Executive Functions across the Adult Life Span: Age-related Differences and Relationships with Intelligence

A cumulative dissertation
Doctorate in Psychology (Dr. rer. nat.)
Submitted to the University of Bremen, Faculty 11

By

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Bremen, February 2017

Colloquium (oral defense) on 8 June 2017

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<tr>
<td>CHC</td>
<td>Cattell-Horn-Carroll</td>
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<td>CTMT</td>
<td>Comprehensive Trail Making Test</td>
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<tr>
<td>CV</td>
<td>coefficient of variation</td>
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<td>D-KEFS</td>
<td>Delis-Kaplan Executive Function System</td>
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<tr>
<td>EFI</td>
<td>Executive Functions Index</td>
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<tr>
<td>EFs</td>
<td>executive functions</td>
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<td>FSIQ</td>
<td>Full Scale IQ</td>
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<td>g</td>
<td>general intelligence</td>
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<td>GAI</td>
<td>General Ability Index</td>
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<td>Gc</td>
<td>crystallized intelligence</td>
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<td>Gf</td>
<td>fluid intelligence</td>
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<td>MANOVA</td>
<td>multivariate analysis of variance</td>
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<td>MCST</td>
<td>Modified Card Sorting Test</td>
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<tr>
<td>NAB</td>
<td>Neuropsychological Assessment Battery</td>
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<td>PASAT</td>
<td>Paced Auditory Serial Addition Task</td>
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<td>PFC</td>
<td>prefrontal cortex</td>
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<td>PRI</td>
<td>Perceptual Reasoning Index</td>
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<td>PSI</td>
<td>Processing Speed Index</td>
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<tr>
<td>SAS</td>
<td>supervisory attentional system</td>
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<tr>
<td>TVCF</td>
<td>Test of Verbal Conceptualization and Fluency</td>
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<tr>
<td>VIF</td>
<td>variance inflation factor</td>
</tr>
<tr>
<td>WAIS-III</td>
<td>Wechsler Adult Intelligence Scale – Third Edition</td>
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<td>WAIS-IV</td>
<td>Wechsler Adult Intelligence Scale – Fourth Edition</td>
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<td>WAIS-R</td>
<td>Wechsler Adult Intelligence Scale – Revised</td>
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<tr>
<td>VCI</td>
<td>Verbal Comprehension Index</td>
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<tr>
<td>WCST</td>
<td>Wisconsin Card Sorting Test</td>
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<td>WM</td>
<td>working memory</td>
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<td>WMI</td>
<td>Working Memory Index</td>
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Abstract

**Background:** Executive Functions (EFs) are considered the most complex human cognitive capacities. Despite the crucial importance of this cognitive domain for overall mental functioning, no consensus on the definition, terminology, and classification of EFs has been reached so far. Investigating age-related differences in EFs and the relationship between EFs and intelligence may help better understand the nature of the construct.

**Aims:** The current thesis is aimed at exploring differences in executive performance between healthy adults; additionally, the aim is to examine the relationship between EFs and intelligence through the comparison of younger and older adults.

**Methods:** The Executive Functions Module of the Neuropsychological Assessment Battery (NAB), as a measure of EFs, and the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV), as a measure of intelligence, were implemented. Data of 485 NAB norming sample participants aged 18-99 were analyzed to examine age-related differences in EFs. Data of 126 NAB norming sample participants aged 18-88, who additionally completed the WAIS-IV, were used to investigate the relationship between EFs and intelligence.

**Results:** Overall, decreases in the mean scores and increases in the dispersion of performance on the NAB Executive Functions Module subtests with advancing age were observed. EF tasks associated with fluid intelligence (i.e., Mazes, Planning, and Categories) exhibited the greatest decrease in mean scores and the highest increase in dispersion; in contrast, EF tasks associated with crystallized intelligence (i.e., Letter Fluency, Word Generation, and Judgment) showed the lowest decrease in mean scores and the lowest increase in dispersion. Additionally, substantial age-independent and age-related relationships between the NAB Executive Functions Module and the WAIS-IV were demonstrated. The Categories and Word Generation subtests correlated substantially with most of the WAIS-IV indices, and were most frequently included in the WAIS-IV prediction models. Age-related differences with regard to the relationship between EFs and intelligence were associated with higher scores in older adults; in particular, the NAB Judgment subtest correlated more strongly with several WAIS-IV scores, and the NAB Executive Functions Index correlated more strongly with the WAIS-IV Verbal Comprehension Index.

**Conclusion:** Ability-related deterioration trends in EFs, the multifactorial nature of EF measures, and age-related relationship patterns between EFs and intelligence must especially be considered within neuropsychological assessments. Substantial relationships between EFs and intelligence should be better reflected within the theoretical framework of cognitive abilities.
Zusammenfassung


**Fragestellung:** Die vorliegende Arbeit hat zum Ziel, gesunde Erwachsene im Hinblick auf exekutive Leistungen zu vergleichen. Des Weiteren wird der Zusammenhang zwischen den EF und Intelligenz untersucht. Hierbei wird der Frage nachgegangen, ob sich dieser Zusammenhang zwischen jüngeren und älteren Erwachsenen unterscheidet.


**Fazit:** Fähigkeitsgebundene Trends der Leistungsabnahme in den EF, die multifaktorielle Beschaffenheit der Messinstrumente und altersabhängige Zusammenhangsmuster zwischen den EF und Intelligenz müssen insbesondere im Rahmen der neuropsychologischen Diagnostik in Betracht gezogen werden. Deutliche Zusammenhänge zwischen den EF und Intelligenz sollten besser in den theoretischen Modellen zu kognitiven Fähigkeiten berücksichtigt werden.
Introduction

Executive functions (EFs) are often classified as the highest level of human cognitive capacities. They are required for the coordination and regulation of cognition, emotion, and behavior; and thus, substantial for intact functioning of every human being (Lezak, 1982; Strauss, Sherman, & Spreen, 2006). Nevertheless, despite much interest in exploring and crucial importance of this cognitive domain, many research questions are still to be answered.

The existing literature shows much inconsistency in terms of the definition, terminology and classification of EFs (Strauss et al., 2006). Thus, working towards a widely accepted theoretical framework is of high priority. Among many issues to be investigated, exploring the influence of age on executive functioning may help achieve this. In fact, findings on age-related changes in EFs across the adult life span are inconclusive (Jurado & Rosselli, 2007; Mejia, Pineda, Alvarez, & Ardila, 1998; Wecker, Kramer, Wisniewski, Delis, & Kaplan, 2000). Particularly, ability-related deterioration trends and interindividual variability in performance are the issues that require further investigations. Additionally, due to the central role of EFs for the coordination of the subordinated cognitive processes, exploring the relationships between EFs and other cognitive domains appears essential. Especially the relationship between EFs and intelligence should be investigated more thoroughly (Lamar, Zonderman, & Resnick, 2002). Despite existing evidence on substantial associations between EFs and intelligence, the relationships between the individual components of the two constructs are not well studied. Furthermore, age-related differences in the relationship between the two constructs require more extensive investigations.

A better understanding of the nature and solid theoretical foundations of the construct of EFs are essential for clinical neuropsychology. In particular, improvements in the field of neuropsychological diagnostics can be achieved by offering assessment tools suitable for detecting cognitive dysfunctions and providing therapy guidelines.

The aim of the current doctoral thesis is to investigate the influence of age on EFs by examining differences in regard to the mean and dispersion in EF performance between several healthy adult age groups across a large age range. Additionally, the thesis is aimed at exploring the general relationship as well as more specific relationships between EFs and intelligence. Furthermore, the influence of age on the association between EFs and intelligence is examined.
Field of research

The current doctoral thesis is based on two research studies accomplished between 2013 and 2016 at the Center of Clinical Psychology and Rehabilitation, University of Bremen. Data used in the thesis were collected within the German standardization of the Neuropsychological Assessment Battery (NAB). In the initial stage of the project, the German adaptation of the NAB was created. After successful examination with a small sample, a country-wide norming was launched. Data used in the first study were collected on four NAB norming sites in Germany including Bremen, Gera, Heidelberg, and Köln, and originated from 485 participants. Data used in the second study were collected in Bremen and originated from 126 participants. For the second study, two assessment tools, the NAB and the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV) were administered. Data collected within the two research studies resulted in three empirical publications, which have been published in peer-reviewed scientific journals.

Study I

Publication 1 (see Appendix A):

Study II

Publication 2 (see Appendix B):

Publication 3 (see Appendix C):
Besides the research conducted within the dissertation, additional research activities were undertaken. This includes activities associated with the German NAB standardization project; in particular, participation in the German adaptation and the coordination of the NAB norming. One additional article and one oral presentation at a scientific conference are listed below.


Buczyłowska, D., & Petermann, F. (2016, September 7-9). *Age-related differences in executive functions*. Oral presentation at the 2nd Neurological Disorders Summit (NDS-2016), Baltimore, MD, USA.

**Organization of the thesis**

The current thesis is structured in two major parts. In the first part, the theoretical foundation and in the second part, the empirical research of the thesis, are presented. The first part is composed of four chapters, starting with an introduction into the concept of EFs from present and historical perspective, followed by the description of the main developmental steps of EFs including childhood, adolescence, adulthood, and age-related decline. In the second chapter, the concept of intelligence, including its evolution and the current theoretical framework, is presented. Additionally, the present state of research on the relationship between EFs and intelligence is discussed. The first part ends with an introduction into the current research by providing the rationale for and presenting the major research questions pursued within the current doctoral thesis. The second part is composed of three chapters, and starts with a chapter on methodological issues describing sample characteristics, assessment tools and statistical methods used. A subsequent chapter provides an overview and discussion of the results derived from the current research. The final chapter summarizes the main findings and presents potential implications for theory and practice. Limitations of the current research and directions for future research are finally outlined in the closing section of the thesis.
Theoretical foundation

1. Executive functions

Executive functions (EFs) are thought to represent the most complex mental domain (Strauss et al., 2006). Yet there is no consensus on the definition of EFs (Jurado & Rosselli, 2007; Miyake, Emerson, & Friedman, 2000; Reynolds & Horton, 2008; Salthouse, 2005; Strauss et al., 2006). The term is rather a collective name for the metacognitive capacities responsible for coordinating basic cognitive processes, such as attention, language, memory, and perception (Alvarez & Emory, 2006; Elliott, 2003; Salthouse, Atkinson, & Berish, 2003; Wecker et al., 2000). Nevertheless, it is widely accepted that executive dysfunctions may affect all aspects of everyday life, and that intact executive functioning is essential for independent living (Lezak, Howieson, Bigler, & Tranel, 2012; Strauss et al., 2006). Hence, growing interest in investigating EFs in recent years reflects the (actual) importance of this cognitive domain.

In the present chapter, the theoretical framework of EFs is presented including the current understanding, history, and theoretical foundations of the concept, followed by a brief overview on the main developmental stages of EFs.

1.1 Current understanding

Although there is a lack of a widely accepted definition, many of the attempts to define EFs are not mutually incompatible since they just emphasize different aspects of the construct (Obonsawin et al., 2002). In general, EFs are believed to represent abilities that are crucial for goal-oriented behavior (Alvarez & Emory, 2006; Welsh, Pennington, & Groisser, 1991), adapting to changing environments (V. Anderson, Jacobs, & Anderson, 2008; De Luca et al., 2003; Jurado & Rosselli, 2007), and coping with novel tasks (Duncan, Burgess, & Emslie, 1995; Passingham, 1993). When dealing with complex circumstances or unfamiliar contexts, well-learned behaviors are less useful. Instead of previously established routines, new strategies must be implemented; essentially, EFs are those processes necessary for creating new approaches to unknown situations (Strauss et al., 2006). Consequently, EFs “consist of those capacities that enable a person to engage successfully in independent, purposive, self-directed, and self-serving behavior” (Lezak et al., 2012, p. 37). Therefore, executive functioning is thought to be crucial for all aspects of everyday life (Strauss et al., 2006).

EFs are frequently defined as higher mental abilities. This seems plausible in the light of the complexity of tasks they are responsible for. However, it is not clear what are the key
cognitive operations involved in executive functioning and how they are related to other cognitive processes. The terms frequently used to describe the components of executive functioning include problem-solving; mental or cognitive flexibility; planning, modifying, and completing complex tasks; inhibition, switching, updating or working memory (WM), sustained and selective attention (Alvarez & Emory, 2006; Arffa, 2007; Baddeley & DellaSala, 1996; Burgess, Evans, Emslie, & Wilson, 1998; Elliott, 2003; Maricle & Avirett, 2012; Miyake, Friedman, et al., 2000; Rabbitt, 1997; van der Sluis, de Jong, & van der Leij, 2007). Furthermore, these complex cognitive operations depend upon multiple sub-processes. Thus, the key role of EFs is to control and coordinate the operation of all these multiple processes to accomplish a particular goal (Funahashi, 2001). “Coordination, control and goal-orientation are, therefore, at the heart of the concept of executive function” (Elliott, 2003; p. 50).

1.2 History of the concept

Despite the lack of agreement on the exact definition, attempts have been made already in the past to define the core aspects of executive functioning. These definitions are partially compatible with the current understanding of the concept. Lezak (1982) proposed a definition, which adequately reflects the significance of EFs for daily functioning: “capacities for formulating goals, planning, and carrying out plans effectively – the executive functions - are essential for independent, creative, and socially constructive behavior” (p. 281). Much earlier, Luria (1966) described impairments caused by the lesions of the frontal lobes generally as intellectual disturbances. He also pointed out that, in the light of evidence showing that a lesion of the frontal lobes leads to a disturbance of intelligent behavior as a whole, and simultaneously leaves the more elementary processes unchanged, it must be concluded that the functions of the frontal lobes are different from the functions of the other parts of the brain; moreover, the functions of the frontal lobes are responsible for the coordination, monitoring, and planning of behavior (Luria, 1976).

Executive functioning as a concept has existed since the late 19th and early 20th centuries; however, the term EFs emerged later. For example, Luria was using the term frontal syndrome, when describing intellectual disturbances related to brain lesions (Luria, 1966). Based on the first findings in frontal pathology obtained from adult patients with large acquired frontal lobes injuries, EFs have primarily been associated with the frontal lobe functioning (Ardila, 2008; De Luca & Leventer, 2008; Stuss & Alexander, 2000). As a result, the term frontal lobe syndrome came into use and has later been used synonymously with executive dysfunction (Ardila, 2008). Likewise, both terms executive and frontal have been used since
then interchangeably (Elliott, 2003; Stuss & Alexander, 2000). However, further clinical investigations have reported executive dysfunctions being related to lesions of other brain areas than frontal lobes (Baddeley & DellaSala, 1996; Stuss, 2011). Moreover, functional imaging studies indicated posterior, cortical, and sub-cortical brain regions being involved in executive functioning (Mesulam, 1998; Roberts, Robbins, & Weiskrantz, 2002). At present, it is thus widely accepted that EFs involve an interaction of dynamic networks, with the prefrontal cortex (PFC) playing a key role (Elliott, 2003; Jurado & Rosselli, 2007; Salthouse et al., 2003). Consequently, executive dysfunctions may result from lesions of the overall frontal system rather than exclusively from lesions of the frontal lobes (Royall et al., 2002).

### 1.3 Seminal theories and models

Since the concept of executive functioning first emerged, numerous theories and models have been proposed. Some of them have exerted substantial influence on the evolution of the concept of executive functioning. Thus, two traditional and influential theories are hereafter presented. Additionally, due to considerable research progress in recent years, the current perspective is outlined as well.

**Multiple-component model of working memory**

Baddeley and Hitch (1974) proposed a three-component model of WM composed of the *central executive* and two subsidiary slave systems, the *phonological loop* and the *visuospatial sketchpad*. The authors postulated that the central executive possesses itself no storage capacity; instead, it controls the two slave systems being responsible for the temporary storage system. The phonological loop holds speech-based information using temporary storage and an articulatory rehearsal system; whereas the visuospatial sketchpad is capable of holding visual, spatial, and kinesthetic information. Both components of the temporary storage system are able to hold information for a few seconds (Baddeley, 2000). The central executive executes its control over the storage system by using sub-processes, such as selective attention and the ability to focus and switch attention. Another important function of the central executive is to access and manipulate information in the long-term memory (Baddeley & DellaSala, 1996). Later on, Baddeley (2000) extended the original model by adding a fourth component - the episodic buffer. This additional temporary store is responsible for holding and utilizing complex information by integrating information from the phonological loop and visuospatial sketchpad.
1. Executive functions

**Supervisory attentional system**
The supervisory attentional system (SAS) proposed by Norman and Shallice (1986) is a model centered on attention and action as its core elements. The SAS is a mechanism located in the PFC, which is responsible for controlling behavior (Shallice, 2002). This mechanism operates on schemas of action, which are triggered according to situational context. The basic assumption is the distinction between automatic and controlled processing involved in the selection and control of action. This refers to the way how certain tasks can be executed. The automatic processes are involved in actions that can be executed without awareness of their performance, which is the case in simple or well learned routine tasks; in contrast, the controlled processes are required for the conscious control and modification of performance, which is crucial in non-routine tasks specifically. The two complementary processes are regulated by *contention scheduling*, a mechanism aimed at avoiding conflicts in performing routine tasks. In novel or complex tasks, however, the SAS is needed for the regulation of action, and this can be accomplished by providing some extra activation and inhibition to schemas.

**Cold versus hot executive functions**
Generally, the emphasis in research and theory has been on the more cognitive aspects of executive functioning (Happaney, Zelazo, & Stuss, 2004). In recent years, however, growing interest on investigating the emotional aspects of EFs has emerged. Several authors proposed a distinction between cognitive or “cold” EFs, associated with the dorsolateral area of the PFC, and emotional/motivational or “hot” EFs, which are linked to ventromedial (i.e., orbitofrontal) cortices (Ardila, 2008; Fuster, 2001; Grohman & Fals-Stewart, 2004; Happaney et al., 2004; Kerr & Zelazo, 2004). Cold components of executive functioning comprise problem solving, planning, strategy development and implementation, and WM; these abilities can typically be well assessed by EF tests; whereas hot EFs are responsible for the control of emotional and instinctual behaviors, and are involved in the coordination of cognition and emotion (Ardila, 2008). The integrative role of hot EFs for affective and non-affective information seems plausible, given the strong connections between the ventromedial PFC and the amygdala as well as other areas of the limbic system (Happaney et al., 2004). The ability to fulfill limbic impulses in accordance with social norms, which is associated with the inhibitory control of behavior (P. Miller & Wang, 2006) or affective decision-making (Happaney et al., 2004), is considered the key competence of the hot executive functioning. Clinical observations support the distinction between cold and hot EFs, as lesions of the underlying cortical structures cause different dysfunctions – predominantly, a lack of cognitive control within the
dorsolateral syndrome and a lack of emotional/motivational control within the orbitofrontal and medial frontal syndrome (Ardila, 2008).

