to recall a series correctly twice in a row, the number of given points is length of series minus one (e.g., failing to reproduce four words twice would result in three points and the task level in the consecutive trial would go back to three words). Therefore, the minimum achievement score is “one point”, because the shortest series is two words. The mean over all 10 trials per task was used as the indicator of the respective variable.

Results

Descriptive Statistics

The means and standard deviations scores for each working memory measure are shown in Table 1 as a function of age group.

Table 1

Means, standard deviation as function of age group

	Age (in years)		
Measure	5-6 (n = 284)	7-9 (n = 690)	10-12 (n = 695)
Word span forward (one syllable)			
M	3.04	3.56	4.13
SD	0.58	0.68	0.73
Word span forward (three syllable)			
M	2.62	2.91	3.20
SD	0.40	0.44	0.50
Digit span forward			
M	3.22	4.08	4.83
SD	0.72	0.75	0.78
Nonword repetition			
M	14.69*	14.5*	13.52*
SD	4.44	4.38	4.39
Matrix span			
M	2.76	4.18	5.57
SD	0.78	1.24	1.37
Corsi-block			
M	2.90	3.88	4.71
SD	0.81	0.82	0.79
Digit span backward			
M	2.13	2.99	3.69
SD	0.62	0.67	0.75
Colour span backward			
M	1.93	2.71	3.50
SD	0.60	0.79	0.86
Complex span			
M	2.06	2.84	3.37
SD	0.59	0.72	0.76
Counting span			
M	1.80	2.90	3.63
SD	0.63	0.81	0.85
Go/no-go			
M	1.22	1.81	2.34
SD	0.84	0.78	0.70
Stroop			
M	49.99	49.99	50
SD	9.94	9.96	9.97

Note. The different age groups received word lists of different difficulties, which explains a stable level of points received in all age groups.

Correlational Analyses

Table 2 shows the correlations of the working memory subtests of the overall sample. In order to control for influence of age, correlations were based on the age specific t-values of the participants. The calculation of the t-values based on the age intervals of 5;0 to 5;5 years, 5;6 to 5;11 years, 6;0 to 6;5 years, 6;6 to 6;11 years, 7;0 to 7;5 years, 7;6 to 7;11 years, 8;0 to 8;11 years, 9;0 to 9;11 years, 10;0 to 10;11 years, 11;0 to 11;11, and 12;0 to 12;11. Correlations of tests within the phonological loop (word span forward tasks, digit span forward, nonword repetition) ranged from r = .44 to r = .62. Measures of the visual-spatial sketchpad (matrix, Corsi-block) correlated with r = .37. Measures of the central executive (digit span backward, colour span backward, complex span, counting span, go/no-go, stroop) correlated from r = .10 to r = .47. It is noteworthy that within the central executive, the go/no-go task only correlated very low with the other tasks, (r = .12 to .19); the same was the case for the stroop task (r = .10 to .15). All correlation coefficients for the 5- to 12-year-old children in Table 2 were significant at the .01 level, except for stroop with word span forward (one syllable), word span forward (three syllables), and with nonword repetition. The significant correlations were low to high in strength (*r*s ranging from .09 to .62).

Table 2

Correlations and retest-reliabilities based on age group specific t-values of the overall sample

WM component		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Phonological Loop													
1	Word span forward (one syllable)	-											
2	Word span forward (three syllable)	.56*	-										
3	Digit span forward	.62*	.60*	-									
4	Nonword repetition	.44*	.44*	.46*	-								
Visual-spatial sketchpad													
5	Matrix span	.16*	.14*	.20*	.13*	-							
6	Corsi-block	.21*	.22*	.30*	.12*	.37*	-						
Central executive													
7	Digit span backward	.41*	.38*	.48*	.28*	.29*	.34*	-					
8	Colour span backward	.36*	.34*	.44*	.26*	.33*	.33*	.47*	-				
9	Complex span	.35*	.34*	.38*	.24*	.27*	.29*	.39*	.37*	-			
10	Counting span	.44*	.39*	.49*	.28*	.26*	.31*	.41*	.41*	.37*	-		
11	Go/no-go	.14*	.15*	.15*	.14*	.14*	.12*	.12*	.18*	.19*	.16*	-	
12	Stroop	.04	.03	.09*	.01	.17*	.16*	.10*	.15*	.12*	.13*	.11*	-
Retest-reliabilities													
5-8 years[a]		.64	.61	.68	.74	.51	.60	.59	.49	.51	.61	.40	.66
9-12 years[b]		.75	.59	.78	.85	.49	.61	.67	.67	.44	.62	.39	.70

Note. Correlations are based on the age group related t-values. This was due to control for age. The age groups are 5;0 to 5;5 years, 5;6 to 5;11 years, 6;0 to 6;5 years, 6;6 to 6;11 years, 7;0 to 7;5 years, 7;6 to 7;11 years, 8;9 to 8;11 years, 9;0 to 9;11 years, 10;0 to 10;11 years, 11;0 to 11;11 years, and 12;0 to 12;11 years.

[a] n = 145

[b] n = 102

*p < .01.

Confirmatory Factor Analysis

In order to model the structure of working memory, confirmatory factor analysis was carried out using AMOS 16 (Arbuckle, 2007). Following McDonald and Ho (McDonald & Ho, 2002), model adequacy was evaluated by global fit indices. In the chi-square statistic, a nonsignificant value is an indicator for a good model fit, stating that there is no significant difference between the model and the collected data. However, this statistic is very sensitive to sample size (Kline, 1998). Therefore, we applied further indices that are more sensitive to model specification, such as the comparative fit index (CFI; Bentler, 1990) and the normed fit index (NFI; Bentler & Bonett, 1980). In these indices, a value equal to or higher than .90 represents a good fit, a value between .90 and .95 is acceptable, and a value above .95 is good. In the RMSEA (Hu & Bentler, 1999) a value equal to or lower than .08 is acceptable, whereas a value equal to or lower .05 represents a good fit (McDonald & Ho, 2002). Similar to the correlational analysis, calculations were based on the participants' age specific t-values in order to control for age.

Age specific models

First, we addressed the question of working memory structure in the different age bands. We found that the same working memory model provided a good fit for the data in all three different age bands: The model for the data of the *5- to 6-year-olds* showed a good model-fit ($\chi 2$ (51, n = 284) = 23.19, p > .05; RMSEA = .03; NFI = .90; CFI = .97). In the group of *7- to 9-year olds*, the model-fit was good: $\chi 2$ (51, n = 690) = 125.16, p < .01, RMSEA = .04, NFI = .94, and CFI = .96. It is noteworthy that the chi-square index may have become significant due to sample size. In the group of *10- to 12-year olds*, the model-fit was good ($\chi 2$ (51, n = 695) = 104.18, p < .01; RMSEA = .03; NFI = .96; CFI = .98). Again, the chi-square statistic may have been significant due to sample size. The phonological loop correlated with the visual-spatial sketchpad (*r* = .48) and with the central executive (*r* = .83). The visual-spatial sketchpad and the central executive correlated with *r* = .81. It is noteworthy that the nonword repetition task had the lowest loading on this factor in the 5- to 6-year olds with .38, as opposed to .56 in the 7- to 9-year olds and .65 in the 10- to 12-year olds. The go/no-go task and stroop task loaded poorly on the central executive factor in all age groups. Table 3 displays the factor loadings of the measurement model for all age groups and the respective model-fits. Figure 1 shows the structural model for the different age groups.

Table 3

Factor loadings for the different age groups

Construct	**Indicators**	**Factor loadings in age group**		
		5-6 (n = 284)	**7-9** (n = 690)	**10-12** (n = 695)
Phonological loop (PL)	Word span forward (one syllable; WSF1)	.68	.75	.80
	Word span forward (three syllables; WSF3)	.67	.76	.74
	Digit span forward (DSF)	.87	.83	.83
	Nonword repetition (NR)	.38	.56	.65
Visual sketchpad (VSSP)	Matrix span (MX)	.51	.62	.58
	Corsi-block (CB)	.61	.68	.62
Central executive (CE)	Digit span backward (DSB)	.64	.64	.71
	Colour span backward (CSB)	.65	.60	.72
	Complex span (KS)	.56	.59	.59
	Counting span (CS)	.61	.66	.67
	Go/no-go (GNG)	.26	.23	.30
	Stroop (SP)	.13	.20	.23
Index of model fit				
Chi-Square		67.060	125.16	104.18
Df		51	51	51
p		.065	.000	.000
CFI		.97	.96	.98
NFI		.90	.94	.96
RMSEA		.03	.04	.03

Note. In the 7 to 9-year olds the chi-square fit-index did not apply due to sample size.

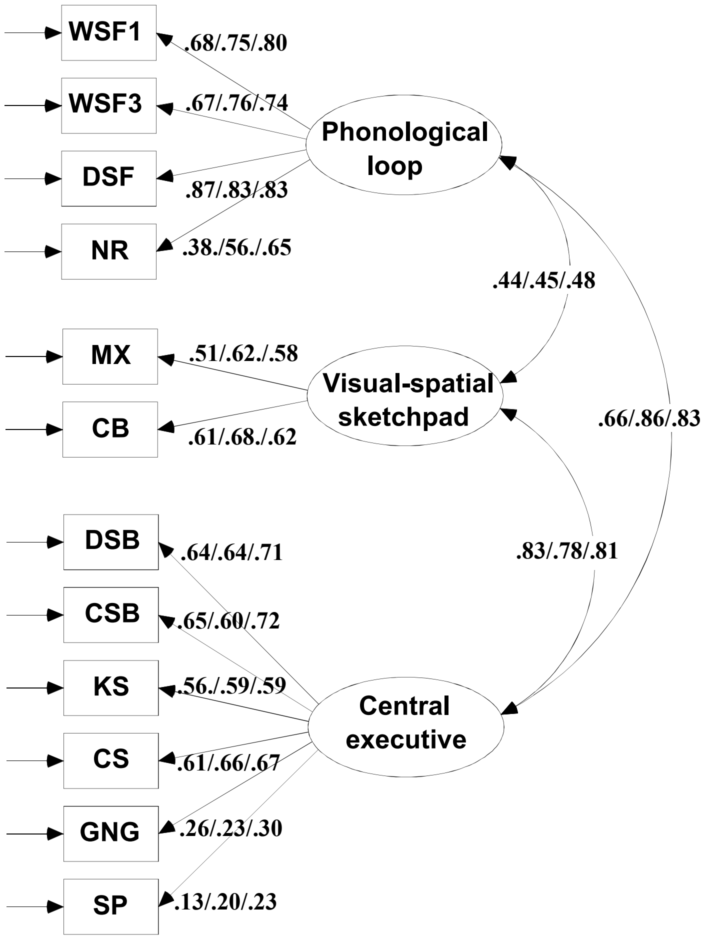

Figure 1. Three factor model across the three age groups. In a row of three values, the first value indicates factor loadings/ latent factor intercorrelations the age group 5 to 6, the second for the age group 7 to 9, and the third for the age group 10 to12.

Functional interrelations of the latent factors: Nested model comparison

Second, we addressed the age invariance of functional interrelations between the different working memory components across the age groups of 5-6-year olds, 7-9-year olds and 10-12-year olds, by comparing the latent factor intercorrelations across the three age groups (e.g., does the phonological loop correlate higher with the central executive in the 5 to 6-year olds than in the 7-9-year olds?). Across the age groups, the phonological loop and the visual-spatial sketchpad correlated with r = .44 to r = .48. The relation between the visual-spatial sketchpad and the central executive showed the highest coefficient in the 5- to 6-year olds (r = .85) and was slightly smaller in the older age groups (7- to 9-year olds: r = .78, 10- to 12-year olds: r = .80). The phonological loop and the central executive correlated with r = .66

(5- to 6-year-olds) and then increased in the older age groups (7-9-year olds: r = .85, 10- to 12-year olds: r = .82). In order to test whether these latent factor intercorrelations differed significantly across the different age groups, we investigated whether the data fulfilled the criterion of factorial invariance (cf., Vandenberg & Lance, 2000). Establishing factorial invariance involves subsequent testing for a hierarchy of configural, weak, strong, and strict factor invariance: Configural invariance implies that the same pattern of non-zero factor loadings fits all age groups. Weak factorial invariance requires factor loadings to be invariant across age groups. Strong factorial invariance implies that, in addition, specific intercepts of the indicator variables are equal across groups. Strict factorial invariance implies that the factor loadings, intercepts, and the residual variances are equivalent across groups. To assess factorial invariance across different age groups, we imposed stepwise constraints on parameters of a model that is tested across different subsamples. After each step, the more constrained and thereby statistically nested model was compared to the previous one. This comparison is based on the chi-square values and results in a chi-square statistic with degrees of freedom corresponding to the difference of degrees of freedom of the two models. A high p-value of this statistic indicates that no reliable difference exists between the two models. If both models are likely to be equal, the more parsimonious model (in which more parameters are fixed as opposed to the previous one) is to be preferred.

Nested model comparison

In a first step, we tested whether the model with all parameters freely estimated (Model 1) was statistically different from a model in which the factor loadings were constrained to be equal across the three different age groups (Model 2). Comparing the chi-square values of the freely estimated Model 1 vs. Model 2 showed no reliable difference between the two models with $\Delta\chi2$ (18, N = 1669) = 23.19, $p > .05$. Therefore, we chose the more parsimonious Model 2. In a second step, we constrained the factor loadings of the latent factors and, in addition, the latent factor variances across the three age groups to be equal (Model 3). Again, the chi-square-difference statistic indicated that the nested model (Model 3) did not significantly differ from the previous one (Model 2) with $\Delta\chi2$ (6, $N = 1669$) = 9.73, $p > .05$ indicating that the more restricted model should be preferred. In a third step, we imposed equal factor loadings, factor variances, and error variances of the manifest variables across the three age groups (Model 4). Model 4 was more parsimonious than Model 3 to estimate the data and showed no difference to the latter with $\Delta\chi2$ (24, $N = 1669$) = 28.25, $p > .05$. In a fourth step, we imposed a model that demanded equal factor loadings, latent factor variances, error variances of the manifest variables, and latent factor covariances (Model 5). The resulting model differed significantly from the previous one $\Delta\chi2$ (6, $N = 1669$) = 16.07, $p < .05$. However, we had expected differences in the latent factor intercorrelations, especially with respect to the relation of the phonological loop and the central executive, in the 5- to 6-year olds. Therefore, in Model 5a, the factor loadings, the variances of the latent factors, the error variances of the manifest variables, and the covariances of the latent factors were set to be equal. Only the covariance of the phonological loop and the central executive in the 5- to 6-year olds was freely estimated. This model was significantly different from model 5 with $\Delta\chi2$ (1, $N = 1669$) = 15.30, $p > .000$ and fitted the data better. In addition, we formally tested if any other model in which one latent factor covariance was estimated freely, with the remaining latent factor covariances being set to be equal across the three age groups, fitted the data better than Model 5, but none did to the degree that model 5a did. Table 4 shows the results of the nested models.

