The influence of attention on the relationship between temporal resolution power and general intelligence

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1 Introduction

Rammsayer and Brandler (2004) showed that various psychophysical timing tasks measuring the acuity of temporal information processing can be assigned to a single latent variable referred to as temporal resolution power (TRP). It has been shown repeatedly that individual differences in TRP are related to individual differences in intelligence (Helmbold & Rammsayer, 2006; Rammsayer & Brandler, 2007). That is, individuals with higher TRP showed higher scores in psychometric intelligence tests than individuals with lower TRP. However, this TRP hypothesis to intelligence is challenged by the fact that the performance on psychophysical timing tasks (Brown, 2008b) as well as the performance on psychometric intelligence tests afford attention (Carroll, 1993). Hence, the relationship between TRP and intelligence might be alternatively explained by attention as common source of variance. However, a systematic investigation of the influence of attention on the relationship between TRP and intelligence is missing. Consequently, the main objective of the present study is to arrive at a better understanding of the interplay among TRP, attention, and intelligence.

In the first part of the introduction, the concept of intelligence and its structure are introduced followed by a brief look at the mental speed approach to intelligence, which postulates that individual differences in the speed of information processing account for individual differences in intelligence. Subsequent, the concept of TRP is introduced in the context of an individual's sensory discrimination ability followed by a focus on TRP's measurement and its relationship to intelligence. In the second part, the concept of attention as limited capacity resource is introduced with its different manifest types and empirical findings on the structure of attention are given. Furthermore, empirical evidence for attention's close relationship with intelligence as well as its role in temporal information processing are presented. The third part of the introduction begins with a brief summary of the introduction up to this point. Subsequent, the measurement of attention with latency-based elementary cognitive tasks, the role of task complexity as experimental manipulation of attention within an elementary cognitive task, the operationalization of attention, the challenge posed associated with the latency-based operationalization of attention, and the appropriate method to handle this challenge are presented. The research questions and related necessary prerequisites are presented in chapter 2.

1.1 Intelligence

Intelligence is one of the oldest and most examined constructs in psychological science. It is reliably measured with psychometric intelligence tests (Mackintosh, 2011) and predicts socioeconomic success (Deary, Strand, Smith, & Fernandes, 2007; Strenze, 2007) as well as physical health and mortality (Deary, 2012). According to Gottfredson (1997), no other psychological construct has such high predictive validity in relation to job performance. Furthermore, more intelligent individuals deal more successfully with the ordinary demands of everyday life (e.g., read and understand news articles or maps) than less intelligent individuals (Gottfredson, 1997). Despite its importance to everyday life and its influence on political agendas or school curricula, it remains a difficulty to define intelligence. Sternberg (2004) remarked that “there seem to be almost as many definitions of intelligence as there are experts asked to define it” (p. 472). However, many of these expert definitions refer to common attributes such as abstract reasoning, problem solving, and decision making as well as the role of metacognitive processes (Sternberg & Detterman, 1986). For example, Wechsler (1944) defined intelligence as “the aggregate or global capacity of the individual to act purposefully, to think rationally, and to deal effectively with his environment” (p. 3). Another often discussed topic is about the structure of intelligence (Deary, 2012; Sternberg & Detterman, 1986). Is there one intelligence or are there many intelligences? A vast amount of data has been collected within different theoretical approaches and has been examined factor-analytically to achieve a better understanding of the structure of intelligence (Carroll, 1993).

1.1.1 The structure of intelligence

Spearman (1904) examined the correlations among various intellectual performance measures (e.g., French and Mathematics) and found that these performance measures were positively correlated, what is known as *positive manifold*. Based on this finding, Spearman concluded that all kinds of intellectual ability must have a common fundamental factor, some sort of mental energy, which Spearman denoted as the general factor of intelligence (*g*). According to Spearman’s two factor theory of intelligence, each particular ability test measures a certain portion of *g* and its own unique factor *s*, which is specific to that particular ability test and independent of *g*. For example, a mathematical ability test measures a certain portion of *g*, but also the specific knowledge about numbers, which is specific to that mathematical ability test and not measured by a verbal ability test. However, according to Spearman, it is *g* and not *s* that accounts for the *positive manifold* in any intellectual test battery. In fact, Spearman claimed that *g* is a complete explanation for a *positive manifold* by means of principal axis factoring (Mackintosh, 2011). However, this assumption of *g* as single source of a *positive manifold* is challenged by the apparent clustering in correlation matrices. That is, a test *a* might be highly correlated with the tests *b* and *c*, but only weakly with the tests *x*, *y*, and *z*. On the other hand, a test *x* might be highly correlated with the tests *y* and *z*, but only weakly with the tests *a*, *b*, and *c*. Thus, two distinct clusters would be visible in a correlation matrix of the six tests *a*, *b*, *c*, *x*, *y*, and *z*. Based on this circumstance, Thurstone (1938) believed that there are several independent components of intelligence instead of a single factor like *g*. In contrast to Spearman, Thurstone was primarily interested in factors that accounted for the intercorrelations among the specific clusters within a correlation matrix. Therefore, Thurstone developed a factor-analytical approach that allowed him to determine the number of latent constructs underlying a correlation matrix. The number of factors identified by Thurstone varied, but seven (what he called) Primary Mental Abilities (PMAs) were clearly interpretable: verbal comprehension, verbal fluency, number, memory, perceptual speed, inductive reasoning, and spatial visualization. In the meanwhile, it is clear that Spearman's two factor theory and Thurstone's seven PMAs did not contradict each other, but are in fact complementary as represented by hierarchical models of intelligence, which contain group factors as well as a *g* factor. For example, Carroll's (1993) three-stratum model of human cognitive abilities comprises three levels of intelligence and represents an amalgamation of Spearman's and Thurstone's theories. Carroll includes *g* at the apex of the hierarchy (third stratum), eight broad abilities - fluid intelligence, crystallized intelligence, general memory and learning, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speediness, and processing speed - at the second level (second stratum), and a large number of indefinite specific factors at the first level (first stratum). As can be seen in Carroll's three stratum model or in Thurstone's PMAs, these models include well-known capacity-related (e.g., fluid intelligence and reasoning) as well as speed-related aspects of intelligence (e.g., processing and perceptual speed).

While the multitude of hierarchical models of intelligence differ referred to the lower levels of the hierarchy (e.g., in relation to the number of levels or the number of group factors at a certain level), there exists broad consensus supporting *g* at the apex of the hierarchy (Carroll, 1993; Jensen, 1998a; Johnson & Bouchard, 2005; McGrew, 2009). Empirical evidence for a unitary *g* comes from two studies, which showed virtually perfect correlations among *g* factors extracted from second-order group factors of conceptually different psychometric intelligence test batteries (Johnson, Bouchard, Krueger, McGue, & Gottesman, 2004; Johnson, te Nijenhuis, & Bouchard, 2008). The advantage of hierarchical modeling is that variance only specific to a particular test is filtered out by modeling group factors and, consequently, *g* modeled based on these group factors represents the portion of variance common to all groups/tasks used in the respective psychometric test battery. The results of Johnson and her colleagues (2004; 2008) did not only show the uniformity of *g*, but also the consistency of its measurement across different psychometric test batteries. According to Jensen and Weng (1994), *g* is very robust and almost invariant across different factor-analytical methods as long as the respective psychometric test batteries contain a diverse set of intellectual ability tests. Furthermore, Visser, Ashton, and Vernon (2006) showed that a diverse set of intellectual ability tests shared strong loadings on a general factor of intelligence, hence, the key requirement for modeling *g* is not necessarily a hierarchical approach of modeling, but a diverse set of intellectual ability tests.