**Unitary and non-unitary nature of executive functions**

Despite of extensive research, none of the existing theories on executive functioning has received sufficient support from findings (Maricle & Avirett, 2012); however, the existing models can be assigned to two currently dominating approaches in the literature. Some consider EFs as a unitary and hierarchical system, whereas the other perceives them as a set of distinct but associated cognitive processes (Jurado & Rosselli, 2007; Maricle & Avirett, 2012). Due to existing evidence for both unitary and non-unitary nature of EFs, this issue remains controversially debated since Teuber (1972) first raised the question (Miyake, Emerson, et al., 2000). Executive functioning from the unity-perspective is regarded as a unitary construct with meta-cognitive character, and, thus, responsible for coordinating other, subordinate, basic cognitive processes (see Baddeley & DellaSala, 1996; Blair, 2006; de Frias, Dixon, & Strauss, 2006; Friedman et al., 2006; R. J. Sternberg, 2003). Proponents of the unity-theory postulate the existence of a unifying, core factor underlying executive functioning, for example general (g) and fluid intelligence (Gf) (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Obonsawin et al., 2002; Rabbitt & Lowe, 2000), WM (Kane & Engle, 2002) or inhibition (Barkley, 1997). The central executive (Baddeley & Hitch, 1974) and SAS (Norman & Shallice, 1986) may be considered as unitary models of executive functioning (Miyake, Emerson, et al., 2000); likewise, Luria’s theory of cognitive functioning and Cattel-Horn- Carroll (CHC; McGrew, 2009) theory (Maricle & Avirett, 2012) are established within this domain. Yet, proponents of the non-unity theory cannot reach an agreement as to what cognitive abilities is executive functioning composed of (Maricle & Avirett, 2012).

From the non-unity perspective, EFs are considered as a collection of distinct but moderately intercorrelated higher-order processes (see Elliott, 2003; Funahashi, 2001; Salthouse, 2005; Stuss & Alexander, 2000). Indeed, factor-analytic studies support the non-unity perspective, as the intercorrelation between different executive tasks is frequently low (Jurado & Rosselli, 2007; Miyake, Friedman, et al., 2000; Obonsawin et al., 2002). Furthermore, studies with frontal lobe patients show inconsistent performance on different EFs tests, suggesting the existence of multiple separable control processes (Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999). The diversity of behavioral disturbances encountered in patients with executive dysfunctions may be considered as another piece of evidence (Drechsler, 2007).
Nevertheless, there is one perspective shared by the proponents of both approaches, namely that of the meta-cognitive role of EFs, which is indispensable for controlling and coordinating cognition (see Friedman et al., 2006; Funahashi, 2001; Salthouse, 2005; Stuss & Alexander, 2000). Furthermore, as evidence exists for both theories (Jurado & Rosselli, 2007), an intermediate position seems plausible. For example, Miyake, Friedman, et al. (2000) suggest the existence of both unitary and non-unitary elements of executive functioning. They propose three, clearly separable functions (i.e., updating, shifting, and inhibition) as basic executive processes. Based on their correlative studies conducted with the three executive components, they conclude that EFs are separable but moderately correlated constructs.

1.4 Developmental trajectories and aging

Crucial stages in the development of EFs take place from early childhood through adolescence until early adulthood (De Luca et al., 2003; Reynolds & Horton, 2008; Romine & Reynolds, 2005). Nevertheless, developmental changes in EFs occur over the entire human life span (De Luca & Leventer, 2008). In the present section, the current state of research on the development of executive functioning throughout the human life span along with the influence of aging is presented.

Childhood and adolescence

The emergence of EFs closely allies with the maturation of the PFC, which already begins in utero and includes building up all the connections both within the frontal lobes and to other brain areas (De Luca & Leventer, 2008). As a result, executive skills are present in an immature state in early childhood and develop protracted through adolescence into early adulthood (Casey, Giedd, & Thomas, 2000; Steinberg, 2005).

The frontal lobes are the last areas of the brain to mature (Casey et al., 2000; Reynolds & Horton, 2008; Rubia et al., 2000) and also one of the first areas to degenerate (De Luca & Leventer, 2008). Maturation of the frontal lobes is associated with synaptogenesis, myelination and pruning (Maricle & Avirett, 2012). In particular, the protracted process of myelination plays a vital role in the development of frontal lobes as it enhances the speed of neural communication (Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999). The frontal lobes, particularly their dorsolateral areas, are the last parts of the brain to complete the process of myelination, which continues into the third decade of life (Klingberg et al., 1999; Rubia et al., 2000; Sowell, Thompson, & Toga, 2004). Due to the protracted maturation of the PCF, EFs are one of the last functions to reach maturity (De Luca & Leventer, 2008). Differences
in the neural maturation of specific areas within frontal lobes ally with the timing of maturation of specific executive abilities (P. Anderson, 2002). According to the hierarchical pattern of brain development, the maturation occurs progressively from more fundamental to more complex skills (De Luca & Leventer, 2008); for example, attentional control and WM are considered crucial to success on all executive tasks and mature earlier, especially as compared with more complex EFs, such as planning and organization skills (Senn, Espy, & Kaufmann, 2004; Smidts, Jacobs, & Anderson, 2004). At the same time, there is much evidence on a bell-shaped curve in the acquisition and loss of executive skills, suggesting rather a stepwise development than existence of linear trajectories in executive functioning (De Luca et al., 2003; Kray, Eber, & Lindenberger, 2004; Reynolds & Horton, 2008; Romine & Reynolds, 2005).

WM and inhibition are among the EFs that emerge earlier, with their first signs being observed between 7 and 8 months of age. Great increases in the development of WM, inhibition, sustained attention, mental flexibility, and concept formation can be seen in the preschool period. Goal-oriented behaviors and planning skills similarly begin to mature during the preschool years (De Luca & Leventer, 2008); however, both functions are considered to be dependent upon the level of WM and inhibition skills (Brocki & Bohlin, 2004).

The 6 to 8 years range is thought to be the period of greatest development in EFs. Between 9 and 12 years of age, more moderate improvements in executive performance are observed. In particular, the ability to shift attention is considered to be complete by 10 years of age (Chelune & Baer, 1986; Welsh & Pennington, 1988). In the period from adolescence to the early 20s, many EFs reach adult levels (V. A. Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Korkman, Kemp, & Kirk, 2001; Passler, Isaac, & Hynd, 2009; Welsh et al., 1991). A meta-analysis conducted by Romine and Reynolds (2005) demonstrated similar age ranges of significant improvement in executive functioning – medium to large increases in performance between the ages ranges 5 to 8 years and 8 to 11 years; small to medium increases between 11 to 14 years; and greater variability in performance ranging from none to medium age-related changes in performance in the 14 to 17 years range.

Adulthood and age-related decline
Consistent with the protracted brain maturation, the second decade of life is expected to be the period of peak level in executive functioning (De Luca & Leventer, 2008). De Luca et al. (2003) support this notion as in their study all assessed executive abilities, including WM, strategic planning, goal setting, and problem solving, reached superior levels in the 20-29 age group. Evidence on the white and gray matter development continuing well into the third dec-
ade (see Paus et al., 2001; Sowell et al., 2004), however, questions the timing of mature adulthood (De Luca & Leventer, 2008). Moreover, since neural degeneration may already begin in the third decade of life (Yang, Ang, & Strong, 2005), it seems plausible why there is only a short time of plateau in the level of EFs; indeed, there is some evidence on decline in executive functioning beginning as early as 30 years of age. For example, De Luca et al. (2003) reported spatial span to decrease significantly in the 30-49 age group and all other measured executive skills being diminished in 50-64-year-olds. Additionally, performance on most executive tasks in the 50-64 age group was coefficient of variation (CV) parable to that of the 8-10 age group. This implies that EFs are particularly sensitive to cognitive decline (De Luca et al., 2003). Furthermore, there is a growing body of evidence on age-related effects on executive functioning; Raz, Gunning-Dixon, Head, Dupuis, and Acker (1998) reported higher likelihood of perseverations with advancing age. Furthermore, several studies demonstrated that younger participants outperform older participants on tower tasks (Brennan, Welsh, & Fisher, 1997; Gilhooly, Phillips, Wynn, Logie, & Sala, 1999), task-switching (Kray, Li, & Lindenberger, 2002; Kray & Lindenberger, 2000), and strategic planning (Levine, Stuss, & Milberg, 1997).

Nevertheless, the impact of age on executive functioning appears to be related to the type of task. For instance, Reynolds and Horton (2008) assessed in their lifespan study a large number of participants (1600-2000 pro task) across the age range of 8-89 years. Two assessment tools used in that study covered a wide range of executive skills. Furthermore, each of the tools is thought to assess different types of EFs. The Test of Verbal Conceptualization and Fluency (TVCF; Reynolds & Horton, 2006) is considered to assess verbal ability; whereas the Comprehensive Trail Making Test (CTMT; Reynolds & Horton, 2006) is considered to reflect the perceptual-motor underpinnings of EFs (Reynolds & Horton, 2008). In fact, the data collected from the two measures showed peak performances at different ages. The skills assessed by the TVCF peaked later than those assessed by the CTMT - category fluency reached highest levels of performance at the 60-69 years group, letter fluency at the 50-59 years group, and verbal classification at the 40-49 years group. Unlike the language-related abilities, all perceptual-motor skills from the CTMT peaked at the 20-25 years group. The authors concluded that there is a parallel between their findings and the research on crystallized and fluid intelligence (Reynolds & Horton, 2008).
2. Intelligence

The concept of intelligence and the assessment of intellectual abilities have a long and rich history (Newton & McGrew, 2010). Although intelligence is perhaps the most researched topic in psychology with many existing theories, the nature of this elusive construct is still difficult to define (Wasserman, 2012). The most popular definition of intelligence is arguably proposed by David Wechsler (1939): “Intelligence is the aggregate or global capacity of the individual to act purposefully, to think rationally and to deal effectively with his environment” (p. 3). The wide acceptance of this definition may be due to the widespread use of the Wechsler intelligence scales; additionally, it reflects the rich theoretical framework from which Wechsler’s understanding of intelligence derives (Wasserman, 2012).

Hereafter, the milestone events in the history of intellectual assessment are outlined, followed by an introduction to the most seminal theoretical models of intelligence, presented both from historical and present perspective.

2.1 History of intellectual assessment

The first practical intelligence measure was published in 1905 by Binet and Simon, with the purpose to distinguish between intellectually retarded and normal school children. Although first implemented in France, the Binet-Simon Scale led to an overall increase in the use of intelligence tests and to the implementation of the Stanford-Binet intelligence scales in the United States. In addition to identifying intellectual disability in school children, early intelligence measures aimed at psychological testing of army recruits. For example, the Army mental tests were created for the use in the U.S. Army during World War I. The Army mental tests comprised two separate tests. The Army Alpha was a language-based assessment tool, used for examinees with an adequate mastery of English, whereas the Army Beta was intended for examinees, who were not able to read and write or who had insufficient mastery of English (Wasserman, 2012). Thus, with the creation of the Army Alpha and Army Beta, the differentiation between verbal and non-verbal intelligence testing has been implemented. The success of the Army mental tests contributed to the widespread use of intelligence testing in other civilian applications of psychology; after World War I, the Army mental tests were adapted to the use in schools, college and industry. The Stanford revisions of the Binet-Simon tests were successful as well, both domestically and internationally (Silverman, 2009; Wasserman, 2012). However, a substantial improvement and a long-lasting influence on the assessment of intellectual abilities were achieved by David Wechsler, who developed intelli-
Intelligence tests for clinical use specifically. Although the first Wechsler intelligence scales were implemented in the 1950s and 1960s already, numerous subsequent revisions of Wechsler tests have dominated intellectual assessment in the second half of the 20th century. Currently, the Wechsler intelligence scales remain the most frequently used measures of intelligence worldwide (Ardila, 1999; Drozdick, Wahlstrom, Zhu, & Weiss, 2012; Flanagan & Kaufman, 2009), and they are considered a standard part of neuropsychological assessment (Ardila, 1999; O'Donnell, 2009).

2.2 Evolution of the concept

General versus specific factors of intelligence

The general-factor theory of intelligence by Charles Spearman (1904) is considered the first seminal model of intellectual abilities (Silverman, 2009). Based on the observation that cognitive variables measured by different tests are positively correlated with one another, Spearman concluded that all these variables have one fundamental function in common, which he labelled general ability factor or \( g \). However, he also observed unique performance variance, which was specific to individual tests. Consequently, Spearman (1927) revised his general-factor theory into the two-factor theory and postulated the general factor \( g \), which is shared across measures, and specific factors \( s \), which are unique to individual measures. While Spearman focused on \( g \), some other researchers sought to construct more complex models of intelligence or to demonstrate that intelligence cannot be regarded as an entity (Silverman, 2009). For example, Burt (1949) and Vernon (1951) extended Spearman’s two-factor theory into more hierarchical models of intelligence. Spearman’s strongest opponent, Louis Thurstone (1938) proposed in his theory of primary mental abilities seven to nine parallel factors. Joy Guilford (1956, 1988) went even further by postulating 120 to 180 intelligences.

Nevertheless, for the first few decades of the 20th century, Spearman’s concept of \( g \) dominated intellectual assessment (Kaufman, 2009; Silverman, 2009). In intelligence tests (e.g., Stanford Binet scales, Wechsler intelligence scales) \( g \) has often been operationalized as a global score with the contribution of all subtest scores. Furthermore, the concept of \( g \) plays a vital role in the contemporary intellectual assessment and is in expert opinion an important predictor of real world outcomes. By contrast, experts did not reach consensus as to the degree of predictive validity of specific factors (Reeve & Charles, 2008).
The concept of crystallized and fluid intelligence

Some researchers acknowledge the existence of an overarching general factor, while simultaneously questioning the unitary nature of intelligence. The concept of crystallized (Gc) and fluid intelligence (Gf) is one of the most successful attempts to define a more complex structure of intelligence. This concept was proposed by Cattell (1943) and extended by Horn and Cattell (1966, 1967). It is based on a distinction between Gc and Gf – two different types of intellectual abilities. Gc comprises mainly verbal skills such as vocabulary, general information, verbal comprehension, and arithmetic; whereas Gf involves more non-verbal skills such as perception of relations, concept formation and attainment, reasoning and abstracting. Gc is thought to be the product of acculturation and education. Furthermore, it usually increases with advancing age. In contrast, Gf is to a larger degree affected by heredity factors, and more vulnerable to aging as well as brain lesions (Horn & Cattell, 1966, 1967).

The model of Gf and Gc has later been extended by Horn and Cattell (1966) from two to five ability factors (i.e., visualization, retrieval, and cognitive speed). Moreover, the number of factors in this model has continuously been growing, lacking agreement among Cattell and Horn, as well as among other researchers, regarding the ultimate number of factors (Wasserman, 2012). Nevertheless, the concept of Gf and Gc has later been integrated also into other models of intelligence, such as the Three-Stratum-Model (Carroll, 1993) and the Cattell-Horn-Carroll (CHC) theory (McGrew, 2009). Furthermore, the concept of Gf and Gc has proven useful in explaining developmental trajectories of cognitive abilities over the lifespan, both by Horn and Cattell (1967) and by other researchers (Ardila & Rosselli, 1989; Ryan, Sattler, & Lopez, 2000).

Hierarchical models of intelligence

As noted previously, several researchers have undertaken attempts to define the structure of intelligence by classifying specific intellectual abilities. Especially, the implementation of correlation and factor analytical methods provided substantial progress in the intelligence research and helped identify a hierarchy among cognitive abilities.

The first comprehensive systematic organization of research on the structure of intelligence and an empirically based taxonomy of cognitive abilities was achieved by Carroll (1993) in his Human Cognitive Abilities: A Survey of Factor-Analytic Studies (McGrew, 2009; Schneider & McGrew, 2012). Furthermore, Carroll postulated a three-stratum hierarchical model of intelligence with an overall g factor at stratum III, eight broad abilities at stratum II and more than 70 narrow abilities at stratum I. Carroll’s research built on the work of
numerous researchers, such as Cattell, Horn, Thurstone, and Thorndike (McGrew, 2009); however, the Cattell-Horn Gf-Gc model had the biggest influence on Carroll’s multiple-stratum model. There are, indeed, remarkable similarities between broad abilities proposed by Carroll - Gf, Gc, general memory and learning (Gsm), broad visual perception (Gv), broad auditory perception (Ga), broad retrieval ability (Gr), broad cognitive speediness (Gs), and processing speed (RT), and Cattell-Horn ability factors.

The commonalities between the Cattell-Horn Gf-Gc concept and Carroll’s taxonomy of cognitive abilities led to the integration of both models into the CHC theory of intelligence (McGrew, 2005, 2009). Horn and Carroll agreed to merge their models into a single theory in the late 1990s (Kaufman, 2009). Since then, originally grounded on hierarchically organized 9 “broad ability domains” and more than 70 specific narrow abilities, the CHC theory has been refined and extended by additional constructs, also those regarding the human sensory domains of tactile, kinaesthetic, and olfactory abilities (McGrew, 2009; Newton & McGrew, 2010; Schneider & McGrew, 2012). The CHC taxonomy is still considered a framework that integrates past and current research and is to be further extended (McGrew, 2009). Currently, the CHC theory is the most popular hierarchical model of intelligence assessment (Keith & Reynolds, 2010; Newton & McGrew, 2010); moreover, the CHC theory plays a crucial role in the current intellectual assessment (Kaufman, 2009; Keith & Reynolds, 2010; McGrew & Wendling, 2010) and is the foundation of many contemporary intelligence tests (Keith & Reynolds, 2010).
3. Relationships between executive functions and intelligence

Considerable evidence exists on a strong association between executive functions (EFs) and intelligence (Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2010; Davis, Pierson, & Finch, 2011; Friedman et al., 2006; Obonsawin et al., 2002; Roca et al., 2010; Salthouse & Davis, 2006). However, it is not well explored exactly how the particular components of the two constructs are interrelated. In addition, the influence of other cognitive and non-cognitive factors on the relationship between the two constructs has been discussed (Friedman et al., 2006; Lamar et al., 2002). Especially, the influence of age has received considerable attention (de Frias et al., 2006; Lamar et al., 2002; Salthouse et al., 2003; Salthouse & Davis, 2006). The current state of research on the relationships between different EFs and the particular components of intelligence, along with the influence of age on those relationships, is provided hereafter.