Table 4

Comparison of fit in the nested models for whole sample

		Model-Fit		**Comparison of models**		
Model	**Parameters set equal across age groups**	*Chi-Square*	*df*	*Chi-Square-Diff*	*df - diff*	*p*
Model 1	All parameters estimated freely.	292.44	153	-	-	-
Model 2	FL	315.64	171	23.19	18	.183
Model 3	FL, Var	325.37	177	9.73	6	.136
Model 4	FL, Var, ErrVar	353.62	201	28.25	24	.250
Model 5	FL, Var, ErrVar, Cov	369.70	207	16.07	6	.013
Model 5a	FL, Var, ErrVar, Cov. Age group 5-6: Cov of PL and CE estimated freely.	354.39	206	15.30	1	0.00

Note. FL: Factor loading of the latent factors; Var: Variance of latent factors; ErrVar: Error variance of manifest variable;
Cov: Covariance of latent factors.

Discussion

In our study, we investigated age differences and invariances of the structure of working memory in 5- to 12-year old children. Our results revealed a good fit of the same structural model in children aged 5 to 6, 7 to 9, and 10 to 12 years. The latent factor intercorrelations of the components did not change. Only in the 5- to 6-year olds, the correlation of the phonological loop and the central executive was lower than in the older age groups. The results indicate that modelling of working memory structure with a phonological loop, a visual-spatial sketchpad, and a central executive (Baddeley, 1986) is adequate even in the age range of 5 to 12 years. As such, our findings add to previous studies (e.g., Alloway, Gathercole, & Pickering, 2006; Gathercole et al., 2004) showing that all three components can be assessed in German children. A second goal of our study was to assess whether the functional interrelations of the working memory components remain age invariant. Across all age groups, the central executive was always highly related to both the phonological loop as well as the visual-spatial sketchpad, whereas the phonological loop was moderately associated with the visual-spatial sketchpad. These findings are in concordance with the hierarchical conception of a central executive that coordinates the flow of information through working memory and is responsible for the transmission and retrieval of information from the slave systems (Baddeley, 1986). Also, the findings are consistent with previous findings in young children (Alloway et al., 2006; Gathercole et al., 2004). As mentioned above, in the present study, the relation of the phonological loop and the central executive was weaker in the 5- to 6-year-olds with $r = .66$ than in the other age groups with $r = .85$ (7- to 9-year-olds) and $r = .82$ (10- to 12-year-olds). A similar increase of the latent factor correlation was reported by Gathercole et al. (2004) where the phonological factor correlated with the central executive factor with $r = .73$ in 6 to 7-year olds and $r = .74$ in 8- to 9-year olds, which then increased to $r = .92$ in 10- to 12-year olds, and $r = .90$ in 13- to 15-year olds. In our study, however, this increase of correlation occurred earlier, that is, after the age of 6 years. With regard to our study, this finding corresponds to the assumption that the spontaneous use of rehearsal strategies occurs in children from the age of 7 years on (for a review, see Gathercole, 1998; Gathercole & Hitch, 1993). An alternative explanation for this finding might be that children in older age groups process central executive tasks more efficiently. This would imply that in older children, these tasks require less central executive effort, and therefore, the variance in these tasks is more related to the capacity of the phonological loop. This, in turn, would mean that in older children, the central executive could be eliminated as a separate factor, at least with regard to the tasks we administered in this study. However, the latent factor of the central executive correlates consistently with the latent factor of the visual-spatial sketchpad.

With regard to the central executive, our data do not suggest central executive changes in terms of structural changes or functional interrelations, except for the relation of the phonological loop and the central executive in the youngest age group. Notably, the central executive factor was heterogeneous as indicated by the factor loadings. However, the factor loadings of the central executive were similar in size across age groups, indicating that a broad conception of the central executive seems to be valid from 5 to 12 years.

Limitations and outlook

In this study, we addressed the working memory structure and its invariance based on Baddeley's model (1986). Notably, different theoretical accounts of working memory exist. Some conceptions favour to view working memory as a limited capacity system in which processing and storing operations compete for a limited pool of resources (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) while others underline the importance of attention (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). Also, an extension of Baddeley's model is conceivable. Baddeley (2000) introduced the episodic buffer as an additional component of working memory. This temporary buffer has a restricted capacity and is a multidimensional representation system fractionated from the central executive. It integrates current representations from other cognitive systems (such as long-term memory and the phonological loop) into so-called episodes. Future research is challenged to test if this new working memory component is apparent across childhood and how it relates to other components.

2.4 Weiterführende Erörterung

Die im voranstehenden Kapitel dargestellte Studie belegt die Gültigkeit der Struktur des Arbeitsgedächtnisses nach Baddeley (1986) im Alter von 5 bis 12 Jahren sowie die überwiegende Invarianz der funktionalen Interdependenz derer drei Komponenten. Lediglich der Zusammenhang der phonologischen Schleife und der zentralen Exekutive stieg bei den 5- bis 6-Jährigen vs. den 7- bis 9-Jährigen signifikant an. Dieser Befund ist erklärbar mit den theoretischen Ausführungen von Gathercole und Hitch (1993), wonach vor dem 7. Lebensjahr kaum mit einem Auftreten von Rehearsalprozessen gerechnet werden kann. Diese

Rehearsalprozesse wiederum werden jedoch zentral-exekutiv mitgesteuert, was sich beispielsweise im Anstieg der latenten Faktorinterkorrelation zwischen phonologischer Schleife und zentraler Exekutive in der Altersgruppe der 7- bis 9-Jährigen im Vergleich zur jüngeren Altersgruppe zeigte. Die signifikant niedrigere latente Faktorinterkorrelation dieser beiden Arbeitsgedächtniskomponenten könnte also auf die noch nicht vorliegende Automatisierung der Aktivierung des subvokalen Rehearsalprozesses (Hasselhorn et al., 2000; siehe Abschnitt 2.1) in der Altersgruppe der 5- bis 6-Jährigen zurückzuführen sein.

Ein weiterer Aspekt, welcher zusätzlich zur Diskussion der vorgelegten Arbeit weiter eruiert werden soll, ist die Zusammensetzung der einzelnen Arbeitsgedächtniskomponenten. Die Arbeiten von Gathercole et al. (2004) und Alloway et al. (2006) fokussieren nicht auf diesen Themenpunkt. Möglicherweise ist dies zum Teil dem üblichen konfirmatorischen Vorgehen innerhalb des Ansatzes interindividueller Differenzen geschuldet. Innerhalb dieses werden (nach Möglichkeit hypothetiko-deduktive) a priori formulierte Annahmen über die Struktur des Arbeitsgedächtnisses unternommen und getestet. Da eine solche Eruierung der Binnenstruktur ein tieferes Verständnis der potentiell involvierten kognitiven Prozesse bei der Arbeitsgedächtnisleistung verspricht, soll an dieser Stelle ergänzend zur Diskussion der angestrebten Veröffentlichung auf die Möglichkeit der Binnendifferenzierung der Arbeitsgedächtniskomponenten eingegangen werden.

Laut Baddeley (2003) ist bisher der phonologischen Schleife in der Forschung die meiste Aufmerksamkeit zuteil geworden. In Hinsicht auf die weiteren Differenzierungen des phonetischen Speichers und des subvokalen Kontrollprozesses (Hasselhorn et al., 2000, siehe Abschnitt 2.1) kann auf Grund der im Rahmen der eigenen empirischen Arbeit vorgestellten Analysen nur wenig Rückschluss gezogen werden. Es bleibt daher nachfolgenden Studien vorbehalten, Veränderungen des Zusammenwirkens dieser weiteren Unterteilungen des phonetischen Speichers und des subvokalen Kontrollprozesses zu ergründen.

Hinsichtlich der Differenzierung des visuell-räumlichen Notizblocks mit einer statischen vs. dynamischen visuell-räumlichen Komponente sensu Logie (1995) zeigte sich, dass der visuell-räumliche Notizblock durch sowohl statische als auch dynamische kognitive Prozesse auch schon im Vorschulalter beschrieben werden kann. Dieses Ergebnis deckt sich mit bisherigen Befunden (z.B. Alloway et al., 2006). Dennoch sind weitere Modellvorstellungen des visuell-räumlichen Arbeitsgedächtnisses möglich. Wie bereits eingangs erwähnt, überprüften beispielweise Mammarella et al. (2008) die Struktur des Arbeitsgedächtnisses bei Dritt- und Viertklässlern. Sie differenzierten innerhalb des visuell-räumlichen Speichers eine aktive visuell-räumliche und drei passive visuell-räumliche Komponenten (sequenziell, simultan-räumlich, visuell). Diese Unterteilung wurde auf Grund der Aufgabenauswahl im Rahmen der vorliegenden Arbeit nicht überprüft, könnte aber einen Folgeschritt im Anschluss an die vorliegende Studie darstellen.

Die zentrale Exekutive ist nach Baddeley (2003) die wichtigste, aber bisher am wenigsten verstandene Komponente des Arbeitsgedächtnisses. Im ursprünglichen Modell (Baddeley & Hitch, 1974) wurde die zentrale Exekutive noch als Pool allgemeiner Verarbeitungskapazität aufgefasst. Komplexe kognitive Prozesse, welche nicht direkt oder spezifisch den Subsystemen zugeordnet werden konnten, wurden dieser zugeschrieben. Wie bereits in Abschnitt 2.1 beschrieben, schlug Baddeley (1986) vor, die zentral-exekutive Funktion der Aufmerksamkeitskontrolle weiter zu differenzieren hinsichtlich des Fokussierens, Teilens und Wechselns von Aufmerksamkeit (Baddeley, 1996). Zusätzlich führte Baddeley (2000) den episodischen Puffer ein, welcher eine von der zentralen Exekutive abgrenzbare Fraktionierung und ein Verbindungsglied zwischen Arbeitsgedächtnis und Langzeitgedächtnis darstellt. Diese Entwicklung zeigt, dass die zentrale Exekutive in der Baddeley'schen Konzeption des Arbeitsgedächtnisses mehr und mehr ihren Status als Homunkulus verlor, wozu die hier vorgelegte eigene empirische Arbeit im Kindesalter ebenfalls einen Beitrag leistet. Allgemein lässt sich festhalten, dass die Differenzierung zentral-exekutiver Prozesse bei Kindern derzeit nicht im gleichen Maße fortgeschritten ist wie in der Forschung an Erwachsenenpopulationen. Allerdings versucht die vorliegende Studie ein weites Spektrum zentral-exekutiver Prozesse abzudecken mittels der Verwendung sowohl von Rückwärtsspannenaufgaben, unterschiedlicher Komplexe Spannen, sowie weniger verbal basierter Inhibitionsparadigmen. Hinsichtlich bisheriger Untersuchungen der Entwicklung der zentralen Exekutive im Kindes- und Jugendalter knüpfen die Ergebnisse der vorliegenden Studie an die Befunde von Alloway et al. (2006) an. Diese Studie unterschied sich allerdings in der Konzeption des zentral-exekutiven Faktors von der vorliegenden. Alloway et al. (2006) erfassten in ihrer Studie die zentrale Exekutive durch Aufgaben, welche zum einen phonologische und zum anderen visuell-räumliche Speicheranforderungen aufwiesen. Die zentral-exekutiven Aufgaben mit phonologischer Speicheranforderung bei Alloway et al. (2006) und der hier vorliegenden Studie waren weitestgehend ähnlich. Während jedoch Alloway et al. (2006) zentral-exekutive Aufgaben mit visuell-räumlicher Speicherkomponente verwendeten, wurden in der vorliegenden Arbeit inhibitionsbasierte Aufgaben sowie Zählspannen und Objektspannen-Paradigmen verwendet. In beiden Studien konnte eine zentral-exekutive Komponente gebildet werden. Diese Ergebnisse sind jedoch nicht konträr, sondern eher komplementär zu betrachten. Grundlegend sprechen die Ergebnisse beider Studien für eine breite Erfassung der zentralen Exekutive schon im Kindesalter und der Stabilität dieser Beschreibung im Entwicklungsverlauf.

Wie bereits erwähnt, ist die Taxonomisierung zentral-exekutiver Aufgaben im Kindesalter noch nicht so weit fortgeschritten wie bei Erwachsenen. Eine mögliche Einteilung zentral-exekutiver Prozesses aus dem Erwachsenenbereich, welche sich auf jüngere Stichproben übertragen lässt, stammt von Miyake et al. (2000). Sie unterscheiden eher basale vs. komplexere zentral-exekutive Prozesse. „Inhibieren“ wäre ein Beispiel für einen eher basalen kognitiven Prozess, während „Planen“, wie es in der Aufgabe „Tower of Hanoi“ (z.B. (Arnett et al., 1997) zum Tragen kommt sollte, für einen komplexeren zentral-exekutiven

Prozess steht. Im Sinne der Einteilung zentral-exekutiver Prozesse nach ihrem Komplexitätsgrad sind die in dieser Arbeit verwendeten zentral-exekutiven Paradigmen eher basaler Art. Die Ergebnisse der Arbeitsgedächtnisstruktur und der weitest gehenden Invarianz der funktionalen Interdependenz ihrer Komponenten ist also nur eingeschränkt generalisierbar, das heißt auf basale zentral-exekutive Funktionen. Zur Überprüfung des Zusammenhangs komplexerer zentral-exekutiver Prozesse betreffs der Gültigkeit der Faktorstruktur im Sinne der Baddeley'schen Modellannahme (1986) wäre es wünschenswert, komplexere Paradigmen auch in jungen Stichproben zu verwenden. Auch in Hinsicht auf die Differenzierung aufmerksamkeitsbezogener Ressourcen lassen sich keine spezifischen Schlüsse auf die von Baddeley (1996) veranschlagten beteiligten Teilprozesse ziehen. Hierzu wäre die Verwendung anderer Paradigmen wie z.B. von Switching-Paradigmen erforderlich und beispielsweise die Adaption bestehender Paradigmen (vgl. Miyake et al., 2000) zu begrüßen.