1.1.2 The mental speed approach to intelligence

The investigation of the cognitive and perceptual underpinnings of intelligence has always been of particular interest. Already Galton (1883) had the hypothesis that individual differences in the speed of information processing (SIP) would be reflected in individual differences in intelligence. Galton believed that the “quickness” of response was an advantage in the natural selection (cf. Jensen, 2006). However, Galton was unsuccessful in confirming such a relationship due to methodological reasons. For instance, Galton operationalized intelligence as an individual’s occupation or, additionally, lacked the appropriate statistical methods to test his hypothesis. Nevertheless, Galton notably influenced the individual differences research on intelligence up until today and in the meanwhile, Galton’s hypothesis has been confirmed repeatedly (Jensen, 2006; Sheppard & Vernon, 2008).

The mental speed approach recognizes that SIP accounts for individual differences in intelligence. That is, more intelligent individuals show a higher speed of execution of cognitive processes than less intelligent individuals, hence, show faster completion of simple cognitive tasks. These simple cognitive tasks are denoted as elementary cognitive tasks (ECTs), which demand rather low cognitive effort and require only a small amount of cognitive processes to arrive at a correct outcome (Carroll, 1993). Due to the simplicity of ECTs, errors tend to be low and individual differences are primarily observed in the SIP, that is, in reaction times (RTs). Based on an individual’s RT, the time taken by a cognitive process such as stimulus apprehension or decision making can be inferred (Jensen, 1998a). One of the most frequently used ECTs is the Hick paradigm (Hick, 1952), which assess SIP with a simple and choice RT task. In the Hick paradigm, the number of possible stimulus locations is increased systematically across several task conditions. In the easiest condition, the simple RT condition, a single stimulus location is presented and individuals are supposed to respond as fast as possible to an upcoming stimulus by pressing a response button. In the more complex conditions, the choice RT conditions, the number of possible stimulus locations is increased so that individuals have to make more and more decisions. For example, in the second condition, two possible stimulus locations are presented, while in the third condition, four possible stimulus locations are presented, and so forth. Hick (1952) discovered a relationship between the amount of information to be processed and RTs. That is, an individual's RT linearly increased with the number of bits of information (i.e., the $\log_2$ of the number of possible stimulus locations) to be processed.

Roth (1964) was the first to relate Hick RT parameters to intelligence and showed that the RT-slope across Hick conditions was steeper for less intelligent individuals compared to more intelligent individuals. Furthermore, Jensen (1987) showed that the RT-slope as well as other Hick parameters (e.g., mean RT or the intercept) are reliably correlated with intelligence. Today, a large number of studies show that individual differences in RTs as measured with various different ECTs account for individual differences in intelligence (Sheppard & Vernon, 2008) no matter if speed (Deary, Der, & Ford, 2001; Neubauer & Bucik, 1996) or power tests of intelligence (Bors & Forrin, 1995; Neubauer & Bucik, 1996; Neubauer, Riemann, Mayer, & Angleitner, 1997; Vernon & Kantor, 1986) were used. Sheppard and Vernon (2008) reviewed empirical findings and found a mean correlation coefficient of r = -.24 between intelligence and RT (based on 172 studies with a total of 1146 correlation coefficients). The correlations between the RTs and intelligence reported by Sheppard and Vernon ranged from r = -.10 up to r = -. 45 with a trend towards strengthening for more complex ECT conditions. For example, Hick conditions containing more bits of information showed stronger correlations with intelligence compared to conditions containing less bits (e.g., Jensen, 1987). This phenomena of stronger correlations between more complex ECTs conditions and intelligence is known as the *complexity* *hypothesis* and has been shown repeatedly (Ackerman & Cianciolo, 2002; Neubauer & Fink, 2003; Rammsayer & Troche, 2016; Stankov, 2000; Vernon & Jensen, 1984; Vernon & Weese, 1993). However, there is evidence for an inverted curvilinear trajectory of the correlation between RTs and intelligence in relation to task complexity (Borter, 2016; Jensen, 2006; Lindley, Wilson, Smith, & Bathurst, 1995). That is, the magnitude of the correlation between RTs and intelligence first increases with increasing task complexity, but then decreases if the task gets exceedingly complex. Schweizer (1996) showed that a speed-accuracy transition takes place when task complexity increases. That is, in exceedingly complex tasks accuracy scores are associated with intelligence instead of RTs.

1.1.3 Sensory discrimination ability

Before the invention of psychometric intelligence tests, Spearman (1904) confirmed a relationship between sensory discrimination and intelligence with a sample of pupils, whose intelligence was rated by their teachers and peers. Spearman showed moderate to strong positive correlations between the performance on weight, color, or pitch discrimination tasks and intelligence. After the early years of the 20th century, research on sensory discrimination and intelligence was neglected and resurged in the last 40 years (for a historical review see Deary, 1994). In these recent years, sensory discrimination performance in different modalities was related to intelligence. For the auditory modality, the performance on duration (Helmbold & Rammsayer, 2006; Helmbold, Troche, & Rammsayer, 2006; Rammsayer & Brandler, 2002, 2007; Troche & Rammsayer, 2009b; Watson, 1991), pitch/frequency (Acton & Schroeder, 2001; N. Raz, Willerman, & Yama, 1987), and loudness discrimination tasks (Deary, Bell, Bell, Campbell, & Fazal, 2004; Troche & Rammsayer, 2009a) was found to be positively related to intelligence. For the visual modality, the performance on duration (Haldemann, Stauffer, Troche, & Rammsayer, 2011, 2012), color (Acton & Schroeder, 2001; Deary et al., 2004), brightness (Troche & Rammsayer, 2009a), and line length discrimination tasks (Meyer, Hagmann-von Arx, Lemola, & Grob, 2010) was found to be positively related to intelligence. In addition, several studies confirmed a positive relationship between the performance on tactile discrimination task (such as pressure, texture, and shape discrimination) with intelligence (Li, Jordanova, & Lindenberger, 1998; Roberts, Lazar, Pallier, & Dolph, 1997; Stankov, Seizova-Cajić, & Roberts, 2001).

Correlations obtained between single measures of sensory discrimination and intelligence are rather low (cf. Acton & Schroeder, 2001; Deary et al., 2004; Rammsayer & Brandler, 2002). Already Spearman (1904) had to correct the obtained correlation coefficients for attenuation and showed that a factor-analytically derived general discrimination ability factor (GDA) based on several indicators of sensory discrimination was related more strongly to *g* than single indicators of sensory discrimination. As a matter of fact, Spearman showed that GDA coincided with *g* and, hence, concluded that sensory functions must represent an essential element of *g*. In recent years, Spearman’s preliminary results on the relationship between GDA and *g* were confirmed with structural equation modeling (SEM) by Deary and colleagues (2004), who showed a near perfect correlation (r = .92) between GDA and *g*. A similar strong correlation (r = .78) between GDA and *g* was found for a sample of children aged between 5 to 10 years (Meyer et al., 2010). These studies only used non-temporal sensory discrimination tasks as indicators of GDA, but temporal discrimination is of particular significance in the context of sensory discrimination ability for the following two reasons. First, time is not a distinct stimulus as for example a tone or a light, and, second, no specific temporal receptor like the known sensory receptor exists (cf. Grondin, 2001).