3.1 Executive functions and general intelligence

Strong relations between EFs and general intelligence ($g$) have been demonstrated by several studies (Crawford et al., 2010; Davis et al., 2011; Duncan et al., 2008; Obonsawin et al., 2002; Salthouse & Davis, 2006). Obonsawin et al. (2002) administered several common EF tests and the Wechsler Adult Intelligence Scale - Revised (WAIS-R; Wechsler, 1981) to healthy adults. Significant correlations between individual EF tests ranged from .20 to .50; however, when the same correlation matrix was covaried with performance on the WAIS-R, most correlations decreased and only a few remained significant. It was concluded that $g$ might account for the shared variance between EF tests. Duncan, Johnson, and Swale (1997) reported similar results from a study conducted with adult patients with brain lesions; after partialling out the Cattel’s Culture Fair (Institute for Personality and Ability Testing, 1973) scores, the correlation between remaining executive and non-executive tests decreased. Duncan et al. (1997) concluded that these tests have little in common besides their $g$ component.

Nevertheless, the correlation pattern between global intelligence scores and individual measures of executive functioning reveals that different EFs might be variously related to $g$. Obonsawin et al. (2002) reported significant correlations between the WAIS-R and EF tests, ranging from .24 to .63. The lowest correlation was observed between the WAIS-R and the Modified Card Sorting Test (MCST; H. E. Nelson, 1976), which is a measure of concept for-
mation and cognitive set-shifting. The highest correlation was observed between the WAIS-R and the Paced Auditory Serial Addition Task (PASAT; Gronwall & Wrightson, 1974), which is a measure of attention and working memory (WM). In addition, a principal components analysis conducted with all EF tests yielded two factors that accounted for 52.8% of the total variance. Scores on the PASAT and verbal fluency tests loaded most highly on the first factor. Perseverative errors from the MCST were the only measure that loaded highly on factor two. Furthermore, in addition to strong correlations with the WAIS-R Full Scale IQ (FSIQ; .73), factor one exhibited equally strong correlations with the verbal and performance scale (.66). In contrast, the score for the second factor was significantly correlated with performance on the WAIS-R FSIQ (-.26) and verbal scale (-.31), whereas it was not correlated with performance on the performance scale.

Additionally, Davis et al. (2011) demonstrated a generally strong, but variable, relationship between g and EFs by conducting a canonical correlation analysis between the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III; Wechsler, 1997) and the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001). The canonical correlation analysis is aimed at finding linear combinations within sets of variables that maximize the correlation between them. The procedure allows for the calculation of correlation coefficients between different sets of variables and shows which variables contribute the most to each linear combination. The canonical variate represents the combination of variables based on their contribution to the canonical correlation. As a result, the correlation between an individual variable and the canonical variate informs about how strongly this variable is related to the correlation between the two sets of variables (Davis et al., 2011). The canonical correlation analysis between broad measures of intelligence represented by the WAIS-III FSIQ, Performance IQ, and Verbal IQ, and EF measures represented by all subtests of the D-KEFS, demonstrated that 54% of the variance of one variable set was accounted for by another. Furthermore, all WAIS-III variables were strongly related to their canonical variate, with the FSIQ (.99) being the strongest contributor followed by the Verbal IQ (.89) and Performance IQ (.81). Among the D-KEFS variables, the Word Context Test, which involves verbal ability, deductive reasoning, hypothesis testing, and mental flexibility, had the highest correlation (.58) with the canonical variate. The correlations of the Sorting Test (.49), the Proverb Test (.42), Design Fluency Test Switching (.39), and the Trail Making Test (.32) met the criterion of being greater than .32 to be considered as an essential contributor to the canonical correlation. In contrast, the correlations of the Color-Word Interference Test and the Tower Test with their canonical variate were too small to make a significant contribution to
the canonical correlation. It can be concluded that those D-KEFS tasks that assess inhibition, set-shifting, and planning, have only modest associations with the WAIS-III, whereas those D-KEFS tasks that assess switching, mental flexibility, and verbal ability, had moderate to strong associations with the WAIS-III.

3.2 Executive functions and fluid versus crystallized intelligence

As demonstrated by studies by Davis et al. (2011) and Obonsawin et al. (2002), diversity among EFs in respect to their association with intelligence must be considered; moreover, different aspects of intelligence must also be taken into account when exploring the relationship between both constructs.

Fluid intelligence (Gf) has been reported to be particularly strongly associated with EFs (de Frias et al., 2006; Duncan et al., 1997; Egger et al., 2011; Salthouse et al., 2003; Salthouse & Davis, 2006; van Aken, Kessels, Wingbermuhle, van der Veld, & Egger, 2016). The overlap between Gf and EFs has also been demonstrated by functional imaging studies, which showed that the two functions share the same neural substrates (Barbey et al., 2012; Roca et al., 2010). Several authors consider Gf as the core aspect of both executive and intellectual functioning. (Crawford et al., 2010; Decker, Hill, & Dean, 2007; Duncan et al., 2008; Egger et al., 2011; Obonsawin et al., 2002; Roca et al., 2012; Salthouse & Davis, 2006).

Duncan et al. (1996) associate executive control with g, but they also suggest that g can be better assessed by Gf, than by crystallized intelligence (Gc), measures. Furthermore, seeing that frontal lesions are frequently associated with deficits in Gf, they concluded that Gf reflects the “functions of the frontal lobe” (Duncan et al., 1995).

A particularly strong relationship between Gf and WM has been observed (Friedman et al., 2006; Miyake, Emerson, et al., 2000; Salthouse & Pink, 2008). Conversely, research studies show a rather modest relationship of Gf with verbal fluency, inhibition, and shifting (Ardila, Pineda, & Rosselli, 2000; Friedman et al., 2006; Miyake, Friedman, et al., 2000; Rabbitt & Lowe, 2000; Salthouse et al., 2003; Salthouse & Davis, 2006). To illustrate, Friedman et al. (2006) investigated the relationship between three basic components of executive functioning and intelligence in healthy young adults. Intelligence measures shared 41% to 48% of their variance with updating, but only 2% to 14% of their variance with inhibiting and shifting. When intercorrelations between EFs were considered, the relationship of intelligence with inhibition and shifting were no longer significant. At the same time, the relationship between intelligence and updating remained undiminished.
Evidence also exists on a considerable association between Gc and EFs (Ardila et al., 2000; Obonsawin et al., 2002; Salthouse & Davis, 2006). For example, moderate to strong relationships of Gc with verbal fluency, concept formation, inhibition, cognitive set-shifting, and WM have been reported (Ardila et al., 2000; Obonsawin et al., 2002; Salthouse & Davis, 2006).

Nevertheless, EFs are considered more strongly related to Gf than to Gc (de Frias et al., 2006; Duncan et al., 1995; van Aken et al., 2016). Yet the relationship between EFs and intelligence has been investigated more frequently in respect to Gf than to Gc (Friedman et al., 2006; Molnar, 2013). Furthermore, several studies demonstrated that some EFs may be equally or more strongly related to Gc than to Gf. For example, in the study by Friedman et al. (2006), updating, inhibiting, and shifting were equally related to Gf and Gc. Additionally, Obonsawin et al. (2002) found that WM and verbal fluency were equally related to Gf and Gc; moreover, perseverative errors from the MCST were related to Gc, whereas they were not related to Gf. Ardila et al. (2000) also demonstrated that perseverative errors from the Wisconsin Card Sorting Test (WCST; Heaton, 1981) were moderately related to Gc, whereas they were not related to Gf. These findings suggest that skills involved in WCST and MCST, such as concept formation, inhibition, and cognitive set-shifting, might be more strongly associated with Gc than with Gf.

### 3.3 The influence of age

When exploring the relationship between EFs and intelligence, there is frequently a substantial portion of variance that remains unexplained (Obonsawin et al., 2002). This suggests the contribution of other cognitive and non-cognitive factors on the relationship between the two constructs (Friedman et al., 2006; Lamar et al., 2002). The level of intellectual performance has been demonstrated to be related to executive performance (Arffa, 2007; Diaz-Asper, Schretlen, & Pearlson, 2004). Additionally, the influence of several non-cognitive factors on the relationship among cognitive variables has been postulated; in particular, the influence of gender (de Frias et al., 2006; Salthouse, 2004), education (Salthouse, 2004), health (Davis et al., 2011; Lamar et al., 2002; Salthouse, 2004), and age especially (de Frias et al., 2006; Lamar et al., 2002; Salthouse et al., 2003; Salthouse & Davis, 2006).

Age correlates with many cognitive variables approximately between -.20 to -.60 (Verhaeghen & Salthouse, 1997); moreover, age contributes more to interindividual variability in cognitive performance than other individual difference characteristics (Salthouse, 2010b).
Although the impact of age on both EFs (e.g., Christensen et al., 1999; De Luca & Leventer, 2008; Reynolds & Horton, 2008) and intelligence (e.g., Ardila, 2007; Ryan et al., 2000; Wisdom, Mignogna, & Collins, 2012) has been frequently investigated, there is a lack of research on the relationship between the two constructs across different ages; however, some evidence shows that this relationship may be variable according to age. For example, in a study by Salthouse and Davis (2006), children, students, and normal adults differed in respect to the relationship structure among several cognitive measures, including EFs tasks. To illustrate, the number of categories in the WCST had moderate to strong associations with Gf in each sample. Additionally, this variable was strongly related to Gc in the children sample, and moderately related to WM in the adult sample. Such variability in the relationship pattern may be connected to changes in both intellectual and executive skills, which have frequently been showed to occur with increasing age (Ardila, 2007; Daseking & Petermann, 2013; De Luca et al., 2003; Wisdom et al., 2012). Furthermore, according to the frontal hypothesis of aging, age-related decline in many cognitive abilities is associated with the deterioration of the frontal lobes (Salthouse et al., 2003). This is important since the frontal lobes are the first areas of the brain to degenerate (De Luca & Leventer, 2008). Such age-related deterioration of the frontal lobes may have an influence on relationships among cognitive abilities, in particular those including executive functioning and intelligence (de Frias et al., 2006; Rabbitt & Lowe, 2000).

**Differentiation-dedifferentiation-hypothesis**

Some evidence exists on the impact of age on the relationship structure among different EF tasks. Using a sample of young college students, Miyake, Emerson, et al. (2000) found a three-factor model of EFs best fitting the data. In contrast, examining middle-aged and older adults, de Frias et al. (2006) found a one-factor solution best fitting the data. de Frias et al. (2006) provide an explanation for the contradictory findings derived from both studies by suggesting that the structure of EFs may change across the lifespan from a multidimensional construct in young adults to a more unidimensional one in aging adults. Consequently, EFs may “dedifferentiate” during the adult life course. This assumption is consistent with the differentiation-dedifferentiation-hypothesis. The differentiation is considered to occur in the course of childhood development, when the structure of cognitive abilities changes from a general ability towards a group of more distinct abilities (Garrett, 1938, 1946). This process of specialization occurs to a certain point during young adulthood and is followed by dedifferentiation of distinct abilities again to a more unidimensional construct (Balinsky, 1941;
Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980). This means that, with increasing age, cognitive abilities tend to become more closely related to one another.

**Investment theory**

Cattell’s (1963, 1987) investment theory provides an explanation with respect to age-related differences in the relationship between cognitive processes as well. The investment theory is based on the concept of Gf and Gc (Horn & Cattell, 1966, 1967). Cattell assumed that Gf and Gc are not independent from one another. For example, Gf usually influences Gc by determining the rate at which people learn. To illustrate, people with low Gf’s levels must put more effort to acquire new knowledge. Hence, Cattell assumed that people are able to enhance their Gc by “investing” their Gf-abilities in Gc. This especially occurs in children and young adults. Nevertheless, the influence of “non-ability” factors, such as the quality of education, family resources, motivation, and personality, must be considered as well. The non-ability factors play a role in the learning process, too. The influence of the non-ability factors on the learning process, however, may alter across adult life. Thus, the investment patterns may change as well. Consequently, interindividual variability in cognitive performance may increase with advancing age.
4. The current research

The existing literature shows much inconsistency in terms of the definition and general understanding of both executive functions (EFs) and intelligence. Thus, investigating the two constructs appears difficult due to their elusive nature. However, empirical investigations are necessary to build a solid theoretical framework; specifically, investigating the relationship between EFs and intelligence may contribute to a better understanding of the nature of the two constructs. Previous research has shown that there are considerable associations between EFs and intelligence; however, the associations between the individual components of both constructs are not well studied. Furthermore, though the influence of age on cognitive abilities has frequently been demonstrated, age-related differences in EFs and age-related differences in the relationship between EFs and intelligence require further investigations.

Based on the theoretical framework and current state of research outlined in the previous chapters, hereafter, the rationale and aims of the empirical research conducted within the present doctoral thesis are presented.

4.1 Age-related differences in executive functions

Theoretical considerations

The influence of age on cognition is a frequently studied issue. Furthermore, it is widely accepted that cognitive decline occurs with advancing age (Ardila, 2007; Salthouse, 2014). However, research findings in respect to the age-related decline in EFs are inconclusive (Jurado & Rosselli, 2007; Mejia et al., 1998; Wecker et al., 2000). This may be due to the different assessment tools that were used in the studies. The characteristics of age groups examined must be considered as well. Certain studies have investigated the differences in executive functioning between limited age ranges (e.g., Boone, Miller, Lesser, Hill, & D'Elia, 1990; Brennan et al., 1997; Raz et al., 1998), but only a few have used several age ranges across the lifespan (De Luca et al., 2003; Reynolds & Horton, 2008; Salthouse et al., 2003).

Moreover, when investigating age-related differences in cognition, the mean or other measures of central tendency are often used. However, using methods that focus on changes in mean performance individual differences might be neglected (E. A. Nelson & Dannefer, 1992). To illustrate, although the mean performance decreases with age, some individuals may exhibit substantial changes in cognition, whereas others may change very little (Christensen et al., 1999). Consequently, investigating the differences between individuals may provide insight into the diversity of cognitive performance and help understand why
some individuals decline in cognition, whereas others do not. Additionally, investigating interindividual variability, either within one or several cohorts, may provide information on whether there are similar or distinct cognitive deterioration patterns for different individuals. Though some studies have focused on interindividual variability in executive functioning, particularly in respect to the factors that contribute to successful and unsuccessful aging (Mejia et al., 1998; Ylikoski et al., 1999), there is a lack of research dealing with age-related differences in interindividual variability. This issue requires investigations because differences in the magnitude of variability in performance across the lifespan may provide essential information for neuropsychological assessment. If there is only little variability in performance between individuals, even small deviations from the mean score of the standardization sample could imply an impairment of the assessed function. In contrast, if there is high variability in the performance of the standardization sample, a relatively great deviation from the mean score does not necessarily imply any pathological impairment.

Some studies have reported that interindividual variability in cognition increases with age; moreover, a meaningful ability-related pattern in cognitive deterioration has been identified. That is, visual-spatial perception, attention, speed, and memory were shown to be more heterogeneous at older, than at younger, ages; furthermore, these abilities were also associated with the substantial decreases in mean scores that occurred with advancing age. In contrast, the studies showed no substantial differences between older and younger participants in the variability of verbal or number-related skills, and the decreases in mean scores were only moderate (Ardila, 2007; Christensen et al., 1994; Christensen et al., 1999; Daseking & Petermann, 2013; Morse, 1993; Ryan et al., 2000; Wisdom et al., 2012). The two identified clusters of cognitive abilities correspond to the concept of fluid (Gf) and crystallized intelligence (Gc). Moreover, the study by Reynolds and Horton (2008) suggests that the deterioration pattern of EFs might also fit the concept of Gf and Gc. However, age-related differences in EFs in respect to mean performance, and particularly in respect to interindividual variability, require further investigations.

**Methodological considerations**

A common way of exploring interindividual variability in cognition is to analyze the dispersion of the test scores between different individuals (Ardila, 2007). The standard deviation (SD) is a frequently used measure of dispersion due to its independence from the unit of measurement. The comparison of standard deviations between different age groups has been frequently used in the studies on age-related interindividual variability (Rönnlund & Nilsson,
2006; Salthouse, 2010a; Schaie, 1994). However, the standard deviation should not by analyzed without taking into account the associated mean, especially when comparing the dispersion between different age ranges. The coefficient of variation (CV) \([\text{CV} = \frac{\text{SD}}{\text{mean}} \times 100]\) (Bartlett, 1946; Hendricks & Robey, 1936; Pearson, 1896; Yablokov, 1974), also referred to as the percentage of the mean (Ardila, 2007; Daseking & Petermann, 2013), is a more informative ratio for dispersion in respect to the heterogeneity of scores because it does not represent the standard deviation alone but rather the percentage of standard deviation in the mean (Ardila, 2007; Daseking & Petermann, 2013; Morse, 1993; Wisdom et al., 2012). The relation of the standard deviation with the mean is meaningful since the mean scores may vary across age groups and so change the meaning of the associated dispersions. As a result, the CV, as the percentage of the standard deviation in the mean, allows for comparisons within and between populations (Lande, 1977). This has already been demonstrated in the analysis of age-related variability in performance on Wechsler intelligence scales (Ardila, 2007; Daseking & Petermann, 2013; Matarazzo, 1972; Wisdom et al., 2012).