Die vorliegende Arbeit befasste sich nicht mit der Entwicklung des episodischen Puffers. Was die Validität des episodischen Puffers als Verbindungsglied zwischen Arbeitsgedächtnis und Langzeitgedächtnis (Baddeley, 2000) betrifft, gibt es bereits Befunde für jüngere Stichproben. Alloway et al. (2005) zeigten, dass der episodische Puffer auch schon ab dem vierten und fünften Lebensjahr erfassbar ist. Die Erweiterung um den episodischen Puffer geht dabei über die Differenzierung der Binnenstruktur der Arbeitsgedächtniskomponenten hinaus, da sie eine gänzlich neue Komponente darstellt.

Die Frage der weiteren Möglichkeiten der Differenzierung der Arbeitsgedächtnisstruktur betreffs der Anzahl ihrer Komponenten (beispielsweise Zwei- oder Vierkomponentenmodelle) wurde in den Analysen der vorgelegten eigenen Arbeiten nicht berücksichtigt. Sie soll hier dennoch kurz ergänzend erörtert werden, da sie für die Modellbildung bedeutsam ist. Alloway et al. (2006) prüften beispielsweise ein Zweikomponentenmodell mit der Konzeption zweier getrennter „ressource pools“ für verbale und visuell-räumliche Information (vgl. Daneman & Tardiff, 1987; Shah & Miyake, 1996). Im Gegenteil zum Modell von Baddeley (1986) wird dabei jede dieser beiden Kapazitäten als unabhängig von der anderen konzipiert und postuliert, sie seien in der Lage Informationen aufrecht zu erhalten und zu manipulieren. Diese Modellvorstellung wird durch Forschungsergebnisse bei Erwachsenen und älteren Kindern gestützt (Friedman & Miyake, 2000; Jarvis & Gathercole, 2003; Miyake, Friedman, Rettinger, Shah & Hegarty, 2001). Alloway et al. (2006) überprüften auch ein Vierkomponentenmodell. Dies war jedoch dem Dreikomponentenmodell unterlegen. Zu Alloway et al. (2006) ist anzumerken, dass in deren Studie Mehrfachladungen von Aufgaben auf latenten Faktoren möglich waren. So luden die zentral-exekutiven Aufgaben mit phonologischer Speicheranforderung auch auf dem Faktor der phonologischen Schleife, und die zentral-exekutiven Aufgaben mit visuell-räumlicher Speicheranforderung auf dem visuell-räumlichen Faktor. Dieses Modell erwies sich einem Dreikomponentenmodell ohne Mehrfachladungen als überlegen, stellte jedoch nicht die grundsätzliche Struktur des Baddeley'schen Modells in Frage und deckte sich hinsichtlich der Anzahl der Arbeitsgedächtniskomponenten mit der Ergebnissen von Gathercole et al. (2004). Auf Grundlage dieser beiden vorhergehenden Arbeiten wurde in der vorliegenden Arbeit daher die Baddeley'sche Strukturannahme (1986) als Ausgangspunkt gewählt. Dennoch wäre eine Prüfung weiterer Modelle, so zum Beispiel die Betrachtung von Zwei- und Vierkomponentenmodellen, möglich. Über die Arbeiten von Alloway et al. (2006) hinausgehend wäre es auch denkbar, gänzlich andere Modellvorstellungen des Arbeitsgedächtnisses bei Kindern zu prüfen (siehe Michalczyk & Hasselhorn, 2010). Eine solche Prüfung weiterer Modelle gegen das Modell von Baddeley (1986) im Vorschulalter könnte zudem einen Beitrag zur allgemeinen Evaluierung des Modells leisten. Da die sehr gute Validierung des Baddeley-Modells (1986) in Erwachsenenstichproben kein Hindernis für eine weiterhin lebendige und keineswegs abgeschlossene Kontroverse alternativer Arbeitsgedächtnismodelle (vgl. Conway, Jarrold, Kane, Miyake & Towse, 2007; Jarrold &

Towse, 2006) darstellt, ist eine solche Debatte auch für jüngere Altersbereiche vorstellbar. In diesem Kontext ist die vorliegende Arbeit als Ausgangspunkt für eine solche mögliche Diskussion zu verstehen. Zum einen legt sie die Konzipierung des Arbeitsgedächtnis sensu Baddeley (1986) nahe, zum anderen illustriert sie auch sehr klar die überwiegende Invarianz der funktionalen Interdependenz der phonologischen Schleife, des visuell-räumlichen Notizblocks und der zentralen Exekutive im Alter von 5 bis 12 Jahren.

3. Vertiefung 2: Arbeitsgedächtnis und frühe numerische Kompetenz

Ausgehend von den in Michalczyk und Hasselhorn (2010) beschriebenen Zusammenhängen des Arbeitsgedächtnisses mit schulischen Leistungen und der Validierung des Modells von Baddeley im Vorschulalter (Michalczyk et al., Einladung zur Resubmission bei European Journal of Psychological Assessment, 22. September 2011), widmet sich die hier vorgelegte zweite empirische Studie (Michalczyk et al., Resubmission bei Cognitive Development am 8. September 2011) dem Zusammenhang einzelner Arbeitsgedächtniskomponenten mit der vorschulischen numerischen Kompetenzentwicklung.

3.1 Das Arbeitsgedächtnis und die Entwicklung früher numerischer Kompetenzen

Das Arbeitsgedächtnis ist ein bereichsunspezifisches Konstrukt basaler Informationsspeicherung und -verarbeitung, welches im Zusammenhang mit einer Reihe beobachtbarer Leistungen bei kognitiven Anforderungen steht. Zu diesen gehören auch die basalen Kulturtechniken als Bestandteil und Grundlage der Schulleistung. So steht das Arbeitsgedächtnis im Zusammenhang zur Lesefertigkeit (z.B. De Jong, 1998; Swanson, 1994), dem Sprachverstehen (z.B. Nation et al., 1999; Seigneuric et al., 2000) und der Mathematikleistung (z.B. Bayliss, Gunn, Jarrold & Baddeley, 2003; Bull & Scerif, 2001; (Mayringer & Wimmer, 2000; Siegal & Ryan, 1989). Selbstverständlich treten diese Fertigkeiten nicht ad hoc mit dem Eintreten in die Schule auf, sondern vielmehr lassen sich bereits im Kindergarten- und Vorschulalter sogenannte Vorläuferfertigkeiten der späteren schulischen Leistungen identifizieren. Wie beim Schriftspracherwerb finden sich auch im mathematischen Bereich eine Vielzahl von Vorläuferfertigkeiten (LeFevre et al., 2010; für ein Review wesentlicher Schritte der numerischen Kompetenzentwicklung siehe Butterworth, 2005). Im mathematischen Bereich gehören zu diesen Vorläuferfertigkeiten auch frühe numerische Kompetenzen. Neuere Befunde konnten zeigen, dass bereits Zusammenhänge der

Entwicklung früher numerischer Kompetenzen und des Arbeitsgedächtnisses bestehen (Bull, Espy & Wiebe, 2008; Geary, 2010; Krajewski & Schneider, 2009a, 2009b; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek & Van de Rijt, 2009; LeFevre et al. 2010; Raghubar, Barnes, & Hecht, 2010). Was jedoch die Modellentwicklung zum Zusammenhang von Arbeitsgedächtnis und der Entwicklung der vorschulischen und schulischen Mathematikleistung betrifft, ziehen Raghubar et al. in ihrem aktuellen Review (2010, S.119) folgende Bilanz des bisherigen Forschungsstandes: *"…what is currently lacking in the field is a sufficiently comprehensive model of mathematical processing, particularly in relation to skill acquisition, that can handle current findings on working memory as well as provide the basis from which to guide new discoveries".* Dabei bringen sie zum Ausdruck, dass das Forschungsfeld bislang kein umfassendes Modell der mathematischen Verarbeitung aufweist, insbesondere was den Fertigkeitserwerb betrifft. Auch deuten sie an, dass ein solches Modell die Befunde zum Arbeitsgedächtnis integrieren sollte. Die erfolgreiche Herstellung eines solchen Brückenschlags für ein tieferes Verständnis des frühen numerischen Kompetenzerwerbs benötigt dabei nicht nur ein fundiertes und umfassendes Modell des Arbeitsgedächtnisses im entsprechenden Altersbereich (z.B. Michalczyk et al., 2010), sondern auch ein Modell der Entwicklung früher numerischer Kompetenzen. Ein entsprechend geeignet erscheinendes Modell bietet Krajewski (2008). Dieses auf längsschnittlichen Studien basierende Modell (Krajewski & Schneider, 2009a; 2009b) beschreibt die Entwicklung der frühen numerischen Kompetenz von Kindern in drei Ebenen. Die Fertigkeiten und Kompetenzen dieser Ebenen sind Prädiktoren der späteren Mathematikleistung, wie z.B. die Mathematikleistung am Ende der vierten Klasse (Krajewski & Schneider, 2009b) und damit als „Vorläuferfertigkeiten" der mathematischen Kompetenz validiert. Auch berichten Krajewski und Schneider (2009b) von Zusammenhängen des visuell-räumlichen Notizblocks und der Entwicklung der in diesem Modell beschriebenen frühen numerischen Kompetenzen. Bevor auf diesen Zusammenhang und andere Zusammenhänge der unterschiedlichen Ebenen der numerischen Kompetenzen mit Indikatoren der kindlichen kognitiven Leistungsentwicklung jedoch näher eingegangen wird, soll im Folgenden das Modell der Entwicklung früher numerischer Kompetenzen von Krajewski (2008) kurz vorgestellt werden.

Das Modell der Entwicklung der frühen numerischen Kompetenz (Krajewski, 2008) basiert unter anderem auf der Theorie von Resnick (1989) und beschreibt die Entwicklung bereichsspezifischer numerischer Kompetenzen, welche Vorläuferfertigkeiten zu mathematischen Kompetenzen in der Schule darstellen (Krajewski & Schneider, 2009a). Wesentliches Merkmal dieses Modells ist, dass es die Entwicklung der frühen numerischen Kompetenzen in drei aufeinander aufbauenden Entwicklungsebenen beschreibt. Die erste Ebene (Quantity-number competencies Level I; QNC Level I[3]) umfasst die numerischen Basisfertigkeiten Mengenverständnis, Zahlwortkenntnis und Zählfertigkeiten. Kinder kommen bereits mit der Fähigkeit auf die Welt, zwischen Mengen in deren Umfang und Ausdehnung zu differenzieren (vgl. Clearfield & Mix, 1999, 2001; Feigenson, Carey & Spelke, 2002; Simon, Hespos & Rochat, 1995; Xu, Spelke & Goddard, 2005). Unabhängig vom Mengenverständnis entwickelt sich in etwa ab dem zweiten Lebensjahr das Zählen (Zählfertigkeit und Zahlenkenntnis), wobei die Zahlwortfolge zu Beginn deren Erwerbs ähnlich dem Aufsagen des Alphabets einfach nur rezitiert wird. Zahlwort und Menge sind dabei nicht miteinander verknüpft. Erst diese Verknüpfung von Zahlwort und Menge markiert den Übergang zur zweiten Kompetenzebene (Quantity-number competencies Level II, QNC Level II), wobei diese zwei Phasen aufweist. In der ersten Phase (unpräzises Anzahlkonzept) entwickeln die Kinder zunächst eine unpräzise Vorstellung der Zuordnung von Zahlwörtern zu groben Mengenkategorien. Beispielsweise verstehen bereits Dreijährige, dass die Zahlen „eins“ oder „drei“ zur Mengenkategorie „ein wenig“, die Zahlen „hundert“ oder „tausend“ zur Kategorie „sehr viel“ gehören. In der zweiten Phase (präzises Anzahlkonzept) sind Kinder

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[3] Aus Gründen der Einheitlichkeit verwendet die vorliegende Arbeit bei den Abkürzungen die englischen Bezeichnungen, da diese in den eingereichten Arbeiten gebraucht wurden.

dann in der Lage, auch nahe beieinander liegende Zahlwörter, also z.B. „elf“ und „zwölf“ zu unterscheiden. Unabhängig des Erlernens des Anzahlkonzepts verstehen Kinder auf dieser Ebene auch, dass Mengen in Teilmengen zerlegt werden können. Beispielsweise lernen sie, dass eine nicht-numerische Menge in Teile zerlegt werden kann, welche beim Zusammensetzen wieder das Ganze ergeben. Die dritte Ebene (Quantity-number competencies Level III, QNC Level III) ist gekennzeichnet durch das Verständnis von Anzahlrelationen. Die Kinder verstehen, dass Teil-Ganze-Relationen von Mengen durch präzise Zahlwörter repräsentiert werden (Zahlzerlegung) und die Differenz zweier Zahlen wieder eine Zahl ergibt (Zahldifferenz). Die Zahl „fünf“ kann also in „drei“ und „zwei“ zerlegt werden. Diese Ebene markiert bereits den Übergang zur arithmetischen Fertigkeit in der Schule und ist insofern nicht mehr als reine Vorläuferfertigkeit zu bezeichnen (Krajewski, Nieding & Schneider, 2008). Krajewski und Schneider (2009a) zeigten, dass die Entwicklung höherer Level früher numerischer Kompetenzen (QNC Level II und III) von der Leistung der visuell-räumlichen Arbeitsgedächtniskapazität mitbestimmt wird. Maße der phonologischen Schleife und der zentralen Exekutive korrelierten zwar moderat bis hoch mit QNC Level I und II sowie der phonologischen Bewusstheit, diese Zusammenhänge wurden allerdings nicht weiter in dem von den Autoren vorgelegten Strukturgleichungsmodell untersucht. Eine differenzierte Betrachtung unterschiedlicher Komponenten des Arbeitsgedächtnisses zur Klärung des möglichen Einflusses dieser auf die frühe numerische Kompetenzentwicklung (vgl. Krajewski & Schneider, 2009a, 2009b; LeFevre et al., 2010) würde daher die bisherigen Befunde ergänzen.