The study by Helmbold, Troche, and Rammsayer (2006) examined the relationship between auditory temporal discrimination, pitch discrimination, and *g*. Temporal and pitch discrimination were moderately correlated (r = .41) and both were substantially related to *g* ($r_{temporal}$ = .43 and r_{pitch} = .39). Furthermore, a standard multiple regression analysis revealed that both predictor variables combined explained a substantial portion of overall variance in *g* (R^2 = .24). The relatedness and the shared predictive power suggested that temporal and non-temporal discrimination ability represent common aspects of sensory acuity. As a matter of fact, subsequent SEM studies showed that temporal and non-temporal discrimination tasks can be conjoined to a single latent variable of GDA (Troche & Rammsayer, 2009a; Troche, Wagner, Voelke, Roebers, & Rammsayer, 2014). The study by Troche and Rammsayer (2009a) showed that GDA predicted a substantial portion of variance in capacity- as well as in speed-related aspects of intelligence. However, when the latent variable GDA was split into a latent variable of temporal and a latent variable of non-temporal discrimination ability (which correlated to r = .94), only temporal discrimination ability predicted capacity- as well as speed-related aspects of intelligence, whereas non-temporal discrimination ability only predicted capacity- but not the speed-related aspects of intelligence. Consequently, despite the high association between temporal and non-temporal discrimination ability, the two constructs are still dissociable. The relationship between temporal discrimination ability and intelligence is what is known as the TRP hypothesis. According to the TRP hypothesis, individuals with higher TRP of the central nervous system show not only higher efficiency of information processing, but also faster SIP, what results in higher scores in psychometric intelligence tests (Rammsayer & Brandler, 2002, 2007). In the past 15 years, the TRP hypothesis received increased interest and was confirmed repeatedly (Haldemann et al., 2012; Helmbold, Troche, & Rammsayer, 2007; Rammsayer & Brandler, 2002, 2007). In the following two subchapters, the psychophysical timing tasks used as indicators of the latent variable TRP are introduced and TRP's relationship with intelligence is presented.

1.1.3.1 Psychophysical timing tasks as indicators of temporal resolution power

Psychophysical timing tasks are used to determine an individual's timing accuracy by computing difference thresholds (sometimes called just noticeable difference), which is a fundamental concept within psychophysics and refers to the minimal difference in stimulus magnitude needed to successfully discriminate two stimuli (W. H. Ehrenstein & A. Ehrenstein, 1999). Typical psychophysical timing tasks are interval comparisons, of which Grondin (2010) distinguishes two categories: forced choice and single stimulus. In a forced choice setting, usually denoted as duration discrimination task, individuals have to judge the duration of two successively presented intervals and have to indicate which of the two intervals was longer. The intervals differ in the range of milliseconds (ms) to seconds and are either empty (i.e., silent) or filled. An auditory empty interval is marked by a brief start and end signal (e.g., white noise bursts), whereas an auditory filled interval is presented as one continuous tone. In a classical single stimulus task, frequently referred to as temporal generalization task (TG), individuals are first familiarized with the duration of a standard interval. Thereafter, individuals have to judge whether each subsequent presented interval was of the same duration as the initially familiarized standard interval. The base duration might vary in the range of ms to seconds.

The following three psychophysical timing tasks were also frequently examined in the context of the TRP hypothesis: temporal-order judgment task (TOJ), rhythm perception task (RP), and the auditory flicker fusion frequency task (AFF). In a typical TOJ, individuals are confronted with two stimuli that are presented with slightly different onsets and the individuals have to judge the temporal order of the two stimuli, that is, which stimulus was presented first. The stimuli are often presented bimodal (e.g., a tone and a light). A typical RP requires an individual to recognize a slight duration deviation in a temporal pattern such as a periodic click-to-click interval. These temporal patterns consist of several clicks of identical duration and a single empty interval between two clicks slightly deviates in duration from all the other empty intervals presented in the given pattern (cf. Rammsayer & Brandler, 2007). A typical AFF involves two stimuli that are presented separated by a short interstimulus interval (ISI) in the range of a few ms (e.g., in the range of 1 to 40 ms) and individuals have to judge whether the two stimuli were perceived as separate or fused events.

The five psychophysical timing tasks introduced in the two paragraphs above and their according variations (e.g., filled versus empty intervals or ms versus seconds) have been used as indicators of TRP, but not all of these indicators showed to be reliable and valid indicators. Rammsayer and Brandler (2004) performed an exploratory factor analysis (EFA) with the following eight auditory psychophysical timing tasks: duration discrimination with empty intervals in the range of ms, duration discrimination with filled intervals in the range of ms and seconds, TOJ, TG in the range of ms and seconds, RP, and AFF. Based on the scree plot, the EFA revealed a single factor on which all tasks showed substantial loadings except for RP and AFF, which showed factor loadings below .25. In addition, when the eigenvalues were considered as determinant of the numbers of factors instead of the scree plot, a second factor was suggested, which consisted only of RP, while AFF still did not show a substantial loading on any of the two factors. Throughout the TRP literature, RP and AFF show rather weak (and sometimes non-significant) correlations with other indicators of TRP and inconsistent factorial results (Haldemann et al., 2012; Rammsayer & Brandler, 2002, 2007). Furthermore, RP and AFF often show rather weak and sometimes even non-significant correlations with intelligence (Haldemann et al., 2012; Helmbold & Rammsayer, 2006; Rammsayer & Brandler, 2002; Troche & Rammsayer, 2009a). Already Jensen (1983) failed to support a relationship between a visual flicker frequency fusion task and intelligence. For these reasons, the present study did not use RP and AFF as indicators of TRP. Based on the successful modeling of TRP in Troche and Rammsayer (2009b), duration discrimination with empty intervals (DDE), TG, and TOJ (all in the range of ms) were used.

1.1.3.2 Temporal resolution power and intelligence

TRP repeatedly showed moderate to strong correlations with intelligence (Haldemann et al., 2012; Helmbold & Rammsayer, 2006; Helmbold et al., 2007; Troche & Rammsayer, 2009a). The moderate correlations were shown when only single indicators of intelligence were used (e.g., Haldemann et al., 2011, 2012), whereas the strong correlations were shown when *g* was derived from a diverse set of cognitive ability tests (e.g., Helmbold et al., 2007). Furthermore, Helmbold and Rammsayer (2006) showed that TRP was related to a speed (r = .36) as well as to a power test of intelligence (r = .47). In the same study, a SIP factor derived from a set of different Hick RT parameters also showed substantial, albeit lower, correlations with the speed (r = -.26) and the power test of intelligence (r = -.28). A stepwise multiple regression analysis revealed that TRP was a more powerful predictor of intelligence than the SIP factor derived. In a subsequent SEM study, Helmbold, Troche, and Rammsayer (2007) investigated the predictive power of TRP and SIP in relation to *g* as well as potential mediating effects among these three constructs. Specified as unrelated predictors, TRP and SIP predicted substantial portions of variance in *g* (R^2_{TRP} = 38.81% and R^2_{SIP} = 6.25%). However, when specified as related predictors, a substantial correlation between TRP and SIP (r = -.65) was observed, but only TRP remained a significant predictor of *g* (R^2_{TRP} = 38.81% and R^2_{SIP} = 1.21%). This result indicated that the relationship between SIP and *g* might be (partially) mediated by TRP. In fact, Helmbold, Troche, and Rammsayer were able to show that the relationship between SIP and *g* was completely mediated by TRP. This result is in line with previous findings suggesting that TRP is a more important predictor of *g* than mere SIP (cf. Helmbold & Rammsayer, 2006; Rammsayer & Brandler, 2007).

Troche and Rammsayer (2009b) proposed that higher TRP not only leads to faster SIP, but also to more efficient coordination of cognitive processes, thus, to an increased working memory (WM) capacity, what consequently should lead to higher scores in psychometric intelligence tests. The authors examined whether TRP and WM capacity were independent predictors of capacity- as well as speed-related aspects of intelligence or whether the relationship between TRP and these two aspects of intelligence was (partially) mediated by WM capacity. The results indicated that WM capacity fully mediated TRP’s relationship to both aspects of intelligence. However, these results have to be taken with caution since WM capacity and capacity-related aspect of intelligence were not clearly dissociable (β = .92). Nevertheless, this study first challenged the TRP hypothesis by bringing up the role of attention in the relationship between TRP and intelligence. As known from research on WM, attention is an integral part of WM (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kane & Engle, 2003) and, consequently, might have caused the mediating effect between TRP and intelligence. Further evidence for that assumption comes from Carroll (1993), who stated that attention is involved in all types of cognitive performance. As a result, there might not be a genuine relationship between TRP and intelligence due to attention as common source of variance. However, the role of attention has never been systematically investigated in the context of the TRP hypothesis. The present study aims to approach this gap, but prior to this undertaking, a closer look at the concept of attention and its relationship to intelligence as well as temporal information processing is necessary.