The calculation of the mean and standard deviation raw scores, as well as the CV for different age groups, is the first step for establishing the extent of variability in performance across age. The analysis of age-adjusted standard scores does not permit meaningful comparisons between age groups with regard to the differences in performance. Only an observed decrease or increase in the mean or standard deviation raw scores between different age groups may indicate age-related differences in cognition. Moreover, the amount of change in the CV determined by the comparison of the age groups with the highest and lowest mean raw scores is more informative in respect to the heterogeneity in cognitive decline (Wisdom et al., 2012). In particular, the comparison between the extent of mean cognitive decline, as measured by the percentage decrease in the mean, and the change in the variability of scores, as measured by the percentage increase in the dispersion, may be helpful in understanding age-related differences in cognition over time.

**General aims and hypotheses**

The aim of the study was to explore the deterioration pattern of EFs by examining age-related differences in respect to the mean and dispersion between healthy adults across a large age range. It was assumed that mean performance on EF tasks would decrease with advancing age; whereas the dispersions would increase with age. Additionally, it was hypothesized that the pattern of deterioration in EFs would depend on the type of task used. That is, performance on EF tasks associated with Gf would show substantial decreases in the mean scores and...
substantial increases in the dispersion from early adulthood. In contrast, performance on EF tasks related to Gc would demonstrate increases in the mean scores, even in late adulthood, but only small increases in the dispersion.

### 4.2 Age-related relationships between executive functions and intelligence

#### Theoretical considerations

Different age groups have been examined in respect to the relationship between EFs and intelligence (Ardila et al., 2000; Arffà, 2007; Boone, Ponton, Gorsuch, Gonzalez, & Miller, 1998; Crawford et al., 2010; Friedman et al., 2006; Salthouse & Davis, 2006; van der Sluis et al., 2007), yet there is a lack of research on the comparison of different age groups with regard to the relationship between the two constructs. As previously discussed in chapter three (Salthouse & Davis, 2006), the pattern of relationships between performance on EFs and other cognitive abilities might not always be consistent across age. Consequently, there might also be unique, age-related associations of EFs with intelligence. This issue should be explored further to better understand the nature of the two constructs. In particular, an adequate understanding of the associations between executive and nonexecutive processes is necessary to build a coherent theory of executive functioning (Lamar et al., 2002). Furthermore, investigating both age-related commonalities and differences in the relationship between EFs and intelligence is essential due to potential implications for neuropsychological practice. To illustrate, the extent of the overlap between the individual components of the two constructs may provide guidelines in respect to the interpretation of assessment outcomes. For example, a substantial overlap between two different components may indicate that these components depend upon the same mechanism or are dependent from one another. The age-dependence of the relationship between two components may reflect developmental trajectories of these components. In addition, indications regarding the kind of information that can be obtained within assessment according to age might be comprehensively observed. In practical terms, information may be derived about how useful it is to implement tasks assessing these components in different age groups.

Investigating the mutual predictability of EFs and intelligence may provide information regarding the extent to which both constructs contribute to the performance of one another. In fact, the relationship pattern between EFs and intelligence has often been investigated in respect to the mutual predictability of both constructs. Given the practical implications for clinical neuropsychology, in particular, the intention to estimate the expected per-
formance on other cognitive abilities (Diaz-Asper et al., 2004), EFs have been more frequently predicted with intelligence (Arffa, 2007; de Frias et al., 2006; Diaz-Asper et al., 2004; Rabbitt & Lowe, 2000; Salthouse & Davis, 2006) than vice versa (Brydges, Reid, Fox, & Anderson, 2012; Friedman et al., 2006; Salthouse et al., 2003). Given that EFs are considered crucial for cognitive functioning (Ardila, 1999; Maricle & Avirett, 2012) and EF tasks are a part of the major intelligence tests (D. C. Miller & Maricle, 2012), the predictive ability of executive performance for intelligence performance should be more accurately examined.

**Methodological considerations**

When investigating the relationship between EFs and intelligence, several methodological issues must be taken into consideration. In particular, the nature of statistics used must be taken into account. Correlation is a commonly used method to assess the relationships between two variables; furthermore, it is the foundation of multivariate statistical procedures such as multiple regression, factor analysis, and structural equation modelling. These more complex statistical methods are also frequently used in studies aimed at investigating the relationship between cognitive variables. Factors affecting the correlation size should therefore be considered in particular. The factors frequently discussed in the literature include the characteristics of the sample, the amount of variability in either variable, differences in the shapes of the distributions, lack of the linearity in the relationship between variables, the presence of outliers in the dataset, and measurement error (Cohen, 2010; Goodwin & Leech, 2006; Hays, 1994; Tabachnick & Fidell, 2013).

Besides the general statistical characteristics, other more research specific factors may affect the size of a correlation. First, a differentiation must be made between studies conducted with frontal lobe patients versus healthy participants (Obonsawin et al., 2002). For example, frontal lobe patients have been reported to be impaired on Gf, but not on Gc, measures (Duncan et al., 1995). In contrast, no substantial discrepancies between Gf and Gc have been demonstrated in healthy people (Friedman et al., 2006; Obonsawin et al., 2002); thus, the relationships between EFs and Gf may be stronger in samples comprised of frontal lobe patients than those comprised of healthy participants.

Second, the relationship between EFs and intelligence depends on the assessment tools used in the studies. Frequently, several scores from a single measure are used in studies. However, single measures usually do not assess all aspects of executive functioning (Pickens, Ostwald, Murphy-Pace, & Bergstrom, 2010). Therefore, multiple measures that assess various aspects of executive functioning should be used (Davis et al., 2011; Lamar et al., 2002).
Third, psychometric properties of EF measures may influence the relationship between the measured constructs. Pickens et al. (2010) report that most reviewed studies on available EF measures lacked the statement of adequate reliability and validity testing. Moreover, only one of 18 reviewed studies reported excellent psychometric properties. Therefore, when assessing measures for possible use, the focus of attention should be on reliability and validity testing procedures.

In the research context especially, ecological validity appears crucial, referring to a differentiation which must be made between measures based on theoretical models and those based on clinical practice. Measures developed by cognitive neuropsychologists may lack ecological validity for patients; conversely, measures validated in a clinical context may be less valid for healthy participants (Bryan & Luszcz, 2000; Chan, Shum, Toulopoulou, & Chen, 2008). As an example, the Wisconsin Card Sorting Test (WCST; Heaton, 1981) and the Modified Card Sorting Test (MCST; H. E. Nelson, 1976), have been shown not to be associated with different Wechsler Intelligence Scales (Adams, Smigielski, & Jenkins, 1984; Wechsler, 1981, 1993) to a considerable degree (Ardila et al., 2000; Boone et al., 1998; Obonsawin et al., 2002; Welsh et al., 1991). However, the two measures have been validated for patients with frontal lobe lesions; thus, due to ceiling effects, they might be inappropriate for use in healthy populations (Arffa, Lovell, Podell, & Goldberg, 1998; Bryan & Luszcz, 2000; Obonsawin et al., 1999). Moreover, although useful in clinical contexts, these measures might be less sensitive to executive dysfunctions encountered in normal aging (Bryan & Luszcz, 2000).

Construct validity should also be taken into account as it is crucial to evaluate a measure in relation to the abilities that are to be assessed. However, although most EF tasks require multiple abilities, exactly which abilities are involved in any particular task is often inaccurately defined (Lamar et al., 2002). The validity of EF tasks is difficult to determine due to the “impurity” of these tasks. That is, also non-executive abilities, for example, attention, memory, language, and spatial skills, may be involved in EF tasks (Boone et al., 1998; van der Sluis et al., 2007). Therefore, it is difficult to distinguish between executive and non-executive tasks. Additionally, different EF tasks may assess similar executive abilities (Rabbitt, 1997). Consequently, when investigating the relationship between EFs and intelligence, the multifaceted nature of both EF and intelligence measures must be considered.
General aims and hypotheses
The aim of the study was to explore the general relationship as well as more specific relationships between EFs and intelligence. Thus, the association between the global scores as well as between individual components of the two constructs was intended to be examined. Furthermore, the influence of age on that association was aimed to be investigated by the comparison of younger and older healthy adults. A significant relationship between the two constructs was assumed. In addition to the mutual relationship between the two constructs, the aim also was to investigate both the general and age-related predictability of intelligence with EFs. Seeing that many studies have shown that changes in both intelligence and EFs occur with increasing age, the association between the two constructs was expected to increase with age. Consequently, also a better predictability of intelligence with EFs in older, rather than in younger, adults, was assumed. Additionally, the influence of the type of EF task on the relationship between both constructs was intended to be examined. It was assumed that intelligence performance can be predicted more effectively by complex or multi-domain EF tasks rather than by well-structured, domain specific EF tasks; however, the predictability was also expected to vary as a function of age, in particular, for the domain specific EF tasks.

In addition, the study aimed at exploring the relationship between EFs and intelligence separately for younger and older adults. Here, the following research question was in focus: How does the relationship between EFs and $g$, as well as individual components of intelligence, vary according to age? In line with existing evidence (see chapter three), it was expected that there are some individual components of intelligence, such as Gf and WM, which are more strongly associated with EFs than others. Yet it was also hypothesized that EFs are more strongly related to $g$ than to any other individual component of intelligence. When taking age into account, however, the strength of this relationship would change; that is, EFs would be as strongly related to some individual components of intelligence, such as Gf and Gc, as they are to $g$. 
Empirical research

5. Methods

In the present chapter, methods used in the current research are presented, including sample characteristics as well as the description of the assessment tools, data management, and statistical analysis.

5.1 Sample characteristics and recruitment procedure

The participants of the present research were recruited for the purpose of norming the German adaptation of the Neuropsychological Assessment Battery (NAB; Petermann, Jäncke, & Waldmann, 2016b). Data were collected between February 2014 and February 2015. The recruitment of participants occurred via advertisements placed in newspapers, job centres, job search websites, senior residencies, and assisted living facilities. Potential participants were excluded if they had a history of known cardiovascular, neurological, or psychiatric conditions. All participants provided written informed consent prior to the administration of both assessment tools. Each participant received a reimbursement for participation of €30. The data used in the present research originated from subjects who completed Form 1 of the NAB on the first occasion. The completion of the NAB took three hours on average. The data used in the study on age-related differences in the relationship between EFs and intelligence originated from participants who, in addition to the NAB, were administered the ten core subtests of the German adaptation (Petermann, 2012a) of the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV; Wechsler, 2008a). The completion of the WAIS-IV took 90 Minutes on average. Both test batteries were administered in the standard order. The time interval between the NAB and WAIS-IV assessments ranged from 1 to 92 days (M = 16.87, SD = 17.99). The assessments with both measures were conducted either by trained psychology students or graduate psychologists with expertise in neuropsychological diagnostics. The author of the present doctoral thesis was involved in the recruitment of participants and the administration of both assessment tools, too.

Study on age-related differences in executive functions

The sample consisted of 485 normal adults, aged 18-99 years, which were divided into ten age groups. Table 1 presents the demographic composition of the sample including age, gender, and education characteristics. The participants were recruited from four different sites in
Germany, including Bremen representing the north, Gera representing the east, Heidelberg representing the south, and Köln representing the west of the country.

### Table 1. Demographic composition of the sample of the study on age-related differences in executive functions

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Gender</th>
<th>Education/Type of School, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Age ± SD</td>
<td>Male</td>
</tr>
<tr>
<td>18-29</td>
<td>22.58 ± 3.17</td>
<td>26</td>
</tr>
<tr>
<td>30-39</td>
<td>33.73 ± 2.88</td>
<td>26</td>
</tr>
<tr>
<td>40-49</td>
<td>46.11 ± 2.22</td>
<td>22</td>
</tr>
<tr>
<td>50-59</td>
<td>55.00 ± 2.91</td>
<td>27</td>
</tr>
<tr>
<td>60-64</td>
<td>61.96 ± 1.54</td>
<td>22</td>
</tr>
<tr>
<td>65-69</td>
<td>66.82 ± 1.59</td>
<td>24</td>
</tr>
<tr>
<td>70-74</td>
<td>71.67 ± 1.48</td>
<td>27</td>
</tr>
<tr>
<td>75-79</td>
<td>76.65 ± 1.40</td>
<td>23</td>
</tr>
<tr>
<td>80-84</td>
<td>81.40 ± 1.40</td>
<td>13</td>
</tr>
<tr>
<td>85-99</td>
<td>88.49 ± 3.74</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>58.85 ± 20.00</td>
<td>226</td>
</tr>
</tbody>
</table>

*Note.* ¹8-9 years of mandatory school, ²10 years of advanced school, ³A-level equivalent after regular 12-13 years of school.

**Study on age-related relationships between executive functions and intelligence**

The sample consisted of 126 normal adults, aged 18-88 years, who were all recruited in Bremen. The full sample was divided into two age groups, based on the median age (i.e., 59 years). The sample characteristics in respect to age, gender, and education are presented in Table 2. The decision to divide the sample at the age of 59 years was for two main reasons. First, age-related changes in cognitive functioning were taken into account, referring to a substantial reduction in executive functioning that is thought to occur in the 50-60 age range (Brennan et al., 1997; De Luca et al., 2003; Raz et al., 1998; Robbins et al., 1998). Crystalized intelligence (Gc) has been reported to decline in the 50-60 age range as well. Moreover, evidence exists on a substantial decline in fluid intelligence (Gf) after the age of 50 years (Ardila, 2007; Salthouse, 2010b). Secondly, a negative impact of retirement on cognitive functioning (Bonsang, Adam, & Perelman, 2012; Rohwedder & Willis, 2010) was considered. The average retirement age in Germany is approximately 59.5 years. The age of 60 years is also the earliest eligibility retirement age in Germany, and many other western countries. Consequently, the age of 59 years was deemed appropriate for separating the older participants from the younger.
Table 2. Demographic composition of the sample of the study on age-related relationships between executive functions and intelligence

<table>
<thead>
<tr>
<th>Age group</th>
<th>Gender</th>
<th>Education/type of school, n (%)</th>
<th>Total N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hauptschule/ Volksschule</td>
<td>Realschule</td>
</tr>
<tr>
<td>18-59</td>
<td>40.17 ± 12.08</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>60-88</td>
<td>70.46 ± 7.46</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>Sample</td>
<td>54.83 ± 18.23</td>
<td>60</td>
<td>66</td>
</tr>
</tbody>
</table>

Note. ¹8-9 years of mandatory school, ²10 years of advanced school, ³A-level equivalent after regular 12-13 years of school.

5.2 Assessment tools

The selection of the assessment tools for the current research was based on criteria such as the scope of assessment, the cognitive functions measured, theoretical foundation, and psychometric properties. The NAB Executive Functions Module was used as a measure of executive functioning; whereas the WAIS-IV was used as a measure of intelligence. Hereafter, some main characteristics of the two assessment tools are presented.

**NAB Executive Functions Module**

The NAB is a battery of neuropsychological tests designed for the comprehensive assessment of cognitive functions in adults with known or suspected disorders of the central nervous system (White & Stern, 2003). In addition to an extensive review of literature and existing neuropsychological measures, the selection of specific neuropsychological functions to be incorporated into the NAB assessment was guided by the results of the publisher’s 1997 survey of neuropsychological assessment practices (Stern & White, 2000). Hence, recommendations from neuropsychology practitioners greatly took influence on the creation of the NAB. Furthermore, the development of the NAB followed two theoretical foundations: (a) empiricism and (b) cognitivism. To meet the requirements of the empirical approach, NAB tests were designed to be sensitive and specific to clinical prediction. Additionally, in the sense of the cognitive approach, the selection of task paradigms and item content was guided by cognitive psychology (e.g., Kellogg, 2002; R. J. Sternberg, 1999) and cognitive neuropsychology (e.g., Morris, 1997; Rapp, 2001). In all cases, tests were created to provide a broad and representative sampling of the five domains being assessed (i.e., Attention, Language, Memory, Spatial, and Executive Functions). Thus, by providing a screening module and five domain-specific modules, the NAB offers a comprehensive assessment of five main cognitive domains.
The NAB Executive Functions Module was used in the present research to assess various aspects of executive functioning. As the NAB is based on a single standardization group, the NAB Executive Functions Module offers a set of conormed tasks, suitable for a broad assessment of executive functioning. Each participant of the present research was administered all six NAB modules. However, in line with the focus of the present research, only data from the Executive Functions Module were used.

For the German adaptation, the four original subtests of the Executive Functions Module were translated into German and, if necessary, adapted to standard conditions in German-speaking countries (Buczylowska, Bornschlegl, Daseking, Jäncke, & Petermann, 2013). The Executive Functions Module of the German NAB adaptation was extended by two additional subtests: Planning (German Planen) and Letter Fluency (German Wortflüssigkeit); however, only Letter Fluency is included in the Executive Functions Index (EFI). Additionally, the Judgment subtest was shortened from ten to eight items. A detailed description of the German NAB Executive Functions Module follows.

Subtests characteristics

- Planning (PLA)
  Planning is based on the Bogenhausener Planungstest (von Cramon, 1988; von Cramon, Matthes-von Cramon, & Mai, 1991), an experimental measure designed to aid diagnostics of complex planning skills in the context of daily living, such as problem solving, strategy implementation, and mental flexibility. The examinee is to put five typical daily-living, time-restricted assignments in the correct order within up to 15 minutes. Each item is scored based on the quality of the presented solution from 0-3 points. The performance score equals the sum of the scores for all items.

- Mazes (MAZ)
  Mazes is designed to assess planning, impulse control, and psychomotor speed. The examinee is to complete seven time-restricted, paper-and-pencil mazes of increasing difficulty. Each item is scored ranging from 0-5 points, depending on performance speed. The performance score is the sum of the scores taken from all accomplished items.

- Letter Fluency (LRF)
  Letter Fluency is newly designed by the authors of the German NAB adaptation and is based on the scheme of a widely accepted concept of verbal fluency (Lezak et al., 2012; Strauss et al., 2006). The examinee is to generate as many words as possible,
within 120 seconds, beginning with a specified initial letter. The performance score equals the number of correct words generated.

- **Judgment (JDG)**
  Judgment is designed to assess problem solving and decision-making capacity in daily-living situations. The examinee is to answer questions associated with home safety, health, and medicine. Each item is scored from 0-3 points, contingent on the quality of presented response. The performance score equals the total obtained from all items.