Ein weiterer Teil des Appells von Raghubar et al. (2010) beinhaltet die Berücksichtigung mediierender Mechanismen bzw. Funktionen zwischen dem Arbeitsgedächtnis und der mathematischen Leistungsentwicklung. Eine solche Rolle könnte die phonologische Bewusstheit einnehmen (Krajewski & Schneider, 2009a). Die phonologische Bewusstheit wird definiert als die Fertigkeit Klangeinheiten der Sprache zu enund dekodieren und manipulieren. Üblicherweise wird diese als Vorläuferfertigkeit des Lesens und Buchstabierens betrachtet (vgl. Bradley & Bryant, 1985; Goswami & Bryant, 1990; Scarborough, 1998; Wagner & Torgesen, 1987). Krajewski und Schneider (2009a) bringen die phonologische Bewusstheit jedoch auch in Zusammenhang mit der Entwicklung basaler numerischer Fertigkeiten (QNC Level I) und beschreiben diesen Zusammenhang in der "isolated number words"-Hypothese. Diese besagt, dass der Erwerb basaler numerischer Fertigkeiten der ersten Ebene (QNC Level I) von der phonologischen Bewusstheit abhängt, nicht jedoch der Erwerb höherer numerischer Kompetenzen (QNC Level II und III, vgl. Krajewski & Schneider, 2009a), da die basalen numerischen Fertigkeiten nicht die Menge-Zahl-Verknüpfung, sondern eher phonologische Leistungen erfordern. Erste Befunde bestätigen diese Hypothese (Krajewski & Schneider, 2009a).

Die Gültigkeit der „isolated number-words“-Hypothese hat zudem Implikationen für die Befunde anderer Studien, welche einen Zusammenhang der phonologischen Bewusstheit zur Entwicklung höherer numerischer Kompetenzen berichten (z.B. LeFevre et al., 2010; Passolunghi, Vercelloni & Schadee, 2007). Laut Krajewski und Schneider (2009a) liegt allerdings in manchen Studien eine Konfundierung hinsichtlich des Einflusses der phonologischen Bewusstheit auf höhere numerische Kompetenzen vor. In solchen Studien (z.B. Passolunghi et al., 2007) wurde bei der Erfassung höherer numerischer Kompetenzen, welche den Ebenen QNC Level II und III entsprechen, der mögliche Einfluss basaler numerischer Fertigkeiten (QNC Level I) nicht statistisch kontrolliert. Die „isolated number-words“-Hypothese von Krajewski und Schneider (2009a) beinhaltet nun die Annahme, dass die phonologische Bewusstheit zwar basale numerische Fertigkeiten, nicht aber höhere numerische Kompetenzen beeinflusst. Kontrolliert man den Einfluss basaler numerischer Fertigkeiten auf höhere numerische Kompetenzen, so vermindert dies den Zusammenhang von phonologischer Bewusstheit und höheren numerischen Kompetenzen. Vor diesem Hintergrund verspricht eine erweiterte Replikation der Befunde zur „isolated number-words“-

Hypothese (Krajewski & Schneider, 2009a) eine Ergänzung zum Verständnis bisheriger Befunde und somit der kindlichen Entwicklung früher numerischer Kompetenzen.

Zeichnet sich nun also der Einfluss der phonologischen Bewusstheit auf insbesondere die basalen Fertigkeiten der frühen numerischen Kompetenzentwicklung ab, so stellt sich zudem die Frage, was die Leistung der phonologischen Bewusstheit begrenzt. Dies wiederum führt zum Arbeitsgedächtnis, für welche Krajewski und Ennemoser (2010) die Metapher des kapazitätsbegrenzenden „Flaschenhalses“ in der kognitiven Informationsverarbeitung verwenden. Da es bei der phonologischen Bewusstheit insbesondere um die Speicherung, Verarbeitung und Manipulation phonembasierter Information geht, sollten hierbei insbesondere phonologische Komponenten des Arbeitsgedächtnisses zum Tragen kommen. Im Sinne der Baddeley'schen Arbeitsgedächtnis-Konzeption wird dies durch die phonologische Schleife und den episodischen Puffer geleistet. Es ist jedoch auch zu vermuten, dass der Vergleich von Reimen und Phonemen auch zentral-exekutive Ressourcen erfordert.

3.2 Zusammenfassung der Forschungsfragen 2

Zusammenfassend stellt sich also die Frage des Zusammenwirkens von Subkapazitäten des Arbeitsgedächtnisses (Baddeley, 1986; 2000) und der phonologischen Bewusstheit bei der Entwicklung früher numerischer Kompetenzen (Krajewski, 2008). Hinsichtlich der Klärung des Zusammenhangs der phonologischen Bewusstheit mit Arbeitsgedächtnisressourcen wird davon ausgegangen, dass vor allem die phonologische Schleife und zentral-exekutive Funktionen die Leistung der phonologischen Bewusstheit mitbestimmen sollten. Auf der Grundlage bisheriger Befunde (Krajewski & Schneider, 2009a; 2009b; LeFevre et al., 2010) soll zudem überprüft werden, welche Rolle die phonologische Bewusstheit beim Erwerb früher numerischer Kompetenzen im Sinne des Entwicklungsmodells von Krajewski (2008) spielt. Daher wird eine erweiterte Replikation der bisherigen Befunde zur „isolated number-words"-Hypothese (Krajewski & Schneider, 2009a) angestrebt. Zusätzlich führt der Anstieg der Anzahl von Kindern mit sprachlichem Migrationshintergrund zu einer Zunahme der sprachlichen Durchmischung im Bildungssystem und somit auch zu Herausforderungen hinsichtlich der Diagnostik und Förderung von Kindern mit Lernschwierigkeiten. Dies erfordert eine Theoriebildung, welche diesem Umstand gerecht wird. Vor diesem Hintergrund sollen daher die Zusammenhänge früher numerischer Kompetenzen mit phonologischer Bewusstheit und Arbeitsgedächtnissubkapazitäten für Kinder mit und ohne sprachlichem Migrationshintergrund geprüft werden.

3.3 Untersuchung 2: Early Quantity-number Competencies, Phonological Awareness, and Working Memory in 5- to 6-year-olds with and without Second Language Background[4]

Over the past decades, researchers have shown that basic mathematical competencies in preschool and early school age are linked to basic information processing mechanisms and skills. Working memory as the capacity to store and manipulate information over short periods of time is part of these mechanisms (Alloway et al., 2005; Berg, 2008; Bull, Espy, & Wiebe, 2008; De Smedt et al., 2009). Recently gained evidence suggests that this might also be the case for phonological awareness (Krajewski & Schneider, 2009a; LeFevre et al., 2010; Passolunghi, Vercelloni, & Schadee, 2007). While the relations of mathematical competencies, phonological awareness, and working memory are not yet fully understood, Krajewski (2008) offers a coherent theory for explaining the development of some specific mathematical skills, that is, early quantity-number competencies, in relation to working memory and phonological awareness (Krajewski & Schneider, 2009a). This model describes

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[4] Die Erstellung dieses Beitrags wurde gefördert durch die LOEWE-Initiative der Hessischen Landesregierung im Rahmen des "Center for Individual Development and Adaptive Education of Children at Risk" (IDeA), Frankfurt, Germany. Das Manuskript wurde am 8.September 2011 bei Cognitive Development als Resubmission eingereicht.

the development of early quantity-number competencies as a succession of different developmental levels in linking number words to quantities.

The occurrence of this linkage can be described by three developmental levels (Krajewski & Schneider, 2009a,b). At the first level, the child possesses basic numerical skills (QNC Level I), but number words are not yet linked to quantities. Infants are already able to differentiate between quantities (Clearfield & Mix, 2001; Feigenson, Carey, & Spelke, 2002; Rousselle, Palmers, & Noël, 2004; Xu, Spelke, & Goddard, 2005). When children acquire language, they start to discriminate these quantities verbally using words such as “more”, “less” and “the same amount” (Resnick, 1989). At the age of about two years, children acquire precise number words and the exact number word sequence forwards and backwards. However, at this stage, they do not yet employ these number words in order to describe quantities. At the second level, children start to link number words to quantities (QNC Level II). Children now acquire the quantitative meaning of number words through linking the number word sequence with quantities. In the first phase of this linkage process, children develop a vague and imprecise conception of the attribution of number words to quantities and assign number words only to rough quantity categories (e.g., “a bit”, “much/a lot”, “very much”). This concept does not enable children to distinguish between the quantitative sizes of number words that are close together (e.g., “eleven” and “twelve”) because these are related to the same rough quantity category (“much”). Only in the second phase of Level II, children link number words also to exact quantities so that they become able to exactly compare the quantitative size of closely related number words. At the third level of early numerical development, children finally link number words to quantity relations and become able to understand the composition and decomposition of numbers as well as differences between numbers. Krajewski proposes that the transition from Level I (isolated number words) to Level II (quantity to number word linkage) can be seen as the most important milestone in early numerical development. Therefore, in this study we especially focused on the first two levels.

Early Quantity-number Competencies and Phonological Awareness

Undoubtedly, phonological awareness is a precursor of reading and spelling (e.g., Bradley & Bryant, 1985; Goswami & Bryant, 1990; Scarborough, 1998; Wagner & Torgesen, 1987). However, recent studies relate phonological awareness also to mathematical achievement (e.g., Alloway et al., 2005; LeFevre et al., 2010; Passolunghi, 2007). Krajewski and Schneider (2009a) found that phonological awareness predicts knowing the number word sequence and Arabic numerals (QNC Level I), but less so higher quantity-number competencies (QNC Level II+III). In their *isolated number words hypothesis*, they explain this pattern of results, stating that phonological awareness is only specifically important for the acquisition of the number word sequence where it is not necessary to link number words to quantities (isolated number words). Otherwise, phonological awareness does *not* contribute *directly* to the acquisition of the quantity to number word linkage because this linkage relies on the conceptual understanding of linking (visual) quantity information with number words and their Arabic notations (QNC Level II, Krajewski, 2008). The *isolated number words hypothesis* offers an explanation of the reported statistical association between phonological awareness and higher mathematical quantity-number competencies via the acquisition of basic numerical skills. Well-developed phonological awareness enhances the development of the number word sequence, which, in turn, facilitates the acquisition of higher quantity-number competencies. However, other theoretical accounts exist on the relationship of phonological awareness and early mathematical competencies. For instance, phonological awareness might tap into phonological representations which are important for the development of arithmetic facts, because they are assumed to be stored in phonological code (Simmons & Singleton, 2008).

Phonological Awareness and Working Memory Capacity

When considering individual preconditions to the emergence of high levels of phonological awareness, a highly functioning phonological working memory is often proposed (e.g., Alloway, Gathercole, Willis, & Adams, 2004; Hecht, Torgesen, Wagner, & Rashotte, 2001; Siegal & Linder, 1984; Stanovich, Cunningham, & Freeman, 1984). According to Baddeley (2000), working memory functioning is related to the capacity of a number of components: The central executive, the phonological loop, the visual-spatial sketchpad, and the episodic buffer. The phonological loop and the visual-spatial subsystem are domain-specific for the storage of phonological and visual-spatial information. In contrast, the central executive works as a flexible master unit that controls and allocates resources and monitors information processing across these informational domains (see Baddeley, Emslie, Kolodny, & Duncan, 1998). In addition, the episodic buffer is independent from the central executive; it integrates representations from the subsystems and long-term memory to so called "episodes" by using multidimensional codes. Recently gained evidence suggests that in children aged four to six years, the different components represent separable entities (Alloway et al., 2006, 2004; Gathercole et al., 2004; Roebers & Zoelch, 2005).

The relations of working memory subcapacities and phonological awareness have been debated throughout the last two decades (Bowey, 1996; Gathercole, Willis, & Baddeley, 1991; Hecht, Torgesen, Wagner, & Rashotte, 2001; Metsala, 1999; Passolunghi & Siegel, 2001). Alloway et al. (2004) suggest that already in 4- to 6-year-olds, phonological awareness is associated with, though separable from, the phonological loop, the episodic buffer, and the central executive. Assuming that these working memory components and phonological awareness are separable in such young children, it makes sense to assume that different working memory capacities facilitate the performance on phonological awareness. For instance, the acquisition of phonological awareness might be positively influenced by the capacity of the phonological loop because a child has to store phonological information (phonological loop) before she or he can assess and manipulate this information (phonological awareness). The efficiency of the episodic buffer could be helpful in performing on phonological awareness tasks as well, because those tasks challenge the integration of learned knowledge (e.g., words and syllables that are encoded in long-term memory) with current information. Successful performance on those tasks requires subjects to bind these representations (Alloway et al., 2005). Also, phonological awareness tasks involve the manipulation of the stimulus material that needs to be held in mind. Hecht et al. (2001) proposed that the processing component of the central executive is involved in phonological awareness (Hecht et al., 2001).

The current study

Despite a vast body of research in the field, the relationships among working memory, phonological awareness and mathematical development in young children still require further clarification. To shed light on how early quantity-number competencies (QNC Level I and II) might be influenced by phonological awareness and phonological working memory resources in 5- to 6-year-olds, the current study investigates the following assumptions:

1. *Early quantity-number competencies (QNC Level I and II) and phonological awareness:* Phonological awareness is assumed to strongly predict QNC Level I, but not higher level numerical competencies such as QNC Level II (isolated number words hypothesis). This should be the case because the acquisition of basic numerical skills like learning the number word sequence especially requires storage and processing of speech based codes in working memory.

2. *Working memory and phonological awareness:* Phonological awareness is thought to rely on the capacities of the phonological loop and the episodic buffer, because both should restrain the amount of information upon which processes of phonological awareness can be carried out. Furthermore, phonological central executive processes should be required in

phonological awareness, because they rely on the storage and manipulation of phonological information in working memory.

3. Phonological awareness mediates the relations of working memory and early numerical competencies: This hypothesis emerges from a combination of the previous two hypotheses. Phonological awareness is hypothesized to mediate the relationship of verbal phonological working memory (with the phonological loop, the episodic buffer, and the central executive) and early quantity-number competencies (QNC Level I and II). Verbal phonological working memory subcapacities should have minor effects on early quantity-number competencies apart from phonological awareness effects, because the latter binds the verbal-phonological working memory resources that are required in QNC tasks.