1.2 Attention

Almost any book concerned with the topic of attention cites James (1890) and Pashler (1998). James stated that “Every one knows what attention is” (p. 256), while Pashler claimed that “no one knows what attention is” (p. 1). These two quotes illustrate the ongoing challenge in the research on attention. On the one hand, researchers and laypersons do have a common, albeit ordinary, notion of what attention is and do understand each other when referring to it. On the other hand, scholarly conceptualizations differ and no clear consensus exists about the nature of attention. Hence, two main metaphors are used to guide the cognitive psychology of attention: the *spotlight metaphor* and the *limited resource metaphor* (Fernandez-Duque & Johnson, 2002).

The *spotlight metaphor* describes the selectivity of attention and an individual’s ability to focus his/her attention on the relevant. In the words of the *spotlight metaphor*, attention is the light, which is oriented towards a relevant spot and persists on that particular spot. Consequently, only a stimulus in the focus of the spotlight is perceived, while the stimuli in the fringe of the spotlight are (temporarily) neglected.

The *limited resource metaphor* - not to be confused with filter theories of attention that propose a structural bottleneck at different stages of information processing (Broadbent, 1958; for a review on filter theories see Lachter, Forster, & Ruthruff, 2004) - can be traced back to Kahneman's (1973) work on the capacity model of attention. According to Kahneman, each individual has a capacity limit in the performance of cognitive processes and this limited capacity can be allocated among different concurrent processes. However, the total amount of attention that can be deployed at the same time is limited, hence, an individual's ability to carry out multiple cognitive processes simultaneously is restricted. Two types of input are needed for the successful completion of a cognitive process: a specific information input to a sensory structure and a non-specific input, which Kahneman terms interchangeably *attention*, *effort*, or *capacity*. In that sense, attention has a modulatory effect on bottom-up guided information processing: *to pay attention* is *to exert mental effort* and *to invest processing capacity* to objects and acts (cf. Kahneman, 1973). Therefore, for the present study, attention is conceptualized as the investment of limited processing resources.

In addition, different types of specific input impose different demands on the limited capacity resources, hence, a more complex task demands more attention compared to an easy task (Stankov & Schweizer, 2007). Consequently, performance in a task fails if there is not enough attention to meet task demands or if the available attention is already allocated to other specific input. Kahneman's idea of a unitary limited capacity was advanced by Navon and Gopher (1979), who suggested that the human information processing system consists of multiple limited capacities, of which processing resources can be allocated to different inputs simultaneously. However, Schweizer, Moosbrugger, and Goldhammer (2005) questioned the notion of multiple capacities for two reasons. First, interferences observed in dual-task performance challenge the notion of several independent capacities. Second, it can be expected that different types of attention measures draw on common capacity resources (e.g., an individual’s ability to divide its attention also involves the ability to focus its attention onto different sources and to sustain that effort).

1.2.1 Theoretical approaches to attention

Alike intelligence, attention is one of the oldest constructs in psychological science dating back to philosophers like Malebranche and Leibniz who were concerned with how individuals perceive their environment and how these perceptual events become conscious (for a historical review on attention see Vu, 2004). Due to these many years of research on attention, it is not surprising that different theoretical approaches and many thereof derived types of attention have been proposed. Most types of attention originated from the following two theoretical approaches: the Posner-based and the WM-based approach (Moosbrugger, Goldhammer, & Schweizer, 2006).

Many prevalent types of attention are based on the model put forward by Posner and colleagues (Petersen & Posner, 2012; Posner & Boies, 1971). Posner and Boies (1971) originally proposed the three independent components of alertness, selectivity, and processing capacity, which to date are referred to as the attentional trinity of the alerting, the orienting, and the executive network, respectively (Petersen & Posner, 2012). Alerting is the ability to achieve and maintain a state of readiness, while orienting is the ability to select the relevant information from the sensory surplus of information. The types of attention referred to by the executive network come by many names as for example supervisory attention, executive attention, conflict resolving attention, or attention control, respectively (Fan, McCandliss, Sommer, A. Raz, & Posner, 2002; A. Raz & Buhle, 2006; Schweizer, 2010). In contrast to the alerting and the orienting network, the executive network emphasizes top-down processes of attention such as the executive control of perceptual and cognitive processes. Data from imaging studies support the attentional trinity (A. Raz & Buhle, 2006). However, these networks are not as independent as previously supposed (Fan et al., 2002; A. Raz & Buhle, 2006), suggesting that the different types of attention have something in common.

Attention as executive control has arisen from research on WM (Moosbrugger et al., 2006). In the context of WM research, controlled attention is what makes short-term memory WM. That is, WM is described as a subset of items that are stored in short-term memory and are currently submitted to capacity limited, attention-controlled cognitive processing (Engle et al., 1999; Schweizer & Moosbrugger, 2004). Baddeley and Hitch (1974) proposed a model of WM, which initially consisted of the following three components: the phonological loop, the visuospatial sketchpad, and the central executive. In later advancements of that WM theory, the episodic buffer was added as forth component (for an overview see Baddeley, 2012). The central executive controls and regulates the coordination of the phonological loop and the visuospatial sketchpad, is associated with shifting between different tasks, and concerned with further attentional processes such as the inhibition of competing responses. Already from the early developments of his theory, Baddeley (1993) saw the central executive as attention controller, but, at that time, research on attention was primarily concerned with perceptual processes, while the executive control of information processing was rather neglected. “Fortunately there was one exception to this general trend” (Baddeley, 1993, p. 155), which was the supervisory attentional system specified in Norman and Shallice’s (1986) model of attention control. Routine activities, such as for example talking while walking, are controlled by a so-called contention scheduler, which coordinates these routine activities with pre-learned schemata. Therefore, the contention scheduler is seen as an automatic attention process, which needs no conscious control. However, if an individual is confronted with a novel situation, conscious control is needed and the supervisory attentional system takes over to avoid processing errors caused by the interferences between the non-routine information and the existing schemata. Today, executive attention is seen as key component of WM models (Baddeley, 2012).

The present chapter 1.2.1 has shown that attention has a perceptual, bottom-up guided aspect and an executive controlled, top-down guided aspect. The former type, perceptual attention, refers to attention as perceptual process such as for example orienting towards or selecting the relevant information from the surplus of sensory input and, additionally, “the appropriate allocation of processing resources to relevant stimuli” (Coull, 1998, p. 344). The latter, executive attention, refers to the higher cognitive processes involved in the integration and control of the sensory input (e.g., Norman & Shallice, 1986) and is closely related to the concept of WM (e.g., Baddeley, 1993; 2012). In the following two chapters, frequently specified types of attention with their associated measurement are introduced, followed by a closer look at the structure of attention.

1.2.1.1 Manifest types of attention

A vast variety of conceptually different types of attention exist. Four types frequently occur throughout the literature with the following or similar denotations: selective-focused attention, sustained attention, divided attention, and executive attention (Coull, 1998; Heitz, Unsworth, & Engle, 2005; Moosbrugger et al., 2006; Moray, 1969; Pashler, 1998; Petersen & Posner, 2012; Robertson & O'Connell, 2010; Van Zomeren & Brouwer, 1994). For a comprehensive overview on different and overlapping types of attention see Schweizer (2010).