- **Categories (CAT)**
  Categories is designed for the assessment of concept formation, cognitive response set, mental flexibility, and generativity. The examinee is to create different two-group categories based on photographs and verbal information about six people. The task is composed of two panels, each of 240 seconds. The performance score equals the sum of scores from correct categories generated within both panels.

- **Word Generation (WGN)**
  Word Generation is a time-restricted task designed to assess verbal fluency and generativity. The examinee is to create three-letter words based on a visually presented group of eight letters (three vowels and five consonants). The performance score is the number of correctly created words within 120 seconds.

**Psychometric properties**

With respect to psychometric characteristics, information regarding reliability and validity must especially be considered. In the manual of the German NAB adaptation, reliability coefficients for the Executive Functions Module are reported as follows: internal consistency reliability, $\alpha = .82$; test-retest reliability for younger age ranges (18-69 years old), $r = .86$, and for older age ranges (70 -> 85), $r = .85$ (Petermann, Jäncke, & Waldmann, 2016a). Evidence for the content, construct, and criterion validity can be obtained from the manual of the original NAB (White & Stern, 2003). Evidence for its clinical validity based on studies with several different patient groups is reported for both the original and German NAB (Petermann et al., 2016a). In addition to clinical utility, research has demonstrated the validity of the NAB for healthy adults (Brooks, Iverson, & White, 2007, 2009; Yochim, Kane, & Mueller, 2009).
The German adaptation (Petermann, 2012a) of the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV; Wechsler, 2008a) was used in the present research for the assessment of intelligence. The WAIS-IV offers a comprehensive assessment of intellectual functioning based on the long-lasting tradition of intelligence tests authored by David Wechsler. The Wechsler intelligence scales are the most frequently used measures of intelligence worldwide (Ardila, 1999; Drozdick et al., 2012; Flanagan & Kaufman, 2009) and considered a standard part of neuropsychological assessment (Ardila, 1999; O'Donnell, 2009). Moreover, researchers have often implemented Wechsler tests when exploring the structure of cognition, in particular, the relationship between EFs and intelligence (Boone et al., 1998; Davis et al., 2011; Friedman et al., 2006; Lamar et al., 2002).

There are a few main reasons for the widespread use of Wechsler tests that are as follows. Primarily, Wechsler intelligence scales are thought to possess strong psychometric properties (Davis et al., 2011); secondly, they are known for their predictive value and clinical utility (Drozdick et al., 2012). Furthermore, the successive versions of Wechsler scales have been revised according to the current state of research (Drozdick et al., 2012).

The WAIS-IV (Wechsler, 2008a) is a revision of the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III; Wechsler, 1997). The structure and the subtests were modified to correspond with advances in the field of intellectual assessment. That is, the theoretical background of the WAIS-IV is coherent with the Cattell-Horn-Carroll (CHC) theory (Keith & Reynolds, 2010). Consequently, the WAIS-IV does not continue the tradition of the Wechsler intelligence scales being composed of the Verbal and Performance IQs. Instead of dual IQ, four index scales representing intellectual functioning in four specific cognitive areas were implemented: Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI) (Wechsler, 2008b). These four indices contain ten core subtests, which are necessary for the calculation of the Full Scale IQ (FSIQ), and five supplemental subtests, which are designed to provide additional clinical information. In addition to the FSIQ, the General Ability Index (GAI) can be calculated, an optional score composed of the VCI and PRI without the contribution of WM and processing speed (Wechsler, 2008b). Figure 1 presents the coherence of the WAIS-IV subtests with the CHC theory. A description of the index structure follows.
5. Methods

Index structure characteristics

- **Verbal Comprehension Index (VCI)**
  The VCI is designed to assess verbal intelligence. It contains three core subtests (Similarities, Vocabulary, and Information), as well as one supplemental subtest (Comprehension). The VCI is considered a good measure of Gc (Wechsler, 2008b).

- **Perceptual Reasoning Index (PRI)**
  The PRI is a measure of nonverbal reasoning and perceptual organization. It is composed of three core subtests (Block Design, Matrix Reasoning, and Visual Puzzles) and two supplemental subtests (Figure Weights and Picture Completion). The PRI is considered a good measure of Gf (Wechsler, 2008b).

- **Working Memory Index (WMI)**
  The WMI is a measure of WM, attention, and concentration. It is composed of two core subtests (Digit Span and Arithmetic), as well as one supplemental subtest (Letter-Number Sequencing).

- **Processing Speed Index (PSI)**
  The PSI is designed to assess the speed of mental and graphomotor processing. It includes two core subtests (Symbol Search and Coding), as well as one supplemental subtest (Cancellation).

Psychometric properties

For the German adaptation of the WAIS-IV, the average reliability coefficients are reported as follows: internal consistency reliability of the composite scores, VCI, $\alpha = .97$; PRI, $\alpha = .94$; WMI, $\alpha = .94$; PSI, $\alpha = .90$; FSIQ, $\alpha = .98$; GAI, $\alpha = .97$. For the subtests, internal consistency reliability coefficients ranged between .78 and .94; test-retest reliability of the composite scores, VCI, $r = .89$; PRI, $r = .91$; WMI, $r = .81$; PSI, $r = .87$; FSIQ, $r = .94$; GAI, $r = .90$ (Petermann, 2012b).

Evidence for the content, construct, and criterion validity is presented in the manual of both the original and German WAIS-IV (Petermann, 2012b; Wechsler, 2008b). Furthermore, the WAIS-IV has been clinically validated by numerous studies with several different patient groups (Petermann, 2012b; Wechsler, 2008b). Moreover, research has proven measurement invariance for the WAIS-IV between individuals with clinical disorders and healthy adults (Weiss, Keith, Zhu, & Chen, 2013).
Figure 1. WAIS-IV subtests CHC classification.

*Note.* Based on Flanagan, Alfonso, and Reynolds (2013); Flanagan and Kaufman (2009), and Benson, Hulac, and Kranzler (2010).
5.3 Data management and statistical analysis

General procedure
Statistical analysis was performed using Microsoft Office Excel 2007 and SPSS (version 22). Test scores were calculated in accordance with manual guidelines. In the first stage of data management, Excel spreadsheets were used for correcting typing errors and detecting missing values. In the next step, the data were transferred into SPSS for further analysis. Prior to analysis, the requirements for statistical methods used were checked.

Study on age-related differences in executive functions
The raw scores of the six subtests of the NAB Executive Functions Module were used to compare 10 age groups (18-29, 30-39, 40-49, 50-59, 60-64, 65-69, 70-74, 75-79, 80-84, and 85-99). For each age group, the mean, standard deviation, and the coefficient of variation (CV) [(SD/mean) × 100] were calculated. To assess the extent of average decline as well as interindividual variability in performance for each subtest over time the percentage decrease in the mean and the percentage increase in the dispersion [(amount of change/highest mean or associated CV) x 100] were calculated. In the next step, the index variance inflation factor (VIF) was calculated to check for the multicollinearity among the six Executive Functions Module subtests. The low values of the VIF (< 2) excluded the risk of multicollinearity (O’brien, 2007) and so allowed for conducting a multivariate analysis of variance (MANOVA). A two-way MANOVA with Bonferroni type post hoc comparisons were applied to all subtests to test the differences in performance with respect to age group and gender.

Study on age-related relationships between executive functions and intelligence
Raw scores of all variables derived from the two assessment tools were transformed into age-adjusted standard scores. The NAB Planning subtest, being a percentile rank score, was excluded from the analysis with standard scores. The standard scores were used to calculate correlations between the NAB Executive Functions Module and the WAIS-IV. To check for normality, the data of both age groups (18-59 and 60-88 years) were subjected to the Kolmogorow-Smirnow test. The data in the NAB subtests were normally distributed. Among WAIS-IV scores, only the WMI showed a skewed distribution in the younger age group, D (65) = 0.15, p = .001; S = -.247, Ss = .297; K = .559, Ks = .586. All variables were checked for extreme scores; no systematic outliers were detected.
The Pearson product-moment correlation coefficient was employed to investigate the relationship between five Executive Functions Module subtests and the EFI with the FSIQ, the GAI, and the four WAIS-IV indices. Pearson correlation coefficients were calculated for both age groups, as well as for the full sample, and subjected to a Fisher r-to-z-transformation. In the next step, a z-test for independent samples was employed to test for significant differences in correlation coefficients between the two age groups. The significance of the differences between correlations within the sample, as well as within the two age groups, was tested using the procedure for comparing correlated correlation coefficients proposed by Meng, Rosenthal, and Rubin (1992).

To investigate the predictability of the WAIS-IV with the NAB Executive Functions Module, the stepwise procedure of linear multiple regression was applied. The best prediction models were established separately for the WAIS-IV FSIQ, VCI, PRI, WMI, and PSI. The five NAB Executive Functions Module subtests (i.e., Mazes, Letter Fluency, Judgment, Categories, and Word Generation), age in years, and sex were used as predictors. Consequently, the same seven predictors were entered into five separate regression analyses, respectively. All regression analyses were performed separately for the age groups and once again for the full sample. The procedure of forward selection was used to establish the best-fitting model for each regression analysis. At each step of the forward selection, only those variables were included into the regression equation that resulted the largest significant gain in the variance accounted for; the probability of F to enter was set at $p \leq .05$ and the probability of F to remove was set at $p \geq .10$. 
6. Results and discussion

This chapter shows and discusses main results of the two studies conducted within the current thesis. First, the findings on age-related differences in executive functions (EFs), and second, the findings on age-related relationships between EFs and intelligence, are presented. As the two studies conducted are interrelated, the aim was to show these interrelations when discussing the study results; the findings from the study on age-related differences in EFs, in particular, were partly employed to explain the influence of age on the relationship between EFs and intelligence.

6.1 Age-related differences in executive functions

The main research aim was to clarify whether there is an age-related effect on executive functioning by exploring differences in performance between ten adult age groups in respect to six NAB Executive Functions Module subtests. Table 3 presents the descriptive statistics of all six NAB subtests for ten age groups. These data were used to establish differences in mean performance and differences in variability in performance between age groups.

Differences in mean performance

Analysis of variance showed a highly significant main effect of age for all subtests. The highest effect sizes were for Mazes, $F(9, 465) = 65.34, p < .001, \eta^2 = 0.53$, and Categories, $F(9, 465) = 27.25, p < .001, \eta^2 = 0.33$; followed by Planning, $F(9, 465) = 12.73, p < .001, \eta^2 = 0.19$, Judgment, $F(9, 465) = 10.23, p < .001, \eta^2 = 0.16$, Letter Fluency, $F(9, 465) = 5.16, p < .001, \eta^2 = 0.09$, and Word Generation, $F(9, 465) = 3.71, p < .001, \eta^2 = 0.07$. Furthermore, there was a significant main effect of Gender for Mazes, $F(1, 465) = 16.54, p < .001, \eta^2 = 0.03$, as men outperformed women, and Letter Fluency, $F(1, 465) = 17.59, p < .001, \eta^2 = 0.04$, where women outperformed men, albeit the effect sizes were small. There was no significant age group-by-gender interaction across all six subtests. Consequently, the present research demonstrated differences in performance in individual EF tasks according to age group. As depicted by Figure 2, there was a general decrease in performance with advancing age for all NAB Executive Functions Module subtests. However, differences due to the type of task appear meaningful because the percentage decrease in the mean performance across the entire age range differed depending on subtest. Moreover, performance on individual NAB subtests peaked and decline at different ages. The highest and lowest test scores were generally observed in the youngest and oldest age groups, respectively. However, perform-
Results and discussion

The results showed that the 80-84 age group achieved higher scores in Letter Fluency and Word Generation than the 85-99 age group. Although, analysis of variance showed no significant differences in performance between these two age groups. Furthermore, although there was a particular age group in each subtest that produced the highest score, analysis of variance showed no significant differences in performance between the age groups with the highest score and other age groups with superior performance. However, the age range of superior performance differed according to subtest. For Mazes, there was no difference in mean performance only between the 18-29 and 30-39 age groups. The age range of superior performance for Planning and Categories was 18-59, whereas for Letter Fluency, Judgment, and Word Generation, it was 18-74 years.

Table 3. Descriptive statistics for the NAB Executive Functions Module subtests based on raw scores

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<thead>
<tr>
<th>Age group</th>
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<th>60-64</th>
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<th>70-74</th>
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<td></td>
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<td></td>
<td></td>
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Note. CV = (SD/mean) x 100; PLA = Planning, MAZ = Mazes, LRF = Letter Fluency, JDG = Judgment, CAT = Categories, WGN = Word Generation; modified from Buczyłowska and Petermann (2016b).
Hence, the first significant difference in performance between the age group with the highest score and any following age group with a lower score may be used to determine age-related onset of decline. Moreover, there is an association between the age-related onset of decline and the percentage decrease in the mean. Thus, Planning, Categories, and Mazes, the subtests with the earliest onset of decline, showed the largest age-related decline, with a decrease in the mean ranging from 58% to 81%; whereas Judgment, Word Generation, and Letter Fluency, the subtests with the latest onset of decline, showed a moderate decrease in the mean ranging from 21% to 32%.

**Figure 2.** Mean performance in the NAB Executive Module subtests across ten age groups.

**Differences in variability**

The coefficient of variation (CV) was used as a ratio of dispersion and the percentage increase in the CV across age was interpreted as the magnitude of change in the variability of performance. As depicted by Figure 3, there was an increase in dispersion in all subtests, varying from 7% to 12% for Letter Fluency and Word Generation, 43% to 65% for Judgment and Categories, and 258% to 289% for Mazes and Planning. Interestingly, there was an association between age-related average decline and age-related variability. That is, the subtests with the greatest decrease in the mean also showed the greatest increase in dispersion and the subtests with the lowest decrease in the mean showed the lowest increase in dispersion. Letter Fluency, Word Generation, and Judgment were those subtests that showed the lowest increase...
in dispersion and the lowest decrease in the mean, as well as the latest onset of decline. The three subtests require verbal skills as well as general knowledge and are associated with crystallized intelligence (Gc). The highest increase in dispersion, the greatest decrease in the mean and the earliest onset of decline were observed in Planning, Mazes, and Categories. The three subtests represent visual and speed-related tasks, which also involve fluid intelligence (Gf).

These findings are not surprising as they are consistent with prior research on developmental trajectories of intelligence (Ardila, 2007; Daseking & Petermann, 2013; Morse, 1993; Ryan et al., 2000; Wisdom et al., 2012). That is, the pattern of development of EFs is consistent with the concept of Gf and Gc. Hence, performance on those EF tasks that require visual-spatial perception, attention, and speed may show greater decrease in the mean and greater increase in interindividual variability. In contrast, performance on those EF tasks that require verbal skills and general knowledge may show smaller decrease in the mean and smaller increase in interindividual variability. However, the Categories and Planning subtests require special attention. These two tasks involve similar skills such as mental flexibility, strategy implementation, and problem solving (Stern & White, 2003; von Cramon et al., 1991). Both subtests also seem to follow the same developmental trajectory with the highest score at 18-29 years and onset of decline at > 60 years of age, with similar extent of deterioration. However, the two subtests differ considerably in the magnitude of variability, with the dispersion in Planning being two-fold higher than that of Categories. The difference in variability may be due to the
multifactorial nature of both subtests. While they involve similar abilities, they might differ in their demand for attentional capacity. Planning, as a paper-pencil-test, might reflect a substantial attentional component with the greater variability observed as age advances.

6.2 Age-related relationships between executive functions and intelligence

The main research aim was to clarify whether there is an age-related effect on the relationship between executive functioning and intelligence by exploring commonalities and differences in that relationship between younger and older adults. In addition to correlationship, the predictive ability of EFs for intelligence was examined. Table 4 presents an overview of performance on the NAB Executive Functions Module and WAIS-IV for each age group, respectively. Further analyses were based on those scores.

First, the correlationship between the NAB Executive Functions Module and the WAIS-IV in the full sample is presented. Second, an overview on intercorrelations between the NAB subtests is given. Third, the results on commonalities and differences between the two age groups in respect to the relationship between the NAB Executive Functions Module and the WAIS-IV are presented and discussed. Fourth, commonalities and differences in the correlationship between the Executive Functions Index (EFI) and individual WAIS-IV index scores within the two age groups and the sample are presented. Fifth, the findings are discussed from statistical and theoretical perspective.

Correlationship within the sample

Figure 4 provides a general overview on the correlationship between the NAB Executive Functions Module subtests and the WAIS-IV. Here, only correlations derived from the full sample with values > .30 are exhibited. First, attention should be directed to the relationship between the subtests of the two measures. In most cases, three of the five NAB EF subtests were at least moderately correlated with the WAIS-IV subtest. This suggests notable relationships between the two measures on the individual task level. The correlation pattern is not surprising as it fulfils the expectations based on the underlying abilities. For example, Letter Fluency correlated with all three Verbal Comprehension Index (VCI) subtests and Mazes correlated with two Perceptual Reasoning Index (PRI) and two Processing Speed Index (PSI) subtests, respectively. Most interestingly, however, Word Generation and Categories were the subtests that most frequently reached the value > .30 in the correlations with the WAIS-IV
subtests. Furthermore, both subtests reached the value > .30 in the correlations with all four WAIS-IV indices and were substantially correlated with the Full Scale IQ (FSIQ). Consequently, the potential meaning of the two subtests is discussed in the following sections.

Table 4. Descriptive statistics for the NAB Executive Functions Module and WAIS-IV

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<thead>
<tr>
<th>Age group</th>
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<th>WAIS-IV</th>
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<td></td>
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<td>EFI</td>
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<table>
<thead>
<tr>
<th></th>
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<th>WMI</th>
<th>PSI</th>
<th>FSIQ</th>
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<td>SD</td>
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</table>

Note. EFI = Executive Functions Index, VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, FSIQ = Full Scale IQ, GAI = General Ability Index; standard score scale for the NAB subtests = 50 ± 10, standard score scale for the EFI and WAIS-IV scores = 100 ± 15.

**Intercorrelations within the NAB Executive Functions Module subtests**

In order to better understand the nature of the individual EF tasks used, the correlationship between these tasks should be considered.