4. Quantity-number competencies, phonological awareness and working memory in children from different language backgrounds. The increase of children of different language backgrounds in many countries leads to difficulties in language adaption, for instance in the education system. Moreover, owing to their verbal-phonological nature, the above described relations of working memory, phonological awareness and early numerical competencies are strongly language based. Therefore, it is of theoretical interest if the assumed relationships of early quantity-number competencies, phonological awareness, and working memory are similar in children with and without a second language background.

Method

Participants

1,343 children attending 159 kindergartens in Frankfurt/ Main (Germany) and the surrounding area participated in this study. The kindergartens were selected from different quarters of the city of Frankfurt and included kindergartens from different organizations (e.g., Catholic Church, Protestant Church, City of Frankfurt/Main). Parental consent had been obtained for testing of each child. The mean age was 70 months (SD = 4.6) with a range from 60 to 83 months. The majority of the children had a European background, 47 % of the sample speaking only German and 41 % speaking German and another language at home with their parents. For twelve per cent of the children, data were missing on what language they spoke with their parents. Only data of children that were sufficiently fluent in German to understand the test instructions were accepted in the study.

Assessment of quantity-number competencies (QNC)

Tasks for the assessment of the first and second level of early quantity-number competencies (QNC Level I and II) were derived from Krajewski and Schneider (2009a,b). Table 1 shows that all reliabilities were adequate.

QNC Level I: Isolated number word sequence. In the *number word sequence* task, the child is asked to recite the number word sequence forwards up to 31 and backwards from 5, and to name three subsequent as well as three preceding number words (e.g., “When counting, do you know which number comes just before 3?”). Children were credited six points for correctly reciting the number word sequence and another six points for naming subsequent and preceding number words.

QNC Level II: Quantity to number word linkage. In order to assess *quantity to number word linkage*, the child is asked to match quantities to the corresponding Arabic numerals, and vice versa, match Arabic numerals to the corresponding quantities. Here, a row of the Arabic Numerals from 1 to 10 is presented in ascending order. Additionally, five cards depicting 5, 6, 8, 10, and 3 stick-figures are displayed. The child is first required to match three cards with different numbers of stick-figures to the corresponding Arabic Numerals. Then, the child is asked to assign two Arabic Numerals to the corresponding cards with stick-figures. In the *Quantity to number word linked seriation* task the child is presented a series of cardboard beetles that have 1 to 8 dots on their backs. The beetles are presented at once and in ascending order (from left to right), with one of the beetles missing. From a set of five beetles, the child is asked to choose the one with the correct number of dots on its back that fits in the row. In the *number word comparison* task, the child is asked to decide which of two number words represents “more” or “less” (e.g., “What is more, 5 or 3”; “What is less, 19 or 18?”).

Assessment of phonological awareness

A phoneme synthesis task and rhyming task were used to assess phonological awareness. In the *phoneme synthesis* task, a sequence of single phonemes is presented. The child is required to match them to the appropriate word and select the corresponding picture out of four pictures (Krajewski & Schneider, 2009a; Lundberg, Frost, & Peterson, 1988). To assess *rhyming*, a slight modification of Bradley and Bryant’s (Bradley & Bryant, 1985) Sound Categorization Task was used. Here, the child is required to listen to a sequence of four words and is then asked to indicate which of these words does not rhyme with the others. As in the study by Krajewski and Schneider (2009a), each four-word sequence was presented three times back-to-back to minimize demands on phonological working memory in this task.

Assessment of working memory capacity

Four tests were used to measure relevant capacities of working memory, three of which were taken from the German Working Memory Test Battery for Children, 5 to 12 years (Hasselhorn et al., in press). This standardized, computer-based and adaptive test battery provides a tool to test a broad range of working memory functions in children. The respective three tests included a word span forward task and a digit span forward task as indicators of the phonological loop as well as a word span backward task tapping the central executive. In addition, and referring to the work by Alloway et al. (2005, see also Alloway et al., 2004), we assessed the capacity of the episodic buffer with a sentence repetition task (Schoeler & Brunner, 2007).

In the *word span forward* task, the child is asked to recall a sequence of one-syllable words in the presented order. Altogether, the test encompasses ten trials. The starting level of the test is pre-set at two words. As the task is adaptive, the number of presented items varies based on the child’s performance. For instance, if a child repeats three presented words correctly in the word span forward task and the three next words in the subsequent trial again, the following trial requires the child to recall four words. If the child fails to reproduce three words correctly in two consecutive trials, a sequence of only two words is subsequently presented. This adaptive principle also applies in the digit span forward task and the word span backward task (see below) with a minimum of two presented items per trial. In the *digit span forward* task the child is required to recall a series of digits with two digits per trial at minimum and nine digits per trial at maximum.

The *word span backward* task as an indicator of central executive capacity requires the child to recite one-syllable words in the reverse order of presentation. If the child does not understand the verbal explanation of "reverse order" presented on a computer in the practice trial, the instructor illustrates the concept manually to visualize the concept of "reverse order". The experimenter pronounces the words (e.g., tree, pot, house) while tapping at different spots at equal distances on the table (from left to right). Then, the experimenter repeats these words backwards (e.g., house, pot, tree) tapping the same spots on the table in reverse order (from right to left).

In the *word span forward, digit span forward*, and *word span backward tasks*, each child is presented ten trials. Through adaptive testing, the number of presented words/digits within each trial is determined by the number of correctly recalled items. For each trial, points are scored and calculated as follows: In a correctly reproduced series of items, the number of given points equals the length of the correctly reproduced series. For example, the correct repetition of three words in the word span forward task results in three points. However, if a child does not reproduce a series correctly, the number of given points is "length of series minus one". For instance, if the child fails to reproduce a series of three words, 3 - 1 = 2 points for this series are scored for the child in this trial (therefore, the minimum score was "one point", because the shortest series is two words). The score for each child was the mean number of points scored in the last four correctly repeated trials. However, due to the adaptive testing, we did not calculate the internal consistencies for the adaptive working memory span tasks. Therefore, retest-reliability measures of the respective tasks were drawn from the norm sample of the test battery (see Table 1).

In the *sentence repetition* task (Schoeler & Brunner, 2007), the child is required to repeat sentences that are presented verbally from an audio file through speakers on the computer. The first sentence starts with two words and the number of words increases until the tenth sentence which consists of ten words. That is, correct repetition of the sentence leads to the presentation of longer and more complex sentences. If a child fails to repeat four sentences in a row, testing in this task is discontinued. With the difficulty only augmenting but not decreasing, Cronbach's alpha was calculated based on a split-half procedure (see Table 1).

Procedure

Data were collected from October 2008 to May 2009. Each child was tested individually in a quiet area of the kindergarten. Testing lasted about 30 minutes for the specific tasks of early quantity-number competencies and phonological awareness. After a break of 30 minutes, the computer-based working memory tasks were administered for about another 30 minutes.

Results

Table 1 provides an overview of the means, standard deviations, ranges and reliabilities for the administered tasks of quantity-number competencies, phonological awareness and working memory. Results are displayed for the whole sample as well as the subgroups “with second language background” and “children without a second language background”. All of the correlations were positive and statistically significant (i.e., all p-values < .01). In the whole sample, working memory tasks correlated with phonological awareness moderately from *r* = .37 to *r* = .50. Phonological awareness correlated moderately with the episodic buffer (*r* = .50), the phonological loop (word span forward *r* = .37; digit span forward *r* = .40), and the central executive (*r* = .43). Phonological awareness correlated strongly with basic numerical skills (QNC Level I) with *r* = .53 (*r* = .54 with rhyme detection, *r* = .32 with phoneme synthesis) as well as with higher quantity-number competencies (QNC Level II), with *r* = .52 (*r* = .54 with rhyme detection, *r* = .32 with phoneme synthesis).

Table 1

Means, standard deviations, ranges, reliabilities and correlations for all tests applied

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) Phonological awareness (sum score)	-	.87	.76	.53	.52	.50	.37	.40	.43
		.85	.78	.46	.46	.39	.27	.30	.39
		.85	.78	.47	.46	.41	.35	.39	.40
(2) Rhyme detection		-	.36	.54	.54	.52	.36	.37	.40
			.34	.41	.41	.35	.23	.24	.30
			.32	.49	.50	.42	.36	.38	.40
(3) Phoneme synthesis			-	.32	.32	.29	.23	.29	.32
				.33	.35	.27	.20	.27	.30
				.26	.24	.23	.20	.25	.24
Early quantity-number competencies									
(4) QNC Level I				-	.74	.44	.33	.43	.42
					.70	.33	.26	.37	.40
					.70	.36	.29	.40	.39
(5) QNC Level II					-	.45	.36	.44	.45
						.30	.28	.40	.41
						.39	.32	.41	.41
Episodic buffer									
(6) Sentence repetition						-	.40	.41	.40
							.30	.31	.34
							.35	.37	.37
Phonological loop									
(7) Word span forward							-	.56	.38
								.50	.33
								.54	.33
(8) Digit span forward								-	.42
									.40
									.37
Central executive									
(9) Word span backward									-
Minimum (empirical)	0	0	0	0	0	0	1	1	1
Maximum (empirical)	18	10	8	12	20	10	5.50	5.25	3.5
M	10.29	5.35	4.92	8.02	15.06	7.27	2.79	2.95	1.93
SD	4.08	2.81	2.11	3.15	4.06	2.24	0.66	0.70	.57
Reliability	.81[a]	.74[a]	.71[a]	.80[a]	.82[a]	.87[c]	64.[b]	68.[b]	59.[b]
	.76[a]	.67[a]	.64[a]	.76[a]	.80[a]	.86[c]			
	.79[a]	.70[a]	.71[a]	.80[a]	.82[a]	.79[c]			

Note. Results are shown for whole sample (first row of a cell), children with second language background (second row of a cell), and children without second language background (third row of a cell).

All span-based tasks (6-9) show the number of points given in the adaptive testing.

All span tests were based on the mean of the four last relevant series, with the possible range reaching from 1 to 7.5.

[a] Cronbach's alpha, values based on the presented sample.

[b] Retest-reliability for the adaptive tests of working memory was drawn from Hasselhorn et al. (in press) and applies in 5- to 8-year-olds.

[c] In the sentence repetition task, the word length only augments, but does not decrease. Therefore, C's alpha was calculated based on a split-half procedure.

*All correlations were significant, p < .01.

Testing the pattern of relationships between QNC, phonological awareness and working memory

In order to assess the relationship of early quantity-number competencies (QNC Level I and II), phonological awareness, and working memory, structural equation modelling was carried out using AMOS 16 (Arbuckle, 2007). Due to the sample size of 1,343 children, model adequacy was evaluated by global fit indices that are more sensitive to model specification than to sample size (Kline, 1998) such as the comparative fit index, (CFI; Bentler, 1990), the normed fit index (NFI; Bentler & Bonett, 1980) and the RMSEA (Hu & Bentler, 1999). In these indices, a value equal to or higher than .90 represents a good fit. In the RMSEA as another commonly used index of model fit, a value equal to or lower than .08 is acceptable, whereas a value equal to or lower than .05 represents a good fit (McDonald & Ho, 2002). Again due to sample size, the significance of the standardized regression weights was tested with a threshold of $p < .01$. We combined all three hypotheses in one structural model (see Figure 1), which was tested on the full data set and showed a good model fit with CFI = .967, NFI = .961, RMSEA = .061. The model-fit indicated structural validity for a hierarchical working memory model (Baddeley, 1986; 2000) with three working memory subcapacities (phonological loop, central executive, episodic buffer), a factor for phonological awareness as well as two separate factors for QNC Level I and II. The model shows how phonological awareness relies on different verbal working memory subcapacities, that is, the central executive, the phonological loop, and the episodic buffer. In accordance with the assumption that the central executive coordinates the flow of information through the subsystems, the central executive accounted for variance in the phonological loop ($\underline{ß}$ = .58) and the episodic buffer ($\underline{ß}$ = .48) in the structural equation model. Table 2 shows the factor loadings of the measurement model. With regard to the first hypothesis, the model shows the influence of phonological awareness on QNC Level I vs. II. Phonological awareness had a strong impact on QNC Level I (ß = .71; p < .01) and accounted for 50 per cent of individual differences in knowledge of the number word sequence.

Table 2

Factor loadings of the measurement model

Construct	**Indicators**	**Factor loadings**		
		Whole sample	**Migrational background**	
			yes	**no**
Phonological loop (PL)	Word span forwards	.70	.63	.67
	Digit span forwards	.81	.79	.81
Central executive (CE)	Word span backwards (odd, even)	.91/.89	.87/.94	.89/87
Episodic buffer	Sentence repetition (odd/even)	.89/.92	.86/.93	.81/.85
Phonological awareness	Rhyme detection	.77	.63	.78
	Phoneme synthesis	.46	.55	.41
QNC Level I	Number-word sequence forward	.81	.82	.79
	Number-word sequence backward	.84	.77	.85
QNC Level II	Quantity to number-word linkage	.55	.54	.56
	Quantity to number-word linked seriation	.67	.64	.59
	Number-word comparison	.70	.68	.72
Index of model fit				
CFI		.967	.979	.968
NFI		.961	.962	.953
RMSEA		.061	.045	.055

In contrast, phonological awareness did not predict QNC Level II (ß = .09; n.s.), even if there was a very strong impact from QNC Level I to QNC Level II (ß = .87; p < .01). Figure 1 shows the results for testing the second hypothesis. Phonological awareness was influenced by all three working memory subcapacities (phonological loop: ß = .30; p < .01; episodic buffer: ß = .49; p < .01; central executive: ß = .21; p < .01). With regard to the third hypothesis, the model indicates that phonological awareness mediates the relationship between working memory and early numerical quantity-number competencies, because of the influence of phonological awareness on QNC Level I vs. II and the influence of the working memory subcapacities on phonological awareness. Notably, the working memory subcapacities had no effects on early quantity-number competencies apart from phonological awareness effects. The phonological loop impacted neither QNC Level I (ß = .11; p < n.s.) nor QNC Level II (ß = .07; n.s.). The same was true for the episodic buffer with no direct effect on QNC Level I (ß = -.07; p < n.s.) and Level II (ß = .01; p < n.s.), as well as the central executive on QNC Level I (ß = .07; p < n.s.) and QNC Level II (ß = .03; p < n.s.).