The concept of selective attention and focused attention are inherently linked and addressed as selective-focused attention. According to Schweizer (2010), this type of attention comes closest to the ordinary meaning of attention (i.e., *the spotlight metaphor*). The ability to select the relevant stimulus from a source of information involves the ability to filter out or attenuate the non-relevant information and to allocate the needed processing resources to the stimulus in focus (Posner & Boies, 1971). Schweizer (2005) exemplified the importance of selective-focused attention: if there would be a state of non-allocation, there would be no allocation of processing resource to relevant stimuli or each new stimulus would attract all processing resources available. Thus, information processing would be diffuse and in the end abortive. In relation to the selectivity aspect of attention, Hoffman and Nelson (1981) used the term spatial attention to refer to the process of scanning different regions of the visual field.

Types of sustained attention are characterized by considerable cognitive effort that is continuously applied over prolonged periods of time. According to Schweizer and colleagues (2005), the ability to sustain attention refers to the opposite of attention's natural state: random shifts in attention. Some researchers use the term interchangeably with vigilance (Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991; Okena, Salinskya, & Elsas, 2006; Sarter, Givens, & Bruno, 2001). However, a typical vigilance task is a rather monotonous and undemanding task, which requires the detection of an infrequent stimulus over a period of up to several hours, while a sustained attention task does not explicitly differentiate between demanding and undemanding task types (Robertson & O'Connell, 2010). A classical vigilance task was designed by Mackworth (1948). In Mackworth's so-called clock test, a black pointer made small jumps around a circumference of a blank clock without any scale markings. Occasionally, within a two hour period, the pointer made larger jumps upon which the individuals had to push a response button. Mackworth showed that the accuracy of signal detection declined after only several minutes. In contrast to Mackworth's clock test, the Continuous Performance Test (CPT; Halperin, Sharma, Greenblatt, & Schwartz, 1991; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) represents a classical sustained attention task, which involves the ability to maintain attention "only" over several minutes by searching for a target stimulus in a sequence of rapidly presented target and distractor stimuli. Further frequently used synonyms for sustained attention are mental concentration and tonic alertness (Schweizer, 2010; Sturm & Willmes, 2001). In comparison to tonic alertness, phasic alertness refers to the ability to increase and maintain response readiness over a very short period (Sturm & Willmes, 2001). In an experimental setting, phasic alertness is typically induced by an external cue such as for example a fixation cross, which directs attention to an impending stimulus.

Divided attention is the ability to process voluntarily more than one source of information at the time. Thus, divided attention refers to the allocation of specific portions of the limited processing resources to several different tasks and, hence, is directly linked to the idea that attentional resources are limited (Coull, 1998; Pashler, 1998; Schweizer, 2010). Most typically, dual-task studies are used to show how performance in one task decreases due to the increased processing capacity demands required by a second simultaneously performed distractor task. Individuals are still highly selective, but in contrast to tasks of selective-focused attention, all stimuli presented in a dual-task setting are of relevance and arise from different sources coupled with different responses (Van Zomeren & Brouwer, 1994). Dual-task paradigms are the classical approach to investigate Kahneman's (1973) or Navon and Gopher's (1979) theories of limited capacity/capacities. In applied research settings, tasks of divided attention typically assess the effects of multi-tasking such as for example conversing on a cellphone while driving (e.g., Strayer & Johnston, 2001).

Executive attention, also called executive control (Petersen & Posner, 2012; Schweizer, 2010) or attention control (Kane & Engle, 2003), refers to the top-down control and regulation of information processing (Fernandez-Duque, Baird, & Posner, 2000) and is conceptually close to what Norman and Shallice (1986) specified as the supervisory attentional system. That is, executive attention is concerned with conflict resolution and inhibitory control (Fernandez-Duque et al., 2000; Kane & Engle, 2002, 2003; Moosbrugger et al., 2006). Schweizer (2010) points out that information processing must be accompanied by higher mental processing that prevents alternative courses of action. As an example, while the primary goal of a task has to be achieved, the supervisory system has to resolve response conflicts, especially when habitual behaviors conflict with response behaviors associated with the current task. In contrast to more perceptual types of attention measures (such as for example the CPT), executive attention is measured with tasks that control the subordinate perceptual attention processes such as rapid switching between concurrent tasks (Moosbrugger et al., 2006).

1.2.1.2 The structure of attention

One of the first studies that applied an individual differences approach to investigate the structure of attention was by Mirsky and colleagues (1991). Based on 13 different measures of attention, Mirsky and colleagues factor-analytically identified four types of attention: focus-execute, sustain, encode, and shift. Subsequent studies only partially replicated the structural model of Mirsky and colleagues (Pogge, Stokes, & Harvey, 1994; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1996) or even failed to do so (Strauss, Thompson, Adams, Redline, & Burant, 2000) mainly due to non-representative clinical samples or a questionable selection of measurements.

Moosbrugger and colleagues (2006) examined 11 latency-based measures of attention with a non-clinical sample by means of confirmatory factor analyses (CFAs). The measures of attention were selected from a set of validated attention test batteries and were categorized as perceptual or as executive measure of attention. Based on that categorization, a latent variable perceptual attention was modeled with tasks measuring alertness, sustained attention, focused attention, and selection for action, whereas a latent variable executive attention was modeled with tasks measuring divided attention, skill-based-interference, behavioral inhibition, action planning, and two measures of attention switching (see Model 1 in Figure 1). Model 1 showed a satisfactory fit and a strong correlation (r = .66) between the two latent variables perceptual and executive attention. To deal with the strong correlation and based on the rationale of a close relationship between attention and perception (cf. Broadbent, 1958; Coull, 1998; Schweizer, 2010), Moosbrugger and colleagues specified a bi-factorial model in which all executive measures also loaded on the latent variable of perceptual attention (see Model 2 in Figure 1). The rationale of bi-factorial modeling is to derive a general factor common to all manifest variables and a second group factor that accounts for the residual variance in an a priori specified set of manifest variables. With this rationale of modeling, the derived factors are independent of each other (for a detailed example of bi-factorial modeling in the context of intelligence see Beaujean, 2015). The bi-factorial attention model specified by Moosbrugger and colleagues represented the data well and showed a better fit than the model in which perceptual attention was specified as group factor and executive attention as general factor. This second model was modeled based on the rationale that all types of attention afford executive control (cf. Heitz et al., 2005). The attention models examined by Schweizer and colleagues (Moosbrugger et al., 2006; Schweizer et al., 2005) suggest that perceptual and executive attention show a strong overlap caused by the fact that all attention measures tap perceptual attention independent of the attention measures used. For this reason, the present study pertained attention to perception.