Table 5 demonstrates that intercorrelations among the individual NAB Executive Functions Module subtests were low to moderate. The variance shared by the EF subtests ranged, in the 18-59 age group from 0.04% to 16%, and in the 60-88 age group from 0.5% to 20%. It may be concluded that NAB EF tasks are not redundant, as they involve somewhat different abilities. Moreover, in addition to executive skills, non-executive skills such as attention, memory, speed, and language, may contribute to performance on the NAB EF tasks. As expected, EF tasks that involve similar abilities were more strongly intercorrelated than EF tasks that involve different abilities. To illustrate, Categories, Word Generation, and Letter Fluency were moderately intercorrelated in both age groups; whereas the correlation between Word Generation and Judgment was low. Nevertheless, differences between the two age groups with regard to intercorrelations among the NAB EF subtests were evident as well.
Figure 4. Correlation between the NAB Executive Functions Module subtests and the WAIS-IV.

Note. $p < .01$, based on two-tailed probability; $N = 126$; FSIQ = Full Scale IQ, VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, SI = Similarities, VC = Vocabulary, IN = Information, BD = Block Design, MR = Matrix Reasoning, VP = Visual Puzzles, DS = Digit Span, AR = Arithmetic, CD = Coding, SS = Symbol Search, MAZ = Mazes, LRF = Letter Fluency, CAT = Categories, WGN = Word Generation.
Commonalities between younger and older adults

In the further step of the analysis, the focus of attention was on commonalities between younger and older participants in the relationship of EFs with intelligence. Table 6 provides an overview on the correlation between the NAB Executive Functions Module and the WAIS-IV in the two age groups and the sample. Not surprisingly, the composite score EFI with the FSIQ and WAIS-IV indices produced highest correlations. There were no significant age-related differences in the correlations between the EFI and FSIQ (see Figure 5 and Figure 6 for bivariate scatterplots for the EFI and FSIQ for both age groups, respectively). In addition, the NAB subtests were substantially correlated with the FSIQ, with only Judgment failing to reach significance in younger participants. In most cases, there were no significant age-related differences in the correlations between the NAB subtests and WAIS-IV indices. Moreover, the correlation pattern between the NAB subtests and WAIS-IV indices was consistent for both age groups in the following cases: Categories and Word Generation correlated substantially with all WAIS-IV indices, with only one correlation failing to reach significance; Letter Fluency was substantially correlated with the VCI and Working Memory Index (WMI), but was not significantly correlated with the PRI. In contrast, Mazes correlated substantially with the PSI, but not with the VCI.
### Table 5. Intercorrelations between the NAB Executive Functions Module subtests in the age groups 18-59\(^1\), 60-88\(^2\), and 18-88\(^3\)

<table>
<thead>
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**Note.** *p < .05; **p < .01; two-tailed probability; N\(^1\) = 65, N\(^2\) = 61, N\(^3\) = 126; MAZ = Mazes, LRF = Letter Fluency, JDG = Judgment, CAT = Categories, WGN = Word Generation, EFI = Executive Functions Index; modified from Buczylowska and Petermann (2016a).

### Table 6. Correlations of the NAB Executive Functions Module with the WAIS-IV in the age groups 18-59\(^1\), 60-88\(^2\), and 18-88\(^3\)

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<td>.16</td>
<td>.11</td>
<td>.35**</td>
<td>.52**</td>
<td>.45**</td>
</tr>
<tr>
<td><strong>PRI</strong></td>
<td>.44**</td>
<td>.23</td>
<td>.35**</td>
<td>.17</td>
<td>.22</td>
<td>.20**</td>
</tr>
<tr>
<td><strong>WMI</strong></td>
<td>.29*</td>
<td>.19</td>
<td>.24**</td>
<td>.37**</td>
<td>.55**</td>
<td>.42**</td>
</tr>
<tr>
<td><strong>PSI</strong></td>
<td>.46**</td>
<td>.37**</td>
<td>.42**</td>
<td>.10</td>
<td>.32**</td>
<td>.21**</td>
</tr>
<tr>
<td><strong>FSIQ</strong></td>
<td>.40**</td>
<td>.29*</td>
<td>.35**</td>
<td>.32**</td>
<td>.50**</td>
<td>.41**</td>
</tr>
<tr>
<td><strong>GAI</strong></td>
<td>.33**</td>
<td>.21</td>
<td>.27**</td>
<td>.30**</td>
<td>.43**</td>
<td>.37**</td>
</tr>
</tbody>
</table>

**Note.** *p < .05; **p < .01; two-tailed probability; N\(^1\) = 65, N\(^2\) = 61, N\(^3\) = 126; MAZ = Mazes, LRF = Letter Fluency, JDG = Judgment, CAT = Categories, WGN = Word Generation, EFI = Executive Functions Index; VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, FSIQ = Full Scale IQ, GAI = General Ability Index; modified from Buczylowska and Petermann (2016a).
6. Results and discussion

Figure 5. Scatterplot with linear regression line depicting the standard scores of 18- to 59-year olds on the WAIS-IV Full Scale IQ (FSIQ) as a function of NAB Executive Functions Index (EFI).
Note. Modified from Buczylowska and Petermann (2016a).

Figure 6. Scatterplot with linear regression line depicting the standard scores of 60 to 88-year olds on the WAIS-IV Full Scale IQ (FSIQ) as a function of NAB Executive Functions Index (EFI).
Note. Modified from Buczylowska and Petermann (2016a).

The current study also revealed some prediction patterns being similar for both age groups. These prediction patterns are based on best-fitting models established for each of the WAIS-IV indices and for the FSIQ, respectively (see Table 7).

The Categories and Word Generation subtests were most frequently included in the best-fitting prediction models of both age groups as well as of the sample. Consequently, the two subtests appear to be the best predictors for the entire WAIS-IV. Both subtests are time
restricted and language-based tasks. Categories involves several crucial executive skills – concept formation, cognitive response set, mental flexibility, and generativity, (Stern & White, 2003). Word Generation is a measure of verbal fluency and generativity (Stern & White, 2003); however, due to the nature of the German language, the generation of three-letter words based on a group of eight letters appears to be a demanding task. Thus, Word Generation requires more complex skills, such as strategy implementation and mental flexibility. Consequently, the Categories and Word Generation subtests as well as the WAIS-IV appear to have common underlying skills. EFs might be the common element. Yet the complexity and multifactorial nature of Categories and Word Generation might also explain why the two NAB subtests strongly correlate with the WAIS-IV and are in general a good predictor of intelligence. Furthermore, similar findings were derived from the study by Davis et al. (2011), which was already discussed in chapter three; the Word Context Test from the D-KEFS, which is an EF measure involving complex verbal skills, demonstrated there the highest relationship with the WAIS-III.

In contrast, Letter Fluency and Mazes showed a fairly consistent correlation and prediction pattern for both age groups only with those WAIS-indices that involve similar specific skills. The Mazes subtest, which involves planning, impulse control, and psychomotor speed, correlated substantially with the PSI and was included in the PSI best prediction model, but was neither significantly correlated with the VCI nor included in the VCI best prediction model. The Letter Fluency subtest, being a time-restricted task with predominant verbal and working memory (WM) components, correlated substantially with the VCI and WMI, but was not significantly correlated with the PRI. Letter Fluency was included in the VCI best-fitting models of both age groups as well. Moreover, the best-fitting model for the FSIQ included in both age groups the Categories and Word Generation subtests; whereas the Letter Fluency subtest was included in the FSIQ best-fitting model of neither age group. Letter Fluency was also the subtest least frequently included in all WAIS-IV best-fitting models. As a result, Letter Fluency may be a less good predictor for general intelligence (g) when compared to the other NAB subtests. In line with previous findings on a strong relationship of verbal fluency tasks with Gc (Ardila et al., 2000; Salthouse & Davis, 2006), Letter Fluency appears to be a good predictor for crystallized abilities. The current findings suggest age-independent, unique relationships between the NAB Executive Functions Module subtests and the WAIS-IV. Furthermore, they demonstrate that there might be executive and non-executive abilities, which are involved in these measures regardless of age.
Table 7. Multiple regression analyses for the WAIS-IV

<table>
<thead>
<tr>
<th>Age</th>
<th>Variable</th>
<th>Predictor</th>
<th>β</th>
<th>p</th>
<th>Predictor</th>
<th>β</th>
<th>p</th>
<th>Predictor</th>
<th>β</th>
<th>p</th>
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<td>.000</td>
<td>CAT</td>
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<tr>
<td></td>
<td></td>
<td>WGN</td>
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<td>.477</td>
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<td>WGN</td>
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<td>.000</td>
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<td></td>
<td></td>
<td>MAZ</td>
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<td>.026</td>
<td>Age</td>
<td>.266</td>
<td>.000</td>
<td>JDG</td>
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<td>.007</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td>.033</td>
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<tr>
<td>60-88</td>
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<td></td>
<td></td>
<td>LRF</td>
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<td>WGN</td>
<td>.335</td>
<td>.000</td>
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<tr>
<td></td>
<td></td>
<td>Age</td>
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<td>.002</td>
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<td></td>
<td>WGN</td>
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<td>Sex</td>
<td>.179</td>
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<td>.032</td>
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<td>CAT</td>
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<td>.288</td>
<td>.014</td>
<td>WGN</td>
<td>.267</td>
<td>.001</td>
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<td>Age</td>
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<tr>
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<td>LRF</td>
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<td>.002</td>
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<td>WGN</td>
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<tr>
<td></td>
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<td>MAZ</td>
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<td>.039</td>
<td>JDG</td>
<td>.186</td>
<td>.014</td>
</tr>
</tbody>
</table>

Note. FSIQ = Full Scale IQ, VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, MAZ = Mazes, WGN = Word Generation, JDG = Judgment, CAT = Categories, LRF = Letter Fluency; modified from Buczyłowska, Daseking, and Petermann (2016).

Differences between younger and older adults

Statistical analysis revealed differences between age groups in regard to the correlation relationship between EFs and intelligence, too. In all significant differences between correlations, the older age group had the higher score. That is, the participants aged 60-88 years showed a stronger relationship between the NAB Executive Functions Module and the WAIS-IV, than those aged 18-59 years. In particular, the NAB Judgment subtest correlated more strongly with the VCI, z = 2.29, p = .011; PRI, z = 2.15, p = .016; WMI, z = 2.01, p = .022; FSIQ, z = 2.38, p = .008; and, General Ability Index (GAI), z = 2.53, p = .006. Additionally, there was a stronger correlation between the EFI and VCI, z = 2.22, p = .013 (see Figure 7 and Figure 8 for bivariate scatterplots for both age groups, respectively). All significant differences between correlations were supported by medium effect sizes (Cohen, 1988) as appears in Table 8.
The current research also suggests that there might be age-related differences in the predictability of intelligence with EFs. Especially, the contrast between prediction models of the younger and older age group, and the entire sample, demonstrates the significance of age in the WAIS-IV predictability. As there was no WAIS-IV index with the same best-fitting model for the two age groups, the prediction models of the entire sample seem to be less accurate.
Among the NAB subtests, Mazes and Judgment demonstrated the strongest age-related predictive validity for the WAIS-IV. The Mazes subtest was included in the FSIQ, PRI, and PSI best-fitting models of the younger age group and in only one best-fitting model (PSI) of the older age group. In contrast, the Judgment subtest was included in FSIQ, VCI, PRI best-fitting models of the older age group and in only one best-fitting model (PSI) of the younger age group. The Mazes subtest is a visual task with strong perceptual-motor underpinnings, short maturation path, and rapid onset of decline (Buczyłowska & Petermann, 2016b). Consequently, differences between individuals in the Mazes performance start increase already in early adulthood. This might explain why Mazes is a good predictor of intelligence in younger age ranges.

Table 8. Effect sizes for differences in the correlations between the NAB Executive Functions Module and WAIS-IV between the age groups 18-59 and 60-88

<table>
<thead>
<tr>
<th></th>
<th>Mazes</th>
<th>Letter Fluency</th>
<th>Judgment</th>
<th>Categories</th>
<th>Word Generation</th>
<th>EFI</th>
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</thead>
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<td>VCI</td>
<td>.08</td>
<td>.22</td>
<td>.42*</td>
<td>.27</td>
<td>.43*</td>
<td>.40*</td>
</tr>
<tr>
<td>PRI</td>
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<td>.39*</td>
<td>.02</td>
<td>.03</td>
<td>.05</td>
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<tr>
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<td>.16</td>
<td>.15</td>
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<td>.17</td>
<td>.30</td>
<td>.07</td>
<td>.11</td>
</tr>
<tr>
<td>FSIQ</td>
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<td>.21</td>
<td>.43*</td>
<td>.22</td>
<td>.21</td>
<td>.18</td>
</tr>
<tr>
<td>GAI</td>
<td>.13</td>
<td>.15</td>
<td>.46*</td>
<td>.12</td>
<td>.23</td>
<td>.15</td>
</tr>
</tbody>
</table>

Note. *p < .05; two-tailed-probability; interpretation guidelines for effect sizes (Cohen, 1988): .10 = small, .30 = medium, .50 = large; EFI = Executive Functions Index, VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, FSIQ = Full Scale IQ, GAI = General Ability Index.

Judgment is a daily living test, assessing the knowledge of key aspects related to home safety, health, and medical issues, as well as problem solving and decisional capacity (Stern & White, 2003). Generally, judgment is defined as the capacity to make decisions after considering available information (Figueirêdo Vale Capucho & Dozzi Brucki, 2011; Rabin, Borgos, & Saykin, 2008). In addition to EFs (Duke & Kaszniak, 2000; Rabin et al., 2008), judgmental capacity requires several other cognitive skills such as language, memory, attention, and reasoning (Allaire & Marsiske, 1999). Furthermore, judgment is considered an essential part of dementia diagnostics (Duke & Kaszniak, 2000; Rabin et al., 2007). The diagnostic utility of the NAB Judgment subtest has been confirmed as well – particularly with patients with traumatic brain injuries (Zgaljardic, Yancy, Temple, Watford, & Miller, 2011).
and Alzheimer’s disease (Gavett et al., 2012). Macdougall and Mansbach (2013), assessing participants with Mild Cognitive Impairment and dementia, as well as normal adults over 60 years of age, demonstrated good predictive validity of the NAB Judgment subtest. In that study, Judgment highly correlated with measures of executive and general cognitive functioning, as well as with instrumental activities of daily living. Moreover, Judgment predicted a significant proportion of variance in activities of daily living, over and above the variance predicted by the executive and general cognitive functioning measures. The current study supports the findings on the superior predictive validity of the NAB Judgment subtest for older populations illustrated in the previous research (Macdougall & Mansbach, 2013). Moreover, the current study demonstrates that the Judgment subtest might be a sensitive measure, not only for patients, but also for healthy older adults.

The influence of age on the WAIS-IV predictability was examined by the comparison between the entire sample and the two age groups; comparatively, age along with sex and the NAB subtests was used as a predictor for the WAIS-IV scores. Indeed, the results suggest that age is a significant predictor within the age groups, too. In 60- to 88-year olds, age was included in the best fitting-model of the FSIQ and VCI, and in 18- to 59-year olds, in the best fitting-model of the PRI. It appears that age can better predict WAIS-IV performance in older participants, especially because age was included in the FSIQ best-fitting model of the older age group. These findings are consistent with the previous research that demonstrated accelerated changes in cognition at older age ranges (Ardila, 2007; Wisdom et al., 2012). Moreover, the older age group demonstrated the highest total variance explained for the FSIQ and the most of the WAIS-IV indices (see Table 9 for R² in % for each criterion variable). In the PRI only, the total variance explained was higher in the younger age group, as well as in the entire sample, when compared to the older age group. The total variance accounted for in older participants, 72% for the FSIQ and 75% for the VCI, suggests that at older ages the two WAIS-IV scores may be accurately predicted with the NAB Executive Functions Module subtests along with age. By contrast, the highest total variance accounted for in younger participants was 46% for the PRI and 45% for the FSIQ. Apparently, besides to EFs, other predictors should be taken into account for younger age ranges.

The contribution of sex to WAIS-IV prediction should be considered as well. The analysis revealed that sex may significantly predict the FSIQ in the entire sample, with male sex being related to better performance. However, sex was not included in the FSIQ best-fitting models of any age group. Sex also was a significant predictor for the PRI in the entire
sample, as well as in the older age group, with male sex being related to better performance. These findings are not surprising as previous research has already demonstrated the advantage of males in visual-spatial abilities (Keith, Reynolds, Roberts, Winter, & Austin, 2011). Nevertheless, the previous and current research indicates that potential sex differences in intelligence might differ according to age. Thus, this issue should be investigated further in future studies.

Table 9. Variance explained by the best-fitting models of the WAIS-IV

<table>
<thead>
<tr>
<th>Variable</th>
<th>Age 18-59</th>
<th></th>
<th>Age 60-88</th>
<th></th>
<th>Age 18-88</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$R^2$</td>
<td>$se$</td>
<td>$R$</td>
<td>$R^2$</td>
<td>$se$</td>
</tr>
<tr>
<td>FSIQ</td>
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<td>.845</td>
<td>.715</td>
<td>7,305</td>
</tr>
<tr>
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<td>.868</td>
<td>.753</td>
<td>6,026</td>
</tr>
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<td>.462</td>
<td>9,760</td>
<td>.603</td>
<td>.364</td>
<td>10,365</td>
</tr>
<tr>
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<td>.694</td>
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<td>.602</td>
<td>.362</td>
<td>10,383</td>
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</table>

Note. FSIQ = Full Scale IQ, VCI = Verbal Comprehension Index, PRI = Perceptual Reasoning Index, WMI = Working Memory Index, PSI = Processing Speed Index, $se$ = standard error of the estimate.

Commonalities and differences within two age groups and sample

In the interest of better understanding the relationships between executive functioning and individual domains of intelligence, differences in the correlations between the EFI and individual WAIS-IV index scores within the age groups and sample were investigated. The analysis resulted in only one significant difference: in the older age group, the correlation between the EFI and VCI was stronger than the correlation between the EFI and PRI, $z = 2.23, p = .013$. Interestingly, in the younger age group and in the entire sample, there were no significant differences in the correlations between the EFI and any of the WAIS-IV indices. As suggested by Friedman et al. (2006), Gc and Gf may be more strongly intercorrelated at younger than at older ages.