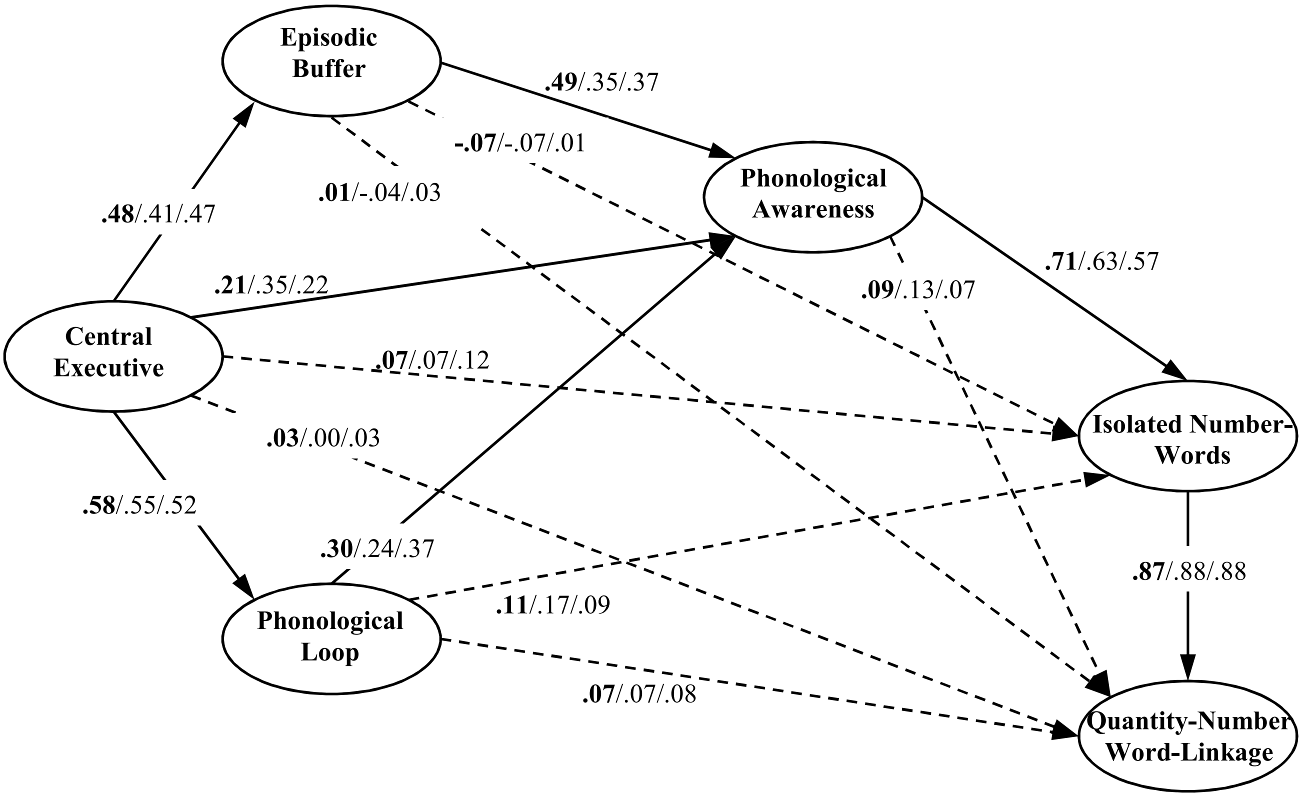

Figure 1. Structural equation model for the whole sample (N = 1,343), children with second language background (n = 546), and children without second language background (n = 631). Standardized regression coefficients are shown for the whole sample (first column of a row), children with second language background (second column of a row), and children with no second language background (third column of a row).

Is the observed pattern of relationships of QNC, phonological awareness and working memory subcapacities independent from children's language background?

In a further step of analysis, we tested whether the observed relations between early quantity-number competencies, phonological awareness, and working memory were comparable for children who spoke German and another language with their parents at home (i.e., second language background) or only German (i.e., without second language background). Table 1 displays correlations for the respective subgroups; Table 3 yields the means, standard deviations, mean differences and effect sizes for the differences between both subgroups.

We tested the structural equation model for two subsamples. The first subsample consisted of *children with second language backgrounds* (n = 546). The overall model-fit was very good with CFI = .979, NFI = .962, RMSEA = .045. Figure 1 shows the structural equation model for this subgroup; the second column of the row of digits attached to each path coefficient indicates the standardized regression weights for this subsample. The central executive was related to the episodic buffer (ß = .41; p < .01) and to the phonological loop (ß = .55; p < .01). Phonological awareness had a strong impact on QNC Level I (ß = .63; p < .01) and could explain 40 per cent of individual differences in these basic numerical skills. In contrast, phonological awareness could not significantly predict variance in QNC Level II, (ß = .13; p < n.s.), even if there was a very strong impact from QNC Level I on QNC Level II (ß = .88; p < .01). Moreover, phonological awareness was influenced by the phonological loop (ß = .24; p < .01), the episodic buffer (ß = .35; p < .01), and the central executive (ß = .35; p < .01). In addition, working memory resources had no impact on quantity-number competencies apart from phonological awareness: The phonological loop on had no effect on QNC Level I (ß = .17; p < n.s.) or QNC Level II (ß = .07; p < n.s.). The episodic buffer had no effects on QNC Level I (ß = -.07; n.s.) or QNC Level II (ß = -.04; p < n.s.). The same was the case for the central executive with no effect on QNC Level I (ß = .07; p < n.s.) or QNC Level II (ß = .00 p < n.s.).

Table 3

Mean differences between children from different language background

Variables	**Second language background (n = 546)**		**Without second language background (n = 631)**		**Mean differences**			**Effect sizes**
	M	SD	M	SD	t	Df	p	Cohen's d
Phonological awareness (sumscore)	8.55	3.72	11.74	3.82	14.32	1153	<.01	0.84
Rhyme detection	3.96	2.47	6.52	2.54	17.34	1556	<.01	1.02
Phoneme synthesis	4.58	2.06	5.20	2.14	5.02	1165	<.01	0.29
Early quantity-number competencies								
QNC Level I	6.96	3.05	8.99	2.87	11.65	1157	<.01	0.68
QNC Level II	13.62	4.01	16.33	3.63	12.12	1167	<.01	0.70
Episodic buffer								
Sentence repetition*	6.02	2.24	8.36	1.61	20.21*	958.45	<.01	1.21[a]
Phonological loop								
Word span forwards	2.64	.62	2.94	.66	7.78	1096	<.01	0.46
Digit span forwards	2.80	.64	3.11	.72	7.42	1093	<.01	0.42
Central executive								
Wordspan backwards	1.82	.56	2.04	.56	6.56	1075	<.01	0.40

[a] The assumption of equal variances was rejected, and therefore, d was calculated on the basis of Cohen's d for unequal variances.
*Equal variances not assumed ($p < 0.05$).

In children *without second language background*, the overall model-fit was very good with CFI = .968, NFI = .953, RMSEA = .055. Figure 1 shows the structural equation model for this subgroup, the third column of the row of digits attached to each path coefficient shows the standardized regression weights for this subsample. The central executive was related to the phonological loop with (ß = .52; p < .01) and to the episodic buffer (ß = .47; p < .01). Again, phonological awareness had a strong impact on QNC Level I (ß = .57; p < .01), explaining for 33 per cent of individual differences in these basic numerical skills. In contrast, phonological awareness predicted no variance in QNC Level II, (ß = .07; p < n.s.). However, QNC Level I predicted QNC Level II (ß = .88; p < .01). Furthermore, the phonological loop had an impact on phonological awareness (ß = .37; p < .01), similar to the episodic buffer (ß = .37; p < .01) and the central executive (ß = .22; p < .01). Moreover, the phonological loop did not significantly impact QNC Level I (ß = .09 p < n.s.) or QNC Level II (ß = .08; p < n.s.). The same held true for the episodic buffer on QNC Level I (ß = .01; n.s.) and QNC Level II (ß = .03; p < n.s.), and the central executive which had no effect on QNC Level I (ß = .12; p < n.s.) or QNC Level II (ß = .03 p < n.s.).

In addition, we tested whether the relation of phonological awareness to QNC Level I vs. II, was comparable across both subgroups. Due to sample size, model comparisons were based on the RDR (Browne & Du Toit, 1992) in which a value smaller than .05 represents no significant difference between two models. The precondition of equality of (1) the measurement model with freely estimated model factor loadings and (2) the measurement model with imposed equal factors loadings across both subgroups was fulfilled (RDR = .03). In a subsequent step, we compared the path coefficients of phonological awareness on QNC Level I vs. Level II (RDR = .00). The results clearly indicate the same pattern of relationships for phonological awareness and QNC Level I vs. II for both subgroups.

Construction of the latent factors

Only one task each represented capacities of the central executive (word span backward) and the episodic buffer capacity (sentence repetition). However, we built sum scores for odd and even items of the respective tasks in order to construct latent variables for these two working memory subcapacities as well. This procedure serves to reduce error variance in the task: Even though method variance may remain, the structural model thus becomes more reliable and thereby easier to interpret (for a discussion see Bowey, 2005).

4. Discussion

In this study, we investigated relations between early quantity-number competencies, phonological awareness and different working memory subcapacities in 5- to 6-year-olds. Phonological awareness predicted knowledge of the number word sequence (QNC Level I), but not higher level numerical competencies that require linking number words with quantities (QNC Level II). Phonological awareness relied on subcapacities of phonological working memory. Moreover, the results indicate that phonological awareness mediates variance between working memory capacities and early numerical competencies (Krajewski & Schneider, 2009a). With phonological awareness being accounted for, the additional influence of working memory subcapacities on early quantity-number competencies was negligible. The basic pattern of findings seems to be independent from language background.

Quantity-number competencies and phonological awareness. The relationships between mathematical competencies and phonological awareness have been subject to investigation before (Alloway et al., 2005; Bradley & Bryant, 1985; Geary, 2010; LeFevre et al., 2010; Wagner & Torgesen, 1987). However, the distinction of different levels of quantity-number competencies (QNC Level I and II) offers introspection into specific and multi-dimensional areas of mathematical competencies. On QNC Level I, manipulation of number(word)s is possible even if a child has not yet linked the number words with quantities, whereas at QNC Level II the quantity-number word linkage is necessary and based on the conceptual understanding that number words represent quantities (see Krajewski, 2008; Krajewski & Schneider, 2009a,b). In the structural equation model, phonological awareness accounted for nearly 50 per cent of the variance in QNC Level I. In contrast, QNC Level II performance was not influenced by phonological awareness. Thus, the results of the present study confirm the isolated number words hypothesis (Krajewski & Schneider, 2009a), which implies that phonological awareness is especially important for the acquisition of basic numerical skills like learning the number word sequence. This is also important for the development of higher levels of quantity-number competencies because knowledge of the number word sequence (QNC Level I) is a precursor of higher level quantity-number competencies (QNC Level II). Therefore, phonological awareness exerts an indirect effect on the acquisition and the development of higher level quantity-number competencies, and represents a crucial construct in early mathematical development.

Different theoretical accounts remain regarding the nature of the relationship between phonological awareness and mathematical achievement, one distinct example being the weak phonological representations hypothesis (Simmons & Singleton, 2008). This hypothesis states that the poorly specified nature of phonological representations in dyslectic children leads to poor performance in tasks that require the retention, retrieval and/or manipulation of phonological codes. Given that some tasks in mathematics require the manipulation of verbal phonological codes, this might explain dyslectic children’s difficulties in specific mathematical tasks, particularly offering an explanation regarding the semantic memory subtype in dyslectic children (Geary, 1993). Based on the weak phonological representations hypothesis (Simmons & Singleton, 2008), it makes sense to assume that the postulated relations hold true for normally developing children as well. However, the weak phonological representations hypothesis (Simmons & Singleton, 2008) would predict that low phonological awareness might directly lead to difficulties in performing on tasks of QNC Level II. However, in that regard, our results are not in concordance with the weak phonological representations hypothesis: Controlling for QNC Level I in the relation between phonological awareness and QNC Level II (which is partly coded phonologically) leads to no direct relation between phonological awareness and QNC Level II.

Phonological awareness and working memory. Findings of this study indicate that phonological awareness relies on various working memory subcapacities such as the phonological loop, the episodic buffer and the central executive. Among these working memory subcapacities, the phonological loop roughly explains 9 per cent of variance, the episodic buffer 24 per cent and the central executive 4 per cent in phonological awareness in the overall sample. Focusing on these subcapacities, findings from earlier studies can be differentiated. For instance, Alloway et al. (2005) found that phonological awareness and the phonological loop correlated with $r = .60$. For children aged about five years, Bowey (2005) reported a correlation of $r = .49$ between phonological awareness (phoneme identity judgement) and a phonological working memory task (nonword repetition). With respect to phonological awareness and the episodic buffer, Alloway et al. (2005) reported that phonological awareness and the episodic buffer correlated with $r = .69$. Moreover, in our study, children with a relatively well functioning episodic buffer performed better on phonological awareness tasks. This might indicate that those tasks require the integration of learned knowledge from long-term memory with current information. The amount of current information that can be held in mind, however, is determined by the phonological loop. This general pattern of results can be taken as evidence that phonological awareness relies on verbal-phonological working memory resources including subcapacities of the phonological loop, the episodic buffer, and phonological central executive functioning.

Phonological awareness mediates the effects of working memory and QNC. Various studies have been presented to show relations between different subcapacities of working memory and early mathematical competencies (for a review, see Raghubar, Barnes, & Hecht, 2010), fewer studies have assessed the relations between phonological awareness and quantity-number competencies in preschool children (e.g., Alloway et al., 2005; Krajewski & Schneider, 2009a; LeFevre et al, 2010; Simmons, Singleton, & Horne, 2008). In our study, we assessed how phonological awareness mediates effects from different subcapacities of working memory (phonological loop, central executive, and episodic buffer) to QNC Level I and II as specific mathematical competencies. Phonological awareness facilitates the acquisition of the number word sequence, which is a precursor for higher level quantity-number competencies. In order to fulfil this function, phonological awareness captures working memory subcapacities of the phonological loop, the episodic buffer and the more active central executive.