1.2.2 Attention and intelligence

Already early intelligence researchers such as Binet or Spearman recognized the important role of attention to intelligence (cf. Heitz et al., 2005). To date, most evidence for a close relationship between attention and intelligence is provided by Posner-based and WM-based models. From a Posner-based approach, the two models of perceptual and executive attention presented in Figure 1 were both related to intelligence (Schweizer, 2010; Schweizer et al., 2005). For Model 1, a second-order latent variable of general attention had to be derived from the two first-order latent variables perceptual and executive attention to optimize the prediction of intelligence. This higher-order latent variable of general attention predicted 32.49% of variance in intelligence (Schweizer et al., 2005). If the latent variable of general attention was removed

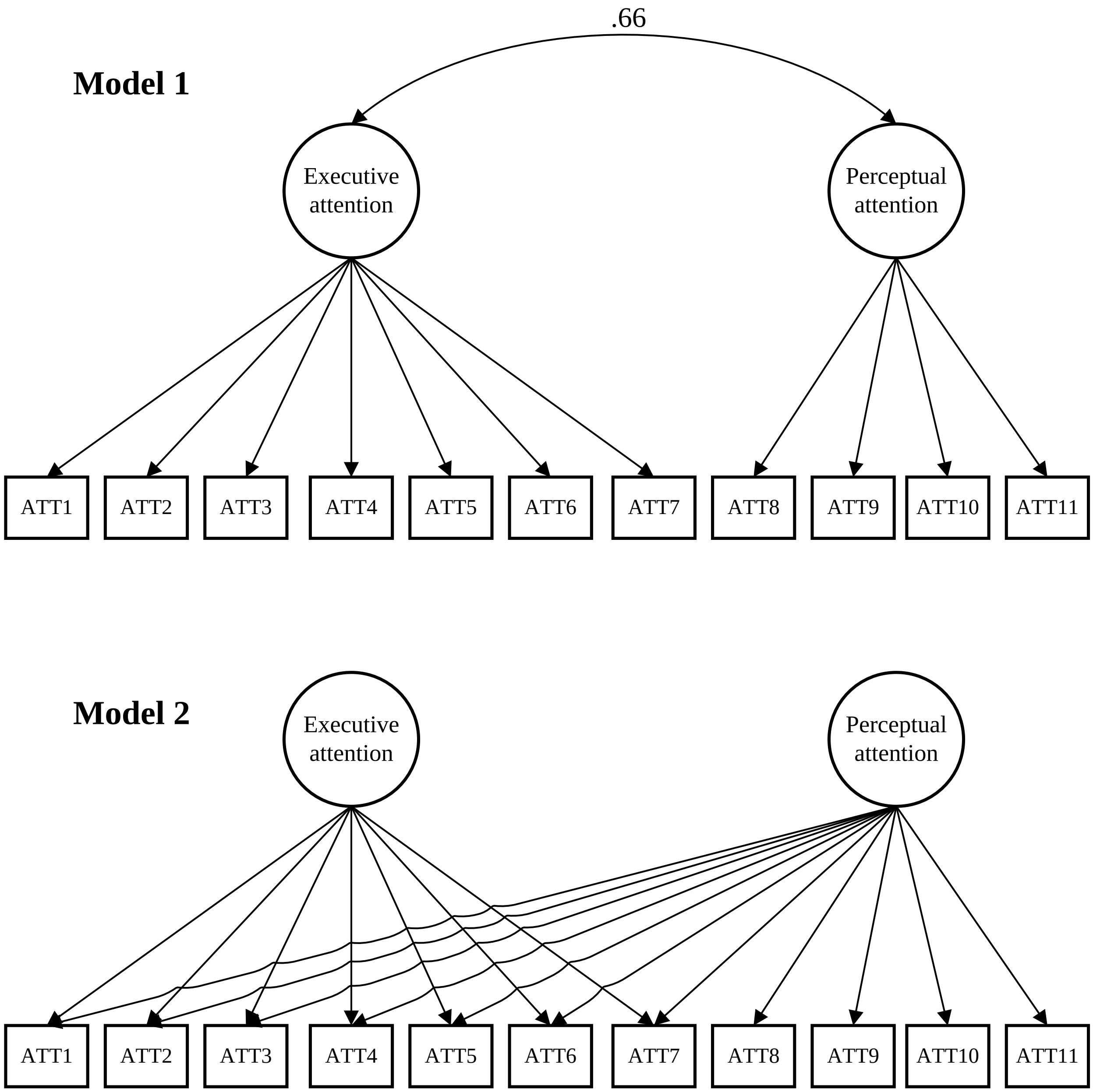

Figure 1. The two models of Moosbrugger, Goldhammer, and Schweizer (2006) representing perceptual and executive attention as the latent factors underlying individual differences in latency-based measures of attention. Model 1 represents a two factor model with a strong correlation of r = .66 between perceptual and executive attention. Model 2 represents the bi-factorial model with the independent latent variables of perceptual and executive attention. ATT1 to ATT7 represent executive types of attention measures, whereas ATT8 to ATT11 represent perceptual types of attention measures.

and the two first-order latent variables were specified as unrelated predictors, only the latent variable of executive attention substantially predicted intelligence (K. Schweizer, personal communication, November 03, 2016), even though both latent variables investigated individually showed to be strong predictors of intelligence (Schweizer, 2010). Consequently, predicting intelligence with the two independent first-order latent variables of perceptual and executive attention is misleading, because executive attention also taps perceptual aspects of attention and, consequently, the predictive influence of perceptual attention on intelligence is concealed. Therefore, bi-factorial model (see Model 2 in Figure 1) accounting for the dissociation of perceptual and executive attention was related to intelligence showing that perceptual attention predicted 17.64% of variance in intelligence compared to 7.29% of variance explained by executive attention (Schweizer, 2010). Altogether, from a Posner-based approach, these results suggest that attention has to be derived from a higher-order or a bi-factorial model in order to obtain a valid structural model of attention (Schweizer, 2010; Schweizer et al., 2005). Furthermore, these results of Schweizer and colleagues (2005) suggest that perceptual attention is a more important predictor of intelligence than executive attention.

In contrast to the Posner-based approach, the WM-based approach assess executive types of attention based on WM tasks. That is, executive types of attention are dissociated from other WM components by means of SEM and the thereby derived components are related to intelligence (Bühner, Krumm, & Pick, 2005; Bühner, Krumm, Ziegler, & Plücken, 2006; Kane et al., 2004; Süss, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). For example, Kane and colleagues (2004) applied bi-factorial modeling to a diverse set of classical WM span tasks and derived three latent variables. A general latent variable of executive attention based on all manifest indicators and two domain-specific storages factors based only on the according set of indicators: a group factor of spatial storage and a group factor of verbal storage. The latent variable of executive attention explained a substantial portion of variance in *g*, but only small portions in spatial and verbal reasoning ability, of which the domain-specific storage factors were better predictors. Kane and colleagues concluded that the aspect of executive attention is the main driver of the correlation between WM and general cognitive-ability.

Schweizer and Moosbrugger (2004) also examined the role of attention and WM as predictors of intelligence. In contrast to Kane and colleagues (2004), attention and WM were assessed with separate measures. That is, attention had not to be dissociated from WM by means of bi-factorial modeling. As in line with previous work (e.g., Burns, Nettelbeck, & McPherson, 2009), Schweizer and Moosbrugger found a close relationship between attention and WM, which indicated that measures of WM indeed included a component that is represented by measures of attention. However, the two mediation models examined by Schweizer and Moosbrugger showed a difference in the prediction of intelligence when measured with a speed or a power test of intelligence (see Figure 2). Attention and WM both predicted a substantial portion of variance in intelligence when measured with a power test compared to the finding that only attention substantially predicted intelligence when measured with a speed test. Consequently, WM might be especially involved in the processing of highly cognitive demanding psychometric intelligence test, whereas attention is the main processing resource when working on a psychometric intelligence test with lower task demands. According to Schweizer and Moosbrugger, this result suggests that the contribution of attention and especially WM depends on task demands required, but only attention being involved in all cognitive processing no matter of task demands required.