In addition, the focus of attention was on the relationship between EFs and $g$ as compared to the relationship between EFs and individual domains of intelligence. As expected, the correlation pattern between the EFI and the FSIQ differed according to age group as well. Not surprisingly, in the sample, the correlation of the EFI with the FSIQ was significantly stronger than the correlations of the EFI with any of the WAIS-IV indices: VCI, $z = 2.88, p = .002$; PRI, $z = 3.90, p < .001$; WMI, $z = 2.57, p = .005$; and, PSI, $z = 3.71, p < .001$. However, in the younger age group, the correlation of the EFI with the FSIQ was stronger only when compared to the correlations of the EFI with the VCI, $z = 2.86, p = .002$ and PSI, $z = 2.17, p = "$
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.015; and in the older group, the correlation of the EFI with the FSIQ was stronger only when compared to the correlation of the EFI with PRI, $z = 3.55, p < .001$, and PSI, $z = 3.04, p < .001$. Hence, in both age groups, as well as in the sample, the EFI was more strongly correlated with the FSIQ than with the PSI. In addition, in both age groups the correlation of the EFI with the FSIQ was not stronger than the correlation of the EFI with the WMI.

As with previous research (Crawford et al., 2010; Duncan et al., 1995; Duncan et al., 1996; Obonsawin et al., 2002; Salthouse & Davis, 2006), the present findings demonstrate a strong relationship between EFs and $g$. Furthermore, EFs may be more strongly related to $g$ than to processing speed. However, strong relationships between EFs and specific components of intelligence might also exist – EFs may be as strongly related to $g$ as to WM. However, taking age into account might change the relationship pattern between EFs and specific components of intelligence. In line with the present research, EFs do not appear to be more strongly related to $g$ than to Gf in younger adults, or to Gc in older adults.

**Deterioration pattern and interindividual variability**

In the current study, commonalities and differences between two different age groups in respect to the relationship between EFs and intelligence are in the focus of attention. Thus, deterioration pattern and variability in performance within both age groups should be considered. That is, combining individuals of different ages into one group may affect the strength of the relationship between two variables. For example, if there are no considerable differences between age groups in interindividual variability on two variables, similar deterioration patterns for different individuals can be expected. Consequently, substantial differences between age groups in respect to the relationship between these two variables are not likely. In contrast, considerable differences in interindividual variability between those age groups may affect the strength of the relationship between the two variables.

The results of the study on age-related differences in the NAB Executive Functions Module presented in the first section of the present chapter may help interpret the current findings. That study demonstrated that in the youngest age group (i.e., 18-29 years), Categories, Word Generation, and Letter Fluency had higher interindividual variability than the other NAB Executive Functions Module subtests. However, in the oldest age groups (i.e., 80-84 and 85-99 years), there was only a small increase in variability for Letter Fluency and Word Generation, and moderate to substantial increase in variability for Categories. This may in part explain the consistent correlation and prediction pattern between the three NAB subtests
and the WAIS-IV in both age groups. Conversely, Judgment and Mazes had relatively modest variability in the youngest age group (i.e., 18-29 years). In Judgment, however, a moderate increase in variability with advancing age was observed, whereas Mazes exhibited the highest increase in variability among all subtests. Moreover, in the current study Judgment and Mazes demonstrated the best age-dependent predictive validity for the WAIS-IV among all other NAB subtests. However, despite of only moderate increase in variability, there were significant differences in the correlation of Judgment and the WAIS-IV between the two age groups; whereas the high increase in variability in Mazes did not produce higher correlations in the 60-88 age group. Nevertheless, the source of variability must also be considered. In the older age group, Mazes correlated moderately with the PSI, while the correlations between Mazes and the other WAIS-IV indices were not significant. Specific skills that are required for Mazes, such as processing speed, might be shared with the PSI to a much greater degree than with the other WAIS-IV indices. It is widely accepted that processing speed substantially decreases with advancing age (Schaie, 1994). Consequently, dispersion in Mazes at older ages might be accounted for by interindividual differences in processing speed. Furthermore, non-cognitive factors might influence performance on cognitive tasks at older ages, too (Salthouse, 2010b). Visual (Bertone, Bettinelli, & Faubert, 2007; Salthouse, 2010a) and motor impairments (Seidler et al., 2010) especially, might affect performance on such highly speed-dependent paper-pencil tasks as Mazes. These factors might affect variability in Mazes more than variability in the WAIS-IV indices VCI, PRI, and WMI. As a result, in the older age group of the current study, the increase in variability in Mazes did not considerably change the size of the correlations between Mazes and the WAIS-IV.

The deterioration pattern and interindividual variability of Judgment should be considered as well because Judgment is the subtest with significant differences between the two age groups. In the older age group, Judgment shared 7% to 22% of its variance with the WAIS-IV indices, which is over twice as much as the variance shared by the two measures in the younger age group (i.e., 1% to 8%). As there was only a moderate increase in variability across age, the increase in the shared variance is apparently not the result of the differences in variability between both age groups. However, the focus of attention should also be on the contrast in the variance shared by Judgment and the other EF subtests between the older age group (i.e., from 3% to 17%) and the younger age group (i.e., from 0.04% to 8%), implying that, at older ages, Judgment may require the executive skills that are also involved in performance on the other NAB EF subtests. Conversely, at younger ages, Judgment may assess
somewhat different abilities than the other EF subtests. Consequently, the relationships between Judgment and other executive abilities, as well as between Judgment and intelligence, may become stronger as age advances.

Variability in performance should also be discussed with regard to the contrast between the two age groups in the total variance explained by the prediction models. Particular attention should be directed to the difference in the total variance explained for the FSIQ (72% in participants aged 60-88 and 45% in participants aged 18-59) and for the VCI (75% in participants aged 60-88 and 28% in participants aged 18-59). On the one hand, these findings could be partially explained by higher variability in performance at older ages, which might result in stronger correlations between the two assessment tools. However, as stated previously, the results of the study on age-related differences in the NAB Executive Functions Module revealed that the predictors of the FSIQ and VCI best-fitting models in the present study were not the NAB subtests with the highest variability of performance in the older age group. On the contrary, Letter Fluency, Word Generation, and Judgment, were the subtests with a modest to moderate increase in variability across ages. Only in Categories, there was a moderate to substantial increase in variability. Importantly, Mazes, which is the subtest with the highest increase in variability, was included neither in the FSIQ nor in the VCI best-fitting model of the older age group. By contrast, it was included in the FSIQ, PRI, and PSI best-fitting models of the younger age group. Thus, the different extent of variability does not seem to be sufficient explanation for the substantial difference between the two age groups in the total variance accounted for. Consequently, a more theoretical approach seems more appropriate and is as follows.

**Differentiation-dedifferentiation-hypothesis and investment theory**

The substantial difference in the total variance accounted for in the FSIQ prediction between the examined age groups can be further explained by the differentiation-dedifferentiation-hypothesis (see chapter three for details). Since some evidence exists on dedifferentiation processes occurring with increasing age (Baltes & Lindenberger, 1997; de Frias, Lövdén, Lindenberger, & Nilsson, 2007; Deary, Whiteman, Starr, Whalley, & Fox, 2004; Li et al., 2004), the dedifferentiation processes might also affect the relationships between EFs and intelligence. Consequently, that relationships may become stronger as age advances; as a result, at an older age both constructs might reflect similar aspects of cognitive functioning. In particular, EFs and Gc may be more strongly associated at an older age – the correlation be-
tween the EFI and VCI was stronger in the older than in the younger age group. Moreover, the contrast in the total variance explained by the VCI best-fitting models between older (75%) and younger participants (28%) demonstrates that Gc-related abilities may be predicted more precisely with EFs at older than at younger ages. Interestingly, there was no such effect in older participants for the PRI. On the contrary, the PRI was the WAIS-IV index with the highest variance accounted for in younger participants. It has already been postulated that the association between EFs and Gf versus Gc may differ as a function of age (Friedman et al., 2006). Yet in a study conducted with a college student sample, EFs were neither more strongly correlated with Gf nor with Gc (Friedman et al., 2006). The authors suggested that this might be the result of a strong relationship between Gf and Gc in young adults. In frontal lobe patients and older adults, however, due to Gf’s sensitivity to brain damage and executive dysfunction (Duncan et al., 1995; Friedman et al., 2006), EFs might be more strongly related to Gf than to Gc. Nevertheless, the current study showed the opposite. Since there is not much research in this area, more theoretical rather than an evidence-based explanation can be presented. First, potential differences between healthy participants and frontal lobe patients must be taken into account. Second, the Gc level may become more meaningful with advancing age. As postulated by Cattell (1963, 1987) in the investment theory (see chapter three for details), the Gc level in children and young adults could be mostly affected by Gf. However, as Gf is considered to rapidly decrease with advancing age, the influence of potential changes in Gf on Gc must be taken into account as well. Additionally, the contribution of non-ability factors to the Gc level may increase as age advances. Adults usually become more different from one another as a result of different lifestyles, occupations, learning opportunities, leisure activities, health conditions, and personal goals (Schneider & McGrew, 2012). For example, people who can create good learning opportunities for themselves, or are involved in intellectually stimulating environments throughout their lives, may be able to improve their Gc. Thus, the given Gc level might have an influence on EFs. In contrast, at younger ages, the relationship between Gc and EFs may be weaker because young adults have not yet reached the highest level of their Gc. Moreover, the contribution of the given level of Gc towards performance on EF tasks may increase only when a considerable reduction in executive functioning occurs. For most EFs, this does not occur before the age of 50-60 years (Brennan et al., 1997; De Luca et al., 2003; Raz et al., 1998; Robbins et al., 1998).
7. Implications for theory and practice

As expected, the results of the current research showed age-related differences in performance on the NAB Executive Functions Module subtests. Generally, decreases in the mean and increases in the dispersion with advancing age were observed. However, performance on executive function (EF) tasks connected to fluid intelligence (Gf) was associated with substantial decreases in the mean scores and substantial increases in the dispersion from early adulthood. The greatest decrease in the mean, the highest increase in the dispersion, and the earliest onset of decline were observed in the Planning, Mazes, and Categories subtests. In contrast, performance on EF tasks connected to crystallized intelligence (Gc) was associated with increases in the mean scores, even in late adulthood, but only small increases in the dispersion. Letter Fluency, Word Generation, and Judgment were those subtests that showed the lowest decrease in the mean, the lowest increase in dispersion, as well as the latest onset of decline.

In addition, the current research demonstrated substantial relationships between the NAB Executive Functions Module and the WAIS-IV; the composite score Executive Functions Index (EFI) with the WAIS-IV Full Scale IQ (FSIQ) and index scores, in particular, produced high correlations. In most cases, there were no significant age-related differences in the correlations between the NAB subtests and WAIS-IV indices. Especially, Categories and Word Generation showed consistent correlation pattern for both age groups. The two subtests correlated substantially with most of the WAIS-IV indices and were most frequently included in the WAIS-IV best-fitting prediction models. However, differences between age groups in regard to the relationship between EFs and intelligence were identified, too. In all significant differences between correlations, the older age group had the higher score. In particular, the NAB Judgment subtest correlated more strongly with the Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), FSIQ, and General Ability Index (GAI). Additionally, there was a stronger correlation between the EFI and VCI. Among the NAB subtests, Mazes and Judgment exhibited the strongest age-related predictive validity for the WAIS-IV.

Hereafter, general conclusions drawn from the current research are presented. First, potential implications for neuropsychological assessment within research and clinical practice are discussed. Second, suggestions for theoretical framework are presented. Third, limitations of the studies conducted and recommendations for further research are provided.
7. Implications for theory and practice

7.1 Implications for neuropsychological assessment

The findings presented in the current thesis highlight potential implications for the interpretation of neuropsychological assessment outcomes and for the development of EF measures. Conclusions derived from the current research in relation to those issues are presented in the following section.

Neuropsychological assessment with the NAB

Several implications of the current research as to the age-related differences in performance between the NAB Executive Functions Module subtests and the relationships between the NAB and WAIS-IV emerge for neuropsychological practice.

First, the current research demonstrated unique developmental trajectories for the individual NAB Executive Functions Module subtests. Thus, the deterioration pattern of a given subtest should be taken into account within neuropsychological assessments. Letter Fluency, Word Generation, and Judgment were those NAB subtests that exhibited the lowest decrease in the mean and the lowest increase in dispersion, as well as the latest onset of decline. Thus, in these subtests, small deviations from the mean of the standardization sample might not have any special meaning; whereas substantial deviations from the mean score may indicate a meaningful deterioration. Consequently, these EF tasks might be less sensitive to age-related decline. On the other hand, Planning, Mazes, and Categories were those NAB subtests that showed the greatest decrease in the mean, the highest increase in the dispersion, and the earliest onset of decline. Thus, in these subtests, even small deviation from the mean may imply a decrease in executive functioning.

Second, the intercorrelations among the individual NAB Executive Functions Module subtests were low to moderate; thus, these tasks assess somewhat different abilities and are not redundant. Consequently, the NAB Executive Functions Module appears suitable for the assessment of multiple executive abilities.

Third, the current results showed considerable correlations between the NAB Executive Module subtests and the WAIS-IV. The NAB subtests Categories and Word Generation were considerably correlated with all WAIS-IV indices and most frequently included in the WAIS-IV best-fitting prediction models of both younger and older participants. Thus, when using the two tasks, the IQ must be considered in the interpretation of the assessment outcomes. The two subtests appear to be suitable for the prediction of intellectual abilities. In contrast, Letter Fluency was the subtest least frequently included in the WAIS-IV best-fitting models. Moreover, Letter Fluency was included in the FSIQ best-fitting model of neither age
group. Hence, Letter Fluency seems not to be a suitable predictor of general intelligence (g). However, Letter Fluency was included in the VCI best-fitting models of both age groups; thus, this NAB subtest might be a good predictor for crystallized abilities.

Fourth, the current research demonstrated differences between younger and older participants in the relationship between the NAB Executive Functions Module and the WAIS-IV. In particular, a significant difference between younger and older participants was observed in the correlation of the EFI with the VCI. Thus, the EFI could be used as an indication of Gc at older ages. Furthermore, as there was a substantial difference between younger and older participants in the VCI variance accounted for by the NAB subtests, it can be concluded that the VCI, and Gc in general, can better be predicted by the NAB EF tasks at older than at younger ages. Additionally, the NAB Judgment subtest was more strongly correlated with the WAIS-IV indices, as well as with the FSIQ, in the older than in the younger age group. Furthermore, Judgment was a part of the FSIQ, VCI, and PRI prediction models in older participants. As a result, the Judgment scores may be interpreted differently according to age. Thus, older adults’ low scores on the Judgment subtest may reflect a decrease in general cognitive functioning or a low premorbid IQ. By contrast, due to low correlation between Judgment and WAIS-IV scores in the younger age group, the Judgment scores do not have any special meaning in the interpretation of the overall assessment outcome at younger ages. However, though the Judgment subtest seems to be suitable for the detection of age-related executive and cognitive decline, the other NAB subtests were also substantially correlated with the FSIQ in older participants, with the exception of Mazes. Thus, the other NAB subtests and the EFI might be used as an indication of g at older ages. At younger ages, this would be possible to a lesser degree, due to the weaker correlations between the scores on both measures. However, in contrast to older ages, the NAB Mazes subtest appears to be a good predictor of intellectual abilities at younger ages. In younger participants, this more specific EF task was significantly correlated with three WAIS-IV indices and FSIQ; furthermore, it was there a part of the FSIQ, PRI, and Processing Speed Index (PSI) best-fitting models; whereas in the older age group, it was included only in the PSI best-fitting model.

Fifth, the NAB EF tasks accounted for 45% of the FSIQ variance in the younger age group and for 72% of the FSIQ variance in the older age group; thus, there might be middle to high overlap between the NAB Executive Functions Module and WAIS-IV. Consequently, the two measures may reflect partially the same or similar abilities. Additionally, the current research revealed differences within the two examined age groups and the sample in respect to the relationship between the EFI and WAIS-IV indices, as well as FSIQ. That is, in the
older age group, the correlation between the EFI and VCI was stronger than the correlation between the EFI and PRI. Additionally, in the sample, the correlation of the EFI with the FSIQ was significantly stronger than the correlations of the EFI with any of the WAIS-IV indices. However, in the younger age group, that correlation was stronger only when compared to the correlation of the EFI with the VCI, and in the older group, only when compared to the correlation of the EFI with PRI. Hence, in both age groups the correlation of the EFI with the FSIQ was not stronger than the correlation of the EFI with the Working Memory Index (WMI). Consequently, when using the EFI as an indicator of performance on the FSIQ and as an indicator of overall cognitive functioning in general, an age-related interpretation of assessment outcomes is recommended as follows. The EFI, as a global measure of executive functioning, may overlap not only with FSIQ, but also with VCI at older ages and with PRI at younger ages. However, regardless of age, a substantial overlap with WMI may be expected. Further, caution is warranted with the interpretation of the EFI as a measure of overall executive functioning. As previously presented, deterioration patterns and the relationships with intelligence differ for the individual NAB Executive Functions Module subtests. Consequently, when interpreting NAB assessment outcomes, the meaning of performance on the individual subtests and the contribution of every single subtest to the EFI should be taken into account.

**Deterioration patterns in executive functions**

The current research showed differences in performance on EF tasks between ten adult age groups across a large life span. Thus, age should always be considered within neuropsychological assessment. When standardizing EF measures especially, separate norms should be provided for age groups that differ greatly in performance on particular tasks. For example, if changes occur rapidly, tasks should be normed in separate small age ranges, according to the pattern of deterioration. High variability in performance in healthy adults may also change the interpretation guidelines for assessment outcomes in brain-damaged patients; for example, an outcome rated beyond the limits of normal performance may not necessary mean any lesion-related impairment; it might rather reflect an age-related deterioration pattern. Consequently, base-rates for impaired performance on EF measures in normal population should be established to help improve clinical diagnosis. Third, information about the approximate age at which cognitive decline begins for different cognitive functions could be used to help prevent or reverse age-related changes, for example by determining the optimum time for implementing interventions (Salthouse, 2009).
As the study conducted demonstrated unique developmental trajectories for individual EF tasks, performance on a given task may depend on the deterioration pattern of the underlying abilities. Thus, when interpreting the outcomes of neuropsychological evaluations, the nature of the underlying abilities and age-related differences in these abilities must be considered. Moreover, there might be EF tasks that are more useful for detecting age-related cognitive decline than others. The current research demonstrated deterioration patterns for different EF tasks similar to those known from intelligence research for Gc and Gf. Consequently, EF tasks with a strong crystallized component might be less sensitive to age-related decline than EF tasks with a strong fluid component. This might be particularly useful in the assessment of subclinical executive dysfunctions in normal adults, which is considered difficult to detect as compared with executive dysfunctions related to brain lesions (Bryan & Luszcz, 2000).