Hecht et al. (2001) addressed the role of the central executive in phonological awareness and arithmetic ability, too. They found that phonological awareness predicts arithmetic ability in normally developing children. This prediction was independent from the rate of access to phonological codes and phonological loop functioning. Therefore, Hecht et al. (2001) attributed this relation to central executive demands of phonological awareness tasks. They suggest that the processing component of the central executive is involved in encoding and storing phonemes in phonological awareness tasks. In concordance, our findings suggest that the central executive seems to be involved in phonological awareness. Notably, the hierarchical model suggests a direct as well as an indirect influence of verbal phonological central executive processes on phonological awareness, because the central executive coordinates the capacities of the subsystems. In sum, the findings suggest that phonological awareness is a crucial construct in early mathematical development that recruits different working memory subcapacities.

Language background. In many education systems, the number of children from different migration backgrounds has increased. In the current study, 41 per cent of the children had a language background different from only German. Given that many of the independent variables in the current study are verbal-phonological in nature, we conducted subgroup analyses with respect to language background. However, regardless if children spoke only German or German and another language with their parents, phonological awareness relied on working memory. Phonological awareness mediated specific working memory variance on basic numerical skills (QNC Level I). The impact of phonological awareness on QNC Level I but not QNC Level II indicates the validity of the isolated number words hypothesis regardless of language background.

However, despite similar correlational patterns, the comparison of the effect sizes in the subgroups yielded large differences. With regard to phonological awareness, this raises the question whether phonological awareness taps the same phonological processing components in children of both subgroups. For instance, the difference might not only be quantitative, but related to another quality of processing in phonological awareness; the familiarity of the sounds in the two administered tasks might play a role. This question might be an objective for future research.

Conclusions

Our study assessed two levels of the developmental model of quantity-number competencies (Krajewski, 2008; Krajewski & Schneider, 2009a,b), phonological awareness and different subcapacities of the working memory model by Baddeley (2000). The results of our study favour the following assumptions: Phonological awareness facilitates the development of basic numerical skills like learning the number word sequence. However, it is less important for higher level quantity-number competencies, which are characterized by the linkage of number words to quantities. In addition, working memory is important for phonological awareness. In particular, phonological awareness strongly relies on the capacity of the episodic buffer, the phonological loop, as well as the central executive. Furthermore, phonological awareness mediates between verbal phonological subcapacities of working memory and early quantity-number competencies. These relations are valid for children with different language backgrounds.

The presented study has several limitations, perhaps the most important restriction being that it is based on a concurrent analysis design: Any causal interpretations, even though based on relevant theories, have to be treated with caution. Preferably, these findings should be replicated in a longitudinal setting. In addition, following the relations of the assessed variables over several time points of measurement would allow an insight into developmental changes in the single constructs and their interplay. Moreover, in research on children, the episodic buffer is a relatively new component that has been little researched so far (c.f., De Smedt et al., 2009). We used a sentence repetition task (Schoeler & Brunner, 2007) to assess the episodic buffer, which was very similar to the task applied by Alloway et al. (2005). However, this task may also measure phonological working memory. Further research might establish the role of the episodic buffer in pre-school aged children. With respect to generalization, our findings are based on a sample of German speaking children. Therefore, the tasks of quantity-number competencies used irregular German number words that might tap different processes in German-speaking children than in children that grow up with German only or German and a second language. To a certain degree, this point may be accommodated by validating the postulated relations for children with different language background. Moreover, the children in this sample were assessed one year before entering school. At this stage, the German kindergarten curriculum does not provide any formalized schooling so that differences in task performance cannot be referred to effects of formal education. Due to the great number of different kindergartens (159), we could not track effects of informal schooling. Also, testing occurred between October and May, so some of the children might have spent longer periods of time in the kindergarten than others. Furthermore, it is important to note that the relationships between working memory and arithmetic outcome may depend on different aspects, that is, the selected areas indicated by variables (e.g., number word sequence, quantity-number word linkage) and the respective time window. Generally speaking, the time window might alter the nature of the relationship between different cognitive variables. For instance, at different stages of their development children could use different cognitive resources and find the same solution to the same problem.

3.4 Weiterführende Erörterung

Allgemein gesprochen kommt der Arbeitsgedächtniskapazität als personenspezifisches Merkmal der kognitiven Informationsverarbeitung eine entscheidende Rolle im Sinne eines „Flaschenhalses“ zu (Krajewski & Ennemoser, 2010). Die Ergebnisse der vorliegenden Studie legen nahe, dass dies auch für die Entwicklung der frühen numerischen Kompetenz gilt. Zur Beschreibung der frühen numerischen Kompetenzentwicklung wurde dabei auf ein Modell zurückgegriffen, welches diese Entwicklung in mehreren Ebenen beschreibt und zudem empirisch validiert ist (Krajewski, 2008; Krajewski & Schneider, 2009a; 2009b). Die Ergebnisse der vorliegenden Studie sprechen für den Schluss, dass der Erwerb früher numerischer Kompetenzen von den Arbeitsgedächtniskapazitäten der phonologischen Schleife, der zentralen Exekutive und des episodischen Puffers über die phonologische Bewusstheit als mediierender Faktor mitbestimmt wird. Das Ergebnis der vorgelegten Studie spricht zudem für die Gültigkeit der „isolated number words“-Hypothese (Krajewski & Schneider, 2009a). Dabei gilt diese Annahme sowohl für Kinder, welche nur Deutsch als Muttersprache haben, als auch für Kinder mit sprachlichem Migrationshintergrund, also solchen Kindern, welche mit ihren Eltern zu Hause noch eine weitere Sprache als Deutsch sprechen. Im Folgenden soll die Bedeutung der Ergebnisse über die Diskussion der vorgelegten eigenen empirischen Arbeit hinaus erörtert werden.

Mit der Gültigkeit der „isolated number-words“-Hypothese validiert unsere Studie nicht nur das Modell von Krajewski (2008), sondern spezifiziert auch die Rolle der phonologischen Bewusstheit innerhalb dieses Entwicklungsmodells der frühen numerischen Kompetenzen: Die phonologische Bewusstheit erleichtert vor allem den Erwerb basaler numerischer Fertigkeiten wie des Erwerbs der Zahlwortkette und spielt bei der Ausbildung höherer numerischer Kompetenzen, welche das Verständnis der Verbindung von Zahlwort und Menge erfordern, keine gewichtige Rolle mehr (vgl. Gersten, Jordan & Flojo, 2005; Okamoto & Case, 1996; Resnick, 1989). Durch den Bezug auf das Modell der frühen numerischen Entwicklung (Krajewski, 2008) differenzieren die hier vorliegenden Befunde die Ergebnisse vorhergehender Studien (z.B. Passolunghi et al., 2007), welche nicht zwischen Mengen-Zahlen-Kompetenzen unterschiedlicher Ebenen unterschieden. Passolunghi et al. (2007) erhoben die phonologische Bewusstheit sowie die Zählfertigkeit zu Beginn der ersten Klasse. Es zeigte sich, dass die Zählfertigkeit die Mathematikleistung am Ende der ersten Klasse vorhersagte. Diese Ergebnisse stimmen mit Krajewski und Schneider (2009a) überein: Die phonologische Bewusstheit steht im Zusammenhang mit frühen numerischen Kompetenzen, zu welchen auch die Zählfertigkeit gehört (QNC Level I). Letztere wiederum ist Vorläufer für die spätere Mathematikleistung. In weiterem Sinne bedeutet dieser Zusammenhang, dass Defizite in der phonologischen Bewusstheit nicht nur zu einem Defizit der Lese- und Rechtschreibfertigkeiten, sondern auch zu Verzögerungen in der mathematischen Entwicklung führen können. Dies liefert zudem eine mögliche Erklärung für die Kovariation mathematischer Fertigkeiten und Lesefertigkeiten, welche von Geary (1993) als der „semantic memory subtype“ beschrieben wurde. Überdies erweitert die vorliegende Untersuchung die Gültigkeit der Ergebnisse für Kinder mit sprachlichem Migrationshintergrund. Die phonologische Bewusstheit ist sowohl bei Kindern mit als auch ohne sprachlichem Migrationshintergrund bedeutsam für die Entwicklung früher mathematischer Kompetenzen.

Die vorgelegten Ergebnisse lassen zudem eine weitere theoretische Einordnung des Konstrukts der phonologischen Bewusstheit hinsichtlich dessen bereichsspezifscher vs. bereichsunspezifischer Funktion bei der Entwicklung des Erwerbs früher numerischer Kompetenzen zu. Zweifelsohne steht die phonologische Bewusstheit im Zusammenhang mit der Entwicklung von Lese- und Rechtschreibfertigkeiten (z.B. Schneider & Näslund, 1999, Wagner & Torgesen, 1987; Wagner, Torgesen & Rashotte, 1994). Dies legt nahe, die phonologische Bewusstheit als bereichsspezifische Vorläuferfertigkeit zu verstehen. Die in der hier vorgelegten Studie beschriebenen, wie auch die Ergebnisse von Krajewski & Schneider (2009a), zeigen jedoch, dass die phonologische Bewusstheit durch ihren Bezug zu basalen numerischen Fertigkeiten als bereichsunspezifisch verstanden werden kann. Natürlich setzt dies voraus, dass die erste Stufe der frühen numerischen Kompetenz (Krajewski, 2008) als nicht rein sprachlich zu aufzufassen ist. In diesem Kontext wäre also die Frage zu erwägen, ob diese Stufe auf Grund ihres stark sprachlichen Charakters weniger eine eigentliche numerische Kompetenz misst, eben da die Verknüpfung von Zahlwort und Menge auf dieser Stufe noch nicht eingetreten ist. Würde man also die erste Stufe der frühen numerischen Kompetenzentwicklung als rein sprachlich auffassen, würde dies für die phonologische Bewusstheit bedeuten, dass letztere doch bereichsspezifisch ist. Der in der hier präsentierten Studie berichtete hohe Zusammenhang der ersten Ebene früher numerischer Kompetenzen als Prädiktor der zweiten Ebene der frühen numerischen Kompetenzen spricht jedoch für die Annahme des Modells von Krajewski (2008) – und somit auch die Bedeutung der phonologischen Bewusstheit als bereichsübergreifendes Konstrukt.

In Ergänzung des Zusammenhangs der phonologischen Bewusstheit und mathematischer Fertigkeiten soll an dieser Stelle die „weak phonological representations“-Hypothese (Simmons & Singleton, 2008) vorgestellt und in Bezug zur „isolated number-words“-Hypothese gesetzt werden, da diese einen alternativen Erklärungsansatz zum Zusammenhang phonologischer Bewusstheit und der Entwicklung mathematischer Fertigkeiten bietet. Die „weak phonological representations“-Hypothese (Simmons & Singleton, 2008) besagt, dass ein Defizit in der phonologischen Bewusstheit alle solche Bereiche der Mathematikleistung einschränkt, welche die Manipulation verbaler Codes einschließen (so auch bei Aufgaben von QNC Level I und II aus dem Modell von Krajewski,

2008) nicht aber solche, die nicht verbal kodiert sind. Wie oben beschrieben, zeigen Krajewski und Schneider (2009a), dass Defizite in der phonologischen Bewusstheit den Erwerb solcher verbaler Codes einschränken, welche in einem frühen Entwicklungsstadium für die numerische Verarbeitung gebraucht werden. Jedoch – und darin besteht ein Unterschied zu Simmons und Singleton (2008) – wird dieser Einfluss der phonologischen Bewusstheit auf frühe numerische Kompetenzebenen kontrolliert (Krajewski & Schneider, 2009a), so zeigt sich, dass Defizite der phonologischen Bewusstheit nicht *direkt* höhere Ebenen der frühen numerischen Kompetenzentwicklung beeinflussen. In diesem Sinne scheint der Einfluss möglicherweise weniger auf ein Defizit in der Kodierung als auf den Inhalt zurückzugehen. Wie bereits oben angesprochen, fanden Krajewski & Schneider (2009a) keinen Einfluss der phonologischen Bewusstheit auf QNC Level II und III. Demnach wird ein Defizit in der phonologischen Bewusstheit keinen direkten, sondern einen indirekten Einfluss via QNC Level I, auf diese Ebenen nehmen. In der vorgelegten Studie 2 dieser Arbeit (Michalczyk et al., Resubmission bei Cognitive Development am 8. September 2011), zeigte sich ebenfalls kein Einfluss der phonologischen Bewusstheit auf QNC Level II, auch wenn die QNC Level II Aufgaben durchaus sprachlich kodiert werden. QNC Level III wurde nicht erhoben, somit kann über letztere keine Aussage getroffen werden. Die Befunde der vorliegenden Studie sprechen also gegen die „weak phonological representations"- Hypothese (Simmons & Singleton, 2008), welche einen direkten Einfluss phonologischer Bewusstheit auf frühe numerische Kompetenzen zweiter Ebene postulieren würde.

Die hier vorgestellte Studie (Michalczyk et al., Resubmission bei Cognitive Development am 8. September 2011) ist grundlagenforschungsorientiert und lässt dabei praktische Implikationen wie z.B. für die Unterstützung des Erwerbs früher numerischer Kompetenzen aus. Aus der anwendungsbezogenen Perspektive kommt dem Arbeitsgedächtnis eine diagnostische Bedeutung im Kontext der Schulleistung zu (vgl. Schumann-Hengsteler et al., 2010) und die Nutzung der Kapazität des Arbeitsgedächtnisses beeinflusst die

Entwicklung der frühen numerischen Kompetenz. Letztere ist Vorläuferfertigkeit für die schulische Mathematikleistung und markiert in Teilen (QNC Level III, siehe Abschnitt 3.1) den Übergang zu dieser. Für die Rolle des Arbeitsgedächtnisses bei der kognitiven Leistung(sentwicklung) wurde schon in Anlehnung an den Broadbent'schen Begriff von der „Flaschenhalsfunktion" des Arbeitsgedächtnisses (Krajewski & Ennemoser, 2010) gesprochen. Selbstverständlich kann dieser Schluss nicht allein aus den Ergebnissen des querschnittlichen Designs der hier vorgelegten eigenen empirischen Studie gezogen werden. Doch fügen sich die Ergebnisse der vorliegenden Arbeit in die allgemeine Befundlage ein (Krajewski & Schneider, 2009a; LeFevre et al, 2010; für ein Review siehe Raghubar et al., 2010).