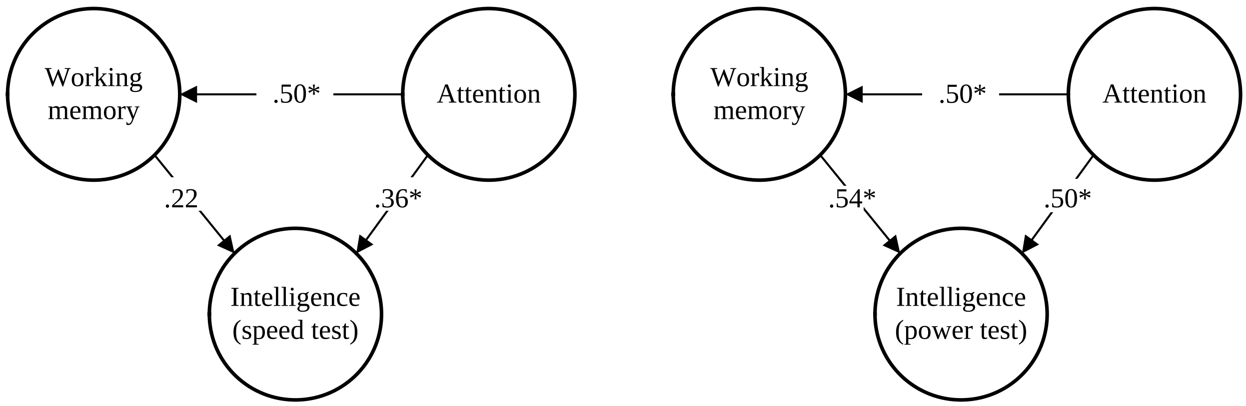

Figure 2. A simplified illustration of the two mediator models of attention, working memory, and intelligence as specified by Moosbrugger and Schweizer (2004). The latent variable of intelligence was either a speed or a power test of intelligence.
*p < .05.

1.2.3 Attention and temporal information processing

To date, the relationship between attention and TRP has not been examined. Therefore, insights are presented from the perspective of temporal information processing. There are two main paradigms used to assess temporal information processing: the prospective and the retrospective paradigm (Grondin, 2010). In prospective timing tasks, individuals know that the task will be about time in advance and attention-based models are often considered to explain prospective timing performance, whereas in retrospective timing tasks, individuals do not know in advance that the task will be about time and memory-based models are considered to explain retrospective timing performance (Block & Zakay, 1997; Grondin, 2010). In the present study, only prospective timing tasks are used. For more details and a review on both paradigms see Block and Zakay (1997).

The role of limited processing resources in temporal information processing is often examined with dual-task performance and its associated interference effect, which refers to the disruption in timing performance in a primary task caused by a secondary distractor task (Brown, 2008b). In a typical dual-task setting individuals simultaneously work on a timing task and a distractor task, either being another timing task or some non-temporal task (e.g., a visual search task or mental arithmetics). As a result of the additional processing resource required by the distractor task, the timing performance in the primary task is affected in such a way that time judgments become shorter, more variable, and more inaccurate as if when compared to a single-task setting, in which individuals only work on one timing task at the time (Brown, 1997, 2006, 2014; Casini & Macar, 1997; Coull, Vidal, Nazarian, & Macar, 2004). According to Brown's (2008b) review based on 55 empirical articles, 70 experiments out 77 (91%) showed an interference effect with various different distractor tasks used.

Several methodological variations of dual-task settings exist, showing the robustness of the interference effect. For example, cognitively more demanding distractor tasks afford more processing resources and consequently fewer processing resources are available for the primary timing task. For example, Zakay, Nitzan, and Glicksohn (1983) had individuals reproduce a duration of an interval during which they solved a verbal distractor task with three different complexity conditions. In the easiest condition, individuals had to simply read out a presented word. In the intermediate condition, individuals had to name pictures of various objects presented. In the most complex condition, individuals had to provide a synonym for a presented word. Zakay and colleagues found that time estimation is a decreasing function of the distractor task's complexity (i.e., the more complex the distractor task the shorter the reproduced time estimate). Several other studies provide evidence for a stronger interference effect when complexity of the distractor task is increased (Brown, 1997; Brown & Boltz, 2002; Hicks, Miller, Gaes, & Bierman, 1977; Zakay & Shub, 1998). A meta-analytical review of Block, Hancock, and Zakay (2010) confirmed that the prospective duration judgment ratio (i.e., the subjective time estimate gets shorter compared to the actual objective duration) decreases if the complexity of the distractor task increases. However, the interference effect is weakened if the primary timing task (Brown, 2008a) or the secondary distractor task (Brown & Bennett, 2002) require fewer processing resources due to pre-experimental practice of the respective task.

Further evidence comes from studies explicitly manipulating attention, by either cueing the focus of attention or by asking individuals to devote specific amounts of attention to one of the two tasks applied in a dual-task setting. For example, Mattes and Ulrich (1998) presented one of two possible stimulus durations either to the auditory or to the visual modality and used cues to indicate the modality of the impending stimulus duration. The cues were either valid, indicating the correct modality of presentation, or invalid, indicating the wrong modality of presentation. The main finding was that individuals perceived the validly cued stimulus durations as longer as compared to the invalidly cued stimulus durations, in which the duration was perceived as being shorter. The finding by Mattes and Ulrich was in line with findings on the interference effect that also showed that durations are perceived as shorter when processing resources have to be shared between concurrent tasks (e.g., Brown, 2008b). Evidence for the role of attentional sharing comes from studies in which individuals are instructed to allocate specified amounts of processing resources to one of the two concurring tasks. Grondin and Macar (1992) had individuals judge the duration and the intensity of a comparison tone to a standard tone. The individuals were instructed to allocate more attention either to the duration or to the intensity of the tone. The results showed that when more attention was allocated to the duration, the duration discriminability was increased, whereas the intensity discriminability was decreased. The opposite pattern resulted when more attention was devoted to the intensity. Consequently, fewer processing resources allocated to the timing task resulted in a poorer temporal resolution, hence, in a decreased precision of timing. This effect of attentional sharing was replicated repeatedly (Coull et al., 2004; Macar, Grondin, & Casini, 1994).

The fact that most types of distractor tasks interfere with timing performance in the primary task is explained with resource-based theories of information processing, which claim that monitoring time (in passing) is a cognitive task that demands limited processing resources (Brown, 1997; Casini & Macar, 1997; Hicks et al., 1977). So far, most of these dual-task studies presented were concerned with timing performance in the range of seconds. However, Rammsayer and Lima (1991) and Rammsayer and Ulrich (2011) showed that the processing of durations in the range of ms (i.e., 50 ms to 100 ms) was not influenced by cognitive distractor tasks suggesting that timing accuracy in the range of ms requires primarily perceptual processes compared to the processing of durations in the range of seconds, which requires processes at a more cognitive level. This finding was in line with Michon (1985), who suggested that temporal processing of brief intervals is rather of perceptual nature and, hence, not accessible to cognitive control. However, Rammsayer and Ulrich (2005) showed that the timing performance in the range of ms can be influenced by a cognitive distractor task.

1.3 Purpose of the present study

In summary, the TRP hypothesis refers to the idea that TRP represents a basic process of the central nervous system that accounts for the speed and the efficiency of information processing and, thus, underlies individual differences in intelligence. Previous studies repeatedly reported this functional relationship irrespective of measures used to assess TRP or intelligence (Haldemann et al., 2012; Helmbold & Rammsayer, 2006; Helmbold et al., 2007; Rammsayer & Brandler, 2007). However, the TRP hypothesis is challenged by the fact that the performance on psychophysical timing tasks as well as the performance on psychometric intelligence tests requires attentional resources (Brown, 2008b; Carroll, 1993; Schweizer et al., 2005). Therefore, the as hitherto considered genuine relationship between TRP and intelligence could be alternatively explained by attention as common source of variance. However, an explicit investigation of the interplay between TRP, attention, and intelligence is missing. Therefore, the present study aims to arrive at a better understanding of the potential mediating role of attention in the relationship between TRP and intelligence.