**Multifactorial nature of executive function measures**

The multifactorial nature of most existing EF measures has previously been discussed (Stuss & Alexander, 2000). The current research also highlights the meaning of various skills contributing to performance on EF tasks. On the one hand, the current research demonstrated that the NAB EF tasks assess somewhat different abilities; on the other hand, the current results showed considerable correlations between the NAB EF tasks and WAIS-IV. Consequently, it should be taken into account that EF and intelligence measures may assess similar abilities. Furthermore, the multifaceted nature of these measures and specific components shared must be considered. For example, EFs are considered a crucial part of cognition (Ardila, 1999); hence, intelligence measures are likely to assess EFs to a certain extent. Furthermore, other cognitive components shared by EF and intelligence measures may affect the strength of the relationship as well. To illustrate, if two different measures mostly require spatial abilities, the relationship between these measures may be considerable. By contrast, if there are additionally other abilities involved, not shared by both measures, the relationship might be weaker. Indeed, in the current research, the tasks that require similar skills were more strongly intercorrelated, rather than the tasks that require different skills. The extent of complexity appears meaningful as well – the current research suggests that EF tasks, which involve multiple abilities, may be more strongly related to intelligence measures. Both the extent of complexity and the individual components shared by measures used should be considered within neuropsychological assessments; if there is a substantial relationship between two measures, only one of the two measures could be used in the initial diagnostics; whereas the second one could be applied within following assessments. In the assessment of EFs especially, the strength and
nature of the relationships between different measures appears crucial. As novelty is considered the core characteristic of EF tasks, many of the existing EF measures cannot be applied more than once (Rabbitt, 1997). Thus, a more aware use of EF measures is indicated. Furthermore, a more aware selection of the type of EF measure is indicated as well, especially, in cases of brain lesions. That is, all specific cognitive functions should be evaluated prior to the assessment of executive functioning and all known cognitive dysfunctions must be taken into account when selecting assessment tools. In cases of language impairments, EF tasks without a strong verbal component should be applied. Similarly, if there are prominent deficits in information processing speed, instead of time-restricted tasks, the use of EF measures without speed components is indicated.

As to the extent of complexity, there are several factors that should be taken into account. Due to substantial relationships between complex EF tasks and intelligence measures, the premorbid IQ should be considered; in cases of multifaceted EF tasks, which are strongly correlated with general intelligence measures, a below average assessment outcome does not necessarily indicate a clinically relevant impairment. Instead, it may correlate with the premorbid level of intelligence. However, if an extensive assessment of executive functioning is indicated, complex EF measures may substantially contribute to the overall neuropsychological evaluation. In particular, the application of any EF measure is indicated, if its complexity corresponds with the requirements of everyday life of the patient examined. Thus, information in regard to the ecological validity of a given measure is essential.

**Relationships between executive functions and intelligence and the meaning of age**

As already noted, the multifactorial nature of EF tasks and the relationships between executive and non-executive functions should be considered within neuropsychological assessment. In particular, the current research demonstrated substantial relationships between EFs and intelligence. Strong relationships between the two constructs were particularly demonstrated by the composite scores of the assessment tools used and by complex tasks rather than by tasks assessing specific abilities. Furthermore, complex multifactorial tasks were significant predictors of intelligence performance. Thus, when interpreting the composite and complex task scores of EF measures, the current and premorbid IQs must be taken into consideration. This appears to be a general rule, which can be applied regardless of age. By contrast, EF tasks involving specific skills generally appear to be significantly related only to the intelligence components involving similar skills. Hence, potential dysfunctions in those skills involved must be considered rather than g. However, the current research also demonstrated...
age-related differences in the relationships between specific EF tasks and individual intelligence components as well as g. Consequently, the degree of overlap between the abilities assessed by different measures may differ as a function of age. Furthermore, EF tasks involving specific skills might also be good predictors of intelligence, for example, NAB Executive Functions Module subtests – Mazes being a good predictor at younger ages and Judgment being a good predictor at older ages.

At older ages specifically, strong relationships between EFs and intelligence can be expected and EF performance might reflect IQ levels. Particularly, Gc and g might be better predicted by EF performance at older rather than at younger ages. Furthermore, while Gc and g might be the aspects of intelligence best predicted with EF performance at older ages, Gf and g appear to be the aspects of intelligence best predicted with EF performance at younger ages. Consequently, the substantial contribution of EFs to Gc and g in older adults, and the substantial contribution of Gf and g in younger adults, must be considered. However, the Gc, Gf, and g levels might contribute to EF performance, too. There is a lack of a coherent and widely accepted theory in respect to both EFs and intelligence. Furthermore, it is not well investigated which mechanism is responsible for the mutual relationship between the two constructs. Hence, the direction of this relationship is still required to be established. On the one hand, it appears plausible that intelligent behavior could be the result of an interaction between executive functioning and other cognitive domains. Thus, executive dysfunctions might lead to disturbances in Gc, Gf, and g. However, since executive functioning is considered a significant component of intelligence, also intelligence dysfunctions might result in disturbances in executive functioning. This should particularly be considered in cases of mental retardation or low premorbid IQ.

Despite substantial relationships between EFs and intelligence, the contribution of other, cognitive and non-cognitive factors to performance must be considered as well. For example, in the WAIS-IV prediction models of the current research, a substantial amount of variance remained unexplained. This was the case in the younger age group especially. As the relationships between EFs and intelligence may be weaker at younger ages, particularly here, attention should be directed to the contribution of other, non-executive cognitive components to intelligence. Additionally, although the relationships between EFs and intelligence generally appear to be stronger in older adults, the source of interindividual variability must particularly be considered here. For example, the current research suggests that at older ages, dispersion in the NAB subtest Mazes might be accounted for by interindividual differences in processing speed. Moreover, non-cognitive factors might influence performance on Mazes,
too. In particular, visual and motor impairments might be crucial for performance on cognitive tasks at older ages. This should be considered in speed-related paper-pencil tasks especially.

7.2 Implications for theoretical framework

The current findings demonstrated both age-independent and age-related relationships between the NAB Executive Functions Module and the WAIS-IV. These relationships were moderate to substantial, depending on age group and subtest or index. Thus, both age and the underlying abilities may play a role in the relationship between EF and intelligence measures. Furthermore, as there might be executive and non-executive abilities, which are involved at the same time, it appears difficult to clearly distinguish between EF and intelligence measures. Moreover, the previous and current research suggests partly considerable relationships between the two kinds of measure. Hence, the NAB and WAIS-IV subtests might assess similar abilities to some extent. This has practical implications, but should also be considered from theoretical perspective. As the WAIS-IV is mostly adherent to the Cattell-Horn-Carroll (CHC) theory, an attempt can be made to put the NAB EF subtests into relation with the CHC theory, given that CHC classifications for the WAIS-IV are available (e.g., Figure 1). This will require further investigations; however, conclusions derived from the current research might give some clues for a better understanding of this relation. At present, the CHC theory represents the most popular hierarchical model of intelligence and since its creation has regularly been updated in accordance with the current state of research. Furthermore, by offering a general interpretation and classification system, the CHC theory has the potential to be better implemented into the field of neuropsychological assessment (Schneider & McGrew, 2012). Within the CHC classification, EFs, as the central executive mechanism composed of inhibition, shifting, and updating, are associated with the narrow ability working memory capacity and placed within Stratum II short-term memory (Newton & McGrew, 2010; Schneider & McGrew, 2012). In fact, the current research demonstrated a substantial relationship between the NAB EFI and the WAIS-IV WMI, being comparable to the relationship between the EFI and FSIQ. However, as depicted by Figure 4, the current research also revealed that in most cases, three of five NAB EF subtests were moderately or strongly correlated with the WAIS-IV scores, including subtest scores. Consequently, it appears that EFs contribute to the intelligence performance that could be classified as associated with more than one CHC narrow ability. Moreover, EFs might be better classified as a separate broad ability and as such implemented into the CHC framework as an additional broad ability factor on stratum II. In that
case, different aspects of executive functioning could be represented as narrow abilities on stratum I. Future research should thus focus on investigating the contribution of EFs to cognitive abilities classified within the CHC theory on all three strata. In particular, factor-analytic studies of EF measures and CHC-based intelligence batteries could reveal more about potential affiliations between EFs and the CHC model of cognitive abilities.

7.3 Limitations and directions for future research

Several limitations in respect to the research presented in the current doctoral thesis must be considered. First, limitations in regard to data collection should be discussed. For the two studies conducted, the samples were derived from the large standardization sample of the German NAB; thus, due to the representative composition of the standardization sample, the participants differed representatively in respect to demographic characteristics. However, as the participants were recruited via public announces and letters and the participation was based on voluntary consent, the requirements regarding random selection and broad cognitive diversity could not be completely fulfilled. For the study on the relationship between EFs and intelligence, the sample composition might have been biased by the intrinsic motivation of the participants; all NAB From I participants were asked to voluntarily participate in an additional WAIS-IV assessment. Especially because no additional remuneration but performance feedback was offered, the intrinsic interests of potential participants might have influenced the sample selection.

Second, caution is warranted in respect to the cross-sectional study design. Comparing cognitive performance between different age ranges is thought to be confounded by cohort influences. To illustrate, differences exist in educational attainment, health, nutrition, and personalities between participants of different ages. These generational differences might affect cognitive performance. As such, this may affect the correlation between performance on different cognitive measures (Schaie & Willis, 2010). Longitudinal studies are thought to be more informative in respect to cognitive changes over time since they are based on within-person comparisons between different occasions (Schaie, 2005). In fact, discrepancies exist between cross-sectional and longitudinal data with respect to age trends in cognitive performance. Between-person comparisons usually demonstrate gradual declines from early adulthood. In contrast, within-person comparisons show stability or an increase in the performance, which can partly be explained by participants’ prior test experience (Rönnlund & Nilsson, 2006; Salthouse, 2009). Consequently, findings derived from longitudinal studies should be interpreted with caution, too. Nevertheless, longitudinal studies will be necessary to
confirm whether interindividual variability exists in cognitive change and to explore whether only some individuals show decline, whereas others remain stable. For a better understanding of the influence of age on the relationship between EFs and intelligence, within-person comparisons will be required as well. It should be examined whether the pattern of relationships between EFs and intelligence remains stable or change in individuals with advancing age.

Due to generational differences between participants in cross-sectional studies, variables affected by cohort influences are difficult to measure. In the current research, educational attainment differed between those aged 18-59 and 60-88. There were, nevertheless, no considerable differences in the IQ between the two age groups. Consequently, the highest educational attainment might not reflect real differences in education. This appears understandable due to the changes to the educational system that have occurred over the last decades. Thus, education could be measured more effectively than through educational attainment; for example, through the number of years of educational qualifications, including vocational training. However, since educational attainment may depend upon the culture, society, and educational system, general guidelines regarding the operationalization of the education variable might not be possible. In the current research, only the highest educational attainment, as measured by the years of school completed, was used. Consequently, potential differences in educational level between participants of different ages cannot be ruled out. Future studies should pay more attention to the influence of education when comparing cognitive performance between different age ranges. Moreover, the influence of other non-cognitive factors should be better investigated; in particular, the influence of sex, state of health, and lifestyle.

Third, the characteristics of the sample used should be considered. As the current research findings are based on the data derived from healthy adults, caution is warranted in terms of the potential implications for patients with brain damage. It must be bore in mind that brain lesions can influence cognitive performance and change the relation pattern among cognitive abilities, so it may differ from that of healthy people. Hence, further research with patients will be required to provide clinicians with guidelines with which to make clinically meaningful decisions.

Fifth, as age is the central aspect of the current doctoral thesis, limitations associated with the age ranges examined must be discussed. In particular, the decision to divide a sample into age groups might influence the study results. That is, when examining the adult life span, comparing cognitive performance between several age groups might be affected by the age range of the individual age groups. In the study on age-related differences in EFs, the sample
was divided into ten age groups; however, the age range across the groups differed. Especially, in greater age groups with substantial cognitive variability on a given function, only general conclusions regarding age trends in performance are permitted. Furthermore, combining participants of different ages into one or several groups may affect the strength of the relationship between cognitive functions measured. In particular, when comparing different age groups composed of participants of different ages, caution is warranted with regard to the generalizability of the findings, too. For the study on the relationship between EFs and intelligence, the sample was divided into two age groups. However, due to real age differences between participants within both age groups, variability in cognitive performance might be substantial and as such influence the size of the correlations. Caution is warranted with the interpretation as only conclusions pertaining general relation patterns may be derived. When using a cross-sectional study design, studies with several small age groups across the adult lifespan, with a sufficient number of participants in each age group, are necessary to determine specific age trends.

Sixth, the nature of the assessment tools used is another aspect that might be a limitation of the current research. Although the NAB and WAIS-IV are thought to be comprehensive assessment tools, they offer a selection of the potential tasks that might be implemented to measure intelligence and EFs. Thus, some aspects of the two constructs may be pronounced, whereas other may be neglected. To illustrate, although the WAIS-IV is based on the CHC classification of cognitive abilities, in fact, it does not assess all aspects of cognition classified there. The NAB Executive Functions Module is thought to measure multiple aspects of executive functioning; however, elementary EF components such as updating, shifting, and inhibition are measured there to a lesser degree. Similarly, the contribution of cognitive aspects, which are less construct specific, might differ as well. As an example, among the six NAB EF subtests, only Mazes is a non-verbal task. Consequently, the NAB Executive Functions Module tends to assess executive functioning rather via verbal modality. The predominant modality as well as the extent of complexity of the tasks used should be bore in mind as this might influence both age-related performance and the relationships between tasks. In both assessment tools used, the subtests are thought to involve multiple abilities. Thus, conclusions regarding developmental changes in EFs and the relationship between EFs and intelligence might be confounded by the multifaceted nature of the tasks used and the mutual relationships between the underlying abilities. Due to practical implications, it is important to investigate EFs and intelligence by the means of multifaceted measures as they seem to be ecologically more valid. However, in order to explore the meaning and nature of a
single ability, tasks involving single or a few clearly distinguishable abilities might be more appropriate. Updating, shifting, and inhibition, as proposed by Miyake, Friedman, et al. (2000) and integrated into CHC classification (Schneider & McGrew, 2012), may be used to examine the basic abilities of executive functioning. On the one hand, a better differentiation between single abilities as well as between complex and basic components of executive functioning is needed. On the other hand, widely accepted terminology and taxonomy organising the relations between the individual executive abilities should be implemented.
References


References


References


Appendices

Appendix A: Publication 1

Appendix B: Publication 2

Appendix C: Publication 3

Appendix D: Statement of the candidate’s contribution to each publication

The current doctoral thesis was conducted by the candidate Dorota Buczyłowska according to § 6 subparagraph 5 of the formal requirements for doctoral candidates at the University of Bremen. The thesis is based on three empirical articles, which were published by internationally peer-reviewed journals. The preparation of all publications required several working steps, which are necessary to accomplish empirical research. These steps include the conception of the study, the review of previous literature, data collection, data preparation, data analysis, and result interpretation, as well as the preparation and revision of the manuscript. Table D1 shows the contribution of the candidate to each publication in each specific working step. The extent of this contribution is indicated either as fully if the candidate solely contributed to a specific working step, or as mostly if she made the most substantial contribution to a specific working step, or as partly if she and at least one further contributor shared the same amount of contribution. Nevertheless, it must be mentioned that all coauthors continuously supported the current research by their suggestions and ideas and so contributed to the current doctoral thesis.

Table D1. The candidate’s contribution to the current research studies

<table>
<thead>
<tr>
<th>Working step</th>
<th>Publication 1</th>
<th>Publication 2</th>
<th>Publication 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conception</td>
<td>Mostly</td>
<td>Fully</td>
<td>Mostly</td>
</tr>
<tr>
<td>Literature research</td>
<td>Fully</td>
<td>Fully</td>
<td>Fully</td>
</tr>
<tr>
<td>Data collection</td>
<td>Partly</td>
<td>Partly</td>
<td>Partly</td>
</tr>
<tr>
<td>Data preparation</td>
<td>Partly</td>
<td>Partly</td>
<td>Partly</td>
</tr>
<tr>
<td>Data analysis</td>
<td>Fully</td>
<td>Fully</td>
<td>Fully</td>
</tr>
<tr>
<td>Result interpretation</td>
<td>Mostly</td>
<td>Fully</td>
<td>Fully</td>
</tr>
<tr>
<td>Manuscript preparation</td>
<td>Fully</td>
<td>Fully</td>
<td>Fully</td>
</tr>
<tr>
<td>Manuscript revision</td>
<td>Mostly</td>
<td>Mostly</td>
<td>Mostly</td>
</tr>
</tbody>
</table>
Dorota Buczyłowska and the other coauthors, Prof. Dr. Franz Petermann, and PD Dr. Monika Daseking, herewith certify that the statement of the candidate’s contribution to each publication made by Dorota Buczyłowska is accurate and that permission is granted for these publications to be included in her doctoral thesis.

Bremen, February, 2017

____________________________
Prof. Dr. Franz Petermann

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PD Dr. Monika Daseking

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Dorota Buczyłowska, Dipl.-Psych.
Appendix E: Declaration of Originality

In accordance with § 6 subparagraph 5 of the formal requirements for doctoral candidates at the University of Bremen, I hereby declare that the present dissertation represents my own original work except where specifically acknowledged. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature. I further declare that this dissertation does not contain any material which has previously been accepted and is not currently considered for the award of any other university degree in my name. In addition, I certify that no part of the present thesis will, in the future, be used in a submission in my name, for any other degree in any university without the prior approval of the University of Bremen.

Bremen, February 2017

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(Dorota Buczyłowska, Dipl.-Psych.)