Was wäre also ein möglicher Zugang zur Förderung der frühen numerischen Kompetenzentwicklung aus der Perspektive der eingereichten Untersuchung? Die Steigerung der Arbeitsgedächtnisleistung durch spezifische Trainings scheint zwar möglich, doch gibt es zu dieser bis dato wenige Befunde und die wenigen vorliegenden basieren auf geringen Stichprobenzahlen (z.B. Holmes, Gathercole & Dunning, 2009). Mit dem Ziel der Förderung einzelner Schüler oder Schülergruppen empfiehlt sich die fundierte Diagnostik gegebenenfalls niedriger Arbeitsgedächtnisressourcen durch geeignete Instrumente (z.B. Hasselhorn et al., in Druck). Im Falle gering ausgeprägter Arbeitsgedächtnisressourcen sollte eine Informationsüberfrachtung durch die Lernumgebung, die Aufgabe selbst, die Darbietungsform der Aufgabe, sowie der dazugehörigen Instruktion vermieden werden. Im Sinne eines Multifacettenansatzes bieten sich dabei mehrere Ansatzpunkte. Hierzu gehören beispielsweise die Gestaltung von Unterrichtsmaterialien (vgl. Krajewski & Ennemoser, 2010) und andere Strategien wie die Instruktionsgestaltung, das Zerlegen von Aufgaben in Teilschritte und das Verwenden externer Merkhilfen (vgl. Gathercole, Lamont & Alloway, 2006). In Hinsicht auf den Erwerb basaler numerischer Fertigkeiten empfiehlt sich zudem auf Grundlage der vorliegenden Ergebnisse und deren theoretischer Begründung vermutlich das

Training phonologischer Bewusstheit und zwar sowohl für Kinder mit als auch ohne sprachlichen Migrationshintergrund. Für den Erwerb früher numerischer Kompetenzen existiert zudem das evaluierte Programm Mengen-Zahlen-Zählen (Krajewski, Nieding & Schneider, 2008).

4. Zusammenfassende Diskussion

Das Arbeitsgedächtnis ist ein grundlegendes Merkmal menschlicher Informationsverarbeitung. In unterschiedlichen Bereichen psychologischer Forschung existiert und konkurriert dabei eine Vielzahl von Modellvorstellungen des Arbeitsgedächtnisses (z.B. Cowan et al., 2007; Michalczyk & Hasselhorn, 2010). Im pädagogisch-entwicklungspsychologischen Bereich stellt dabei insbesondere die Konzeption von Baddeley (1986) ein prominentes Modell dar. Kontrovers diskutiert werden dabei die Anzahl, Art und Anordnung der Komponenten zueinander, aber auch ihr Zusammenhang mit anderen Bereichen der kognitiven Leistungsentwicklung (z.B. Jarrold & Towse, 2006). Was bedeuten die hier vorgelegten empirischen Untersuchungen also für die Struktur des Arbeitsgedächtnisses, der entwicklungsbezogenen Veränderung dieser Struktur und den Zusammenhang mit der Entwicklung früher numerischer Kompetenzen? Die erste eigene empirische Arbeit (Michalczyk et al., Einladung zur Resubmission bei European Journal of Psychological Assessment, 22. September 2011) ist eine der bisher wenigen Studien, welche die Arbeitsgedächtnisstruktur nach Baddeley (1986) schon im vorschulischen Altersbereich prüft. Es zeigt sich, dass auch schon im Vorschulalter eine Dreikomponentenstruktur bestehend aus der phonologischen Schleife, dem visuell-räumlichen Notizblock und der zentralen Exekutive erfasst werden kann. Dies bestätigt die Annahme einer Dreikomponentenstruktur (Gathercole et al. 2004) und repliziert sowie ergänzt die Befunde von Alloway et al. (2006) für den deutschen Sprachraum. Auch erweitert dies die Befunde von Roebers und Zoelch (2005) welche für den Altersbereich von vier bis fünf Jahren die Trennbarkeit der phonologischen Schleife und des visuell-räumlichen Notizblocks berichten. Im Gegensatz zu der Arbeit von Gathercole und Pickering (2000) ließ sich in der hier vorgelegten Studie die visuell-räumliche Komponente von der zentral-exekutiven Komponente abgrenzen. Zusammenfassend sprechen die Befunde also für eine

Dreikomponentenstruktur im Sinne der Baddeley'schen Konzeption (1986) schon ab dem Vorschulalter.

Doch ändert sich das Verhältnis der unterschiedlichen Arbeitsgedächtniskomponenten zueinander im Laufe der kindlichen kognitiven Entwicklung? Diese Frage führt zur Prüfung der entwicklungsbezogenen Varianz oder Invarianz der funktionalen Interdependenz der unterschiedlichen Arbeitsgedächtniskomponenten (vgl. Alloway et al., 2006; Gathercole et al, 2004). Die hier vorgelegte eigene Untersuchung zeigte die weitestgehende Invarianz der Arbeitsgedächtnisstruktur in der kindlichen kognitiven Entwicklung, was die hierarchische Ordnung der Arbeitsgedächtniskomponenten im Sinne der Baddeley'schen Annahmen (1986) einschließt. Lediglich der Zusammenhang der phonologischen Schleife und der zentralen Exekutive vor dem 7. Lebensjahr fiel geringer aus als in den höheren Altersgruppen. Dieser Befund ist möglicherweise durch das Einsetzen spontan auftretender Rehearsalstrategien ab dem 6. Lebensjahr auf Grund der fortschreitenden Entwicklung des subvokalen Kontrollprozesses erklärbar (vgl. Hasselhorn et al., 2000). Die Ergebnisse sind somit annähernd konform mit bisherigen, welche zeigten, dass Rehearsal-Strategien vor dem 7. Lebensjahr zumindest nicht reliabel auftreten (z.B. Gathercole & Hitch, 1993). Die vorgelegte Studie stützt also die Modellvorstellung des Arbeitsgedächtnisses, welche sich aus bereichsspezifischen Speicherkomponenten und einer hierarchisch übergeordneten, bereichsunspezifischen zentralen Exekutive zusammensetzt. Es ist hervorzuheben, dass die zentrale Exekutive mit einer großen Bandbreite an Paradigmen bzw. Aufgaben erfasst wurde. Dies spiegelt zum einen die Heterogenität der zu dieser Komponente gehörigen kognitiven Prozesse wider und zeigt zugleich, dass eine solch heterogene Erfassung der zentralen Exekutive schon im vorschulischen Altersbereich möglich ist. Die Invarianz dieser Struktur in der kindlichen Entwicklung bildet die Grundlage der Verwendung des Arbeitsgedächtnisses als diagnostischen Indikator, welcher z.B. mit anderen Konstrukten der Leistungsfähigkeit in Verbindung gebracht werden kann. Aus praktischer Sicht rechtfertigt sie die Anwendung von

Arbeitsgedächtnisaufgaben wie der Testbatterie AGTB 5-12 (Hasselhorn et al., in Druck) als Diagnostikum, da deren Aufgabenauswahl auf dieser latenten Modellvorstellung basiert.

Wie hängen unterschiedliche Subkapazitäten des Arbeitsgedächtnisses mit der frühen numerischen Kompetenzentwicklung zusammen? Die zweite vorgelegte empirische Studie (Michalczyk et al., Resubmission bei Cognitive Development am 8. September 2011) prüfte diesen Zusammenhang unter Einbezug der phonologischen Bewusstheit und eines Modells früher numerischer Kompetenzentwicklung, welches diese Entwicklung in mehreren Ebenen beschreibt (Krajewski, 2008). Diese vorgelegte Untersuchung unternahm somit einen Brückenschlag zwischen dem Forschungsfeld des Arbeitsgedächtnisses und der Entwicklung früher numerischer Kompetenzen (vgl. Raghubar, 2010). Durch die Bestätigung der „isolated number-words“-Hypothese (Krajewski & Schneider, 2009a) unterstreichen die Ergebnisse der vorgelegten zweiten eigenen empirischen Arbeit die tragende Rolle der phonologischen Bewusstheit in der Entwicklung früher numerischer Kompetenzen, wobei die phonologische Bewusstheit auf unterschiedliche phonologische Arbeitsgedächtnissubkapazitäten zurückgreift und einen mediierenden Einfluss zwischen dem Arbeitsgedächtnis und der frühen numerischen Kompetenzentwicklung einnimmt. Dieser Zusammenhang bietet eine Erweiterung und Differenzierung bisheriger Befunde zum Zusammenhang phonologischer Bewusstheit und früher mathematischer Kompetenzen (z.B. Passolunghi et al., 2007), steht dabei jedoch im Widerspruch zur Annahme der „weak phonological representations“-Hypothese (Simmons & Singleton, 2008). Zudem konnten im Rahmen der vorliegenden Arbeit die Befunde von Krajewski (2009a) auf Kinder mit sprachlichem Migrationshintergrund erweitert werden: Es zeigte sich auch hier die Gültigkeit der „isolated number words“-Hypothese. Dieser Befund festigt die Rolle der phonologischen Bewusstheit in der frühen numerischen Kompetenzentwicklung unabhängig des sprachlichen Migrationshintergrunds und mag auch als Hinweis auf potentielle Ansatzpunkte der

Förderung für insbesondere die Entwicklung basaler numerischer Fertigkeiten (QNC Level 1) als Vorläufer höherer numerischer Kompetenzen (QNC Level II und III) gelten.

Kritik und Ausblick

Beide Studien unterstreichen insgesamt die Möglichkeit und Bedeutung der dezidierten Erfassung der einzelnen Komponenten bzw. Subkapazitäten des Arbeitsgedächtnisses im Vorschulalter. In Hinsicht auf die Struktur des Arbeitsgedächtnisses sind sicherlich erweiternde und ergänzende Binnendifferenzierungen innerhalb der Baddeley'schen Komponenten denkbar (vgl., Alloway et al., 2006; Mammarella et al., 2008). Vor allem für Erwachsenenpopulationen existieren allerdings auch stark von der Baddeley'schen Modellvorstellung (1986) abweichende Konzeptionen und konkurrieren mit dieser (vgl. Cowan et al., 2007; Michalczyk & Hasselhorn, 2010). Zusätzlich zur weiteren Binnendifferenzierung ist daher sicher auch die Prüfung anderer Modellvorstellungen wie z.B. Zwei- oder Dreikomponentenmodelle schon in vorschulischen Stichproben möglich. Sind bisherige Studien im Kindesalter zur Struktur des Arbeitsgedächtnisses meist dem Ansatz interindividueller Differenzen zu zuordnen, so sind auch andere methodische Zugänge denkbar wie beispielsweise experimentelle Studien. Des Weiteren basieren die Analysen der Invarianz der Struktur und funktionalen Interdependenz der Arbeitsgedächtniskomponenten der hier vorgelegten und bisherigen Studien (Alloway et al., 2006; Gathercole et al, 2004) auf dem Vergleich unterschiedlicher querschnittlich erhobener Alterskohorten. Hier wäre ein längsschnittlicher Ansatz zumindest denkbar. Der Bedarf längsschnittlicher Analysen als keine hinreichende aber notwendige Voraussetzung kausaler Schlussfolgerungen trifft auch auf den Zusammenhang von Arbeitsgedächtnis, phonologischer Bewusstheit und früher numerischer Kompetenzentwicklung zu, da die Schlussfolgerungen der eigenen empirischen Arbeit auf einem querschnittlichen Design basieren. Durch die Verwendung längsschnittlicher Designs könnte zusätzlich dem Umstand Rechnung getragen werden, dass gerade in der kindlichen Entwicklung kognitive Fertigkeiten in kurzen Zeitspannen große Veränderungen aufweisen. Überdies hinaus ist der Einfluss weiterer Konstrukte der Informationsverarbeitung wie beispielsweise der Intelligenz nebst Arbeitsgedächtniskomponenten und phonologischer Bewusstheit sinnvoll. Der Einbezug dieser könnte in weiteren Untersuchungen Berücksichtigung finden, um das Zusammenwirken unterschiedlicher Faktoren in der kindlichen kognitiven Leistungsentwicklung weiter aufzuklären.

Zusammenfassung

Die vorgelegte Arbeit setzt sich aus drei Veröffentlichungsstücken zusammen. Im ersten Teil zeigten Michalczyk und Hasselhorn (2010) einen Überblick über die Vielfalt der Modellvorstellungen des Arbeitsgedächtnisses. Dabei wurde insbesondere das Baddeley Modell (1986) hervorgehoben. Dieses steht für eine ganze Klasse komponentenbasierter, meist dem experimentellen oder dem Ansatz interindividueller Differenzen zugehöriger, Modellvorstellungen und ist zudem maßgeblich im pädagogisch-entwicklungspsychologischen Kontext für Theorie und Praxis von Bedeutung. Die Ergebnisse der ersten empirischen Vertiefung der hier vorgelegten Arbeit bestätigten die Gültigkeit der Dreikomponentenstruktur (Baddeley, 1986) und deren weitestgehende Altersinvarianz hinsichtlich der funktionalen Interdependenz der Komponenten phonologische Schleife, visuell-räumlicher Notizblock und zentrale Exekutive im Laufe der kindlichen Entwicklung. Lediglich bei Kindern jünger als 7 Jahre war der Zusammenhang der phonologischen Schleife und der zentralen Exekutive weniger stark ausgeprägt als bei älteren Kindern. In der zweiten empirischen Untersuchung wurden Subkapazitäten des Arbeitsgedächtnisses und die phonologische Bewusstheit zur Entwicklung früher numerischer Kompetenzen (Krajewski, 2008; Krajewski & Schneider 2009a,b) in Beziehung gesetzt. Es zeigte sich, dass die phonologische Bewusstheit auf die phonologische Schleife, den episodischen Puffer und phonologische, zentral-exekutive Prozesse zurückgreift. Zudem beeinflusste die phonologische Bewusstheit frühe numerische Basisfertigkeiten (QNC Level I), nicht aber (höhere) Mengen-Zahlen Kompetenzen (QNC Level II), was die „isolated number words“-Hypothese (Krajewski & Schneider, 2009a) bestätigte. Diese Zusammenhangsmuster, bei denen die phonologische Bewusstheit eine mediierende Rolle zwischen Arbeitsgedächtnissubkapazitäten und frühen numerischen Kompetenzen einnimmt, galten gleichermaßen für Kinder mit und ohne sprachlichem Migrationshintergrund.

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