As presented in the introduction on attention, different conceptualizations of attention and multiple measures do exist. According to Rapp (1982), this versatility of attention comes from the fact that attention is a hypothetical construct that cannot be directly observed and is not a distinct function clearly detachable from other psychological functions. In fact, attention is always bonded to perceptual and cognitive processes in that manner that the allocation of processing resources increases their efficiency (Kahneman, 1973; Rapp, 1982). For the present study, based on Kahneman (1973) and Schweizer and colleagues (Moosbrugger et al., 2006; Schweizer et al., 2005), attention is defined as the appropriate allocation of limited processing resources in stimulus-driven information processing (see also Coull, 1998; Schweizer, 2010). In other words, perceptual attention (in the sense of Moosbrugger et al., 2006) is seen as the major source of efficiency in bottom-up information processing. Since it is plausible to assume that timing performance in the range of ms primarily requires perceptual processes (e.g., Michon, 1985), perceptual types of attention might be the most likely candidates for the mediation of the relationship between TRP and intelligence. In the following, the measurement of perceptual attention is considered in detail.

1.3.1 Measuring attention with elementary cognitive tasks: the role of task complexity

As previously introduced, ECTs demand rather low cognitive effort, require only a small amount of cognitive processes to arrive at a correct outcome, errors tend to be low, and individual differences are primarily observed in RTs (Carroll, 1993; Jensen, 1998a). To examine a cognitive process of interest with an ECT, several conditions are needed, none of them uniquely identify the effect of the cognitive process under study, but taken together define such an effect (Pachella, 1974). For the purpose of identifying the effect of perceptual attention in an ECT, complexity has to be manipulated across several conditions of an ECT based on the rationale that less complex conditions place lower demands on information processing, whereas more complex conditions place higher demands on information processing (Stankov & Schweizer, 2007). Therefore, the manipulation of complexity is directly linked to attention since higher task demands require more of the limited processing resources, hence, an increase in complexity should lead to prolonged processing what is visible in an increase of RTs across ECT conditions. According to Jensen (2006, 2011), complexity refers to the amount of information to be processed, which can be the number of cognitive steps required by an individual to achieve a correct response, the number of elements an individual has to attend to, the degree of stimulus-response compatibility, or the amount of prior-learned information that has to be retrieved from memory (see also Spilsbury, Stankov, & Roberts, 1990; Stankov & Crawford, 1993).

Together with the manipulation of complexity, the speed-accuracy transition (Schweizer, 1996) has to be considered, because the correlation between RT and intelligence diminishes when a task gets exceedingly complex (Borter, 2016; Jensen, 2006; Lindley et al., 1995). Furthermore, very complex tasks tap different cognitive processes such as WM and individual differences are rather observed in the number of correct responses (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Kane et al., 2004; Stankov & Schweizer, 2007; Süss et al., 2002). Task assessing perceptual types of attention are rather less complex and individual differences are primarily observed in RTs (Schweizer, 2010; Stankov & Schweizer, 2007). In the following, the three ECTs used to assess perceptual attention are presented.

1.3.2 Operationalization of attention

For the present study, the Hick paradigm, the Flanker task, and the CPT were used as measures of perceptual attention, each consisting of three conditions differing in complexity. The Hick paradigm and the Flanker task were operationalized as phasic measures, in which a cue disclosed the impending stimulus. The Hick paradigm was used as measure of selective-focused attention (Schöttke, Matthes-von Cramon, & von Cramon, 1993), in which complexity was manipulated by increasing the number of possible stimulus locations across conditions. Previous studies showed that RTs increase along with the number of possible stimulus locations (e.g., Jensen, 1987; Neubauer et al., 1997; Sleimen-Malkoun, Temprado, & Berton, 2013).

The Flanker task was used as measure of selective-focused attention and behavioral inhibition (B. A. Eriksen & C. W. Eriksen, 1974; Pashler, 1994). Complexity was manipulated by increasing the demands put on the focus aspect of selective-focused attention with a transition from focusing to behavioral inhibition from the second to the third condition. In the first condition, two different target stimuli were alternately presented in the center of the screen, both indicating a directional response (i.e., left or right). However, the individual had to respond the same way to both stimuli neglecting the irrelevant directional information. In the second condition, the target stimulus afforded the directional response. In the third condition, an individual’s ability to inhibit an inappropriate response induced by interfering information was manipulated. Again, the target stimulus afforded a directional response (i.e., left or right) and each target stimulus was either flanked by non-target stimuli corresponding to the directional response indicated by the target stimulus (congruent trials) or corresponding to the opposite directional response not indicated by the target stimulus (incongruent trials). Therefore, the individual had to focus on the center stimulus, while inhibiting or responding to the automatic response activated by the flanker stimuli. Congruent and incongruent trials were mixed in order to keep complexity at a high level. Incongruent trials typically show a response slowing due to increased demands of inhibitory control (Ridderinkhof, van der Molen, Band, & Bashore, 1997; Scheres et al., 2003).

Sustained attention was assessed with the CPT, one of the most popular clinical measures of sustained attention (for a comprehensive review see Riccio, Reynolds, Lowe, & Moore, 2002). The CPT is an experimenter-paced ECT in which individuals monitor a rapid sequence of several different stimuli and have to respond whenever a previously defined imperative stimulus appears. Complexity was manipulated by increasing the number of distractors presented across conditions. The first condition was rather a simple RT condition, in which only the imperative stimulus was presented repeatedly without distractor stimuli, hence, complexity was kept at a minimal level (cf. Schweizer, 1996). In the second and third condition, complexity was increased by adding distractors into the sequence of imperative stimuli. In order to increase complexity from the second to the third condition, a new imperative stimulus was determined and the imperative stimulus of the second condition was added as distractor stimulus to the set of distractor stimuli in the third condition. Therefore, the third condition also measured inhibitory control of a previously habituated response in addition to sustained attention. In comparison to the Hick paradigm and the Flanker task, which demanded only phasic alertness, the CPT required individuals to sustain their attention continuously (i.e., tonic alertness) at a very high level in order to detect the imperative stimuli. There was no mean of compensation for missed stimuli.

All three ECTs with their according complexity manipulation are described in more detail in the method subchapters 3.3.1 to 3.3.3. In addition, the manipulation of complexity will be tested and discussed.

1.3.3 The impurity problem

It is difficult to decide whether the correlations observed between latency-based measures of attention and intelligence are caused by better attention or by faster SIP in individuals with higher intelligence. Krumm, Schmidt-Atzert, Michalczyk, and Danthiir (2008) showed that it is difficult to disentangle a latent variable assessing sustained attention from a latent variable assessing SIP. This problem becomes especially evident by the fact that identical measures are used to assess attention and SIP (Krumm et al., 2008; Schweizer, 2010; Schweizer et al., 2005). For example, the Hick paradigm, one of the most frequently used measures of SIP (Jensen, 2006; Sheppard & Vernon, 2008), is also used as measure of selective-focused attention in the research on schizophrenia and traumatic brain injuries (Schöttke et al., 1993). Based on this confound, some authors claimed that tasks assessing SIP correlate with intelligence to that extent with which they tap attention (Heitz et al., 2005; Stankov & Roberts, 1997; Wilhelm & Schulze, 2002). There is good evidence for the notion that SIP is more strongly correlated with intelligence when measured with complex rather than simple task conditions (Ackerman & Cianciolo, 2002; Neubauer & Fink, 2003; Rammsayer & Troche, 2016; Stankov, 2000; Vernon & Jensen, 1984; Vernon & Weese, 1993). Recently, Schweizer (2010) suggested that the allocation of processing resources is accompanied by the recruitment of additional neurons of the brain in order to improve performance in any given cognitive task. Speed of these neurons or neuronal networks is referred to as attention-paced speed (Schweizer, 2010) and may be functionally dissociable from residual speed, which is the speed associated with all other processes independent of the experimental manipulation of attention. Schweizer concluded that "attention-paced speed is a major source of the correlation between processing speed […] and intelligence" (p. 256). Therefore, latency-based measures of attention (or any other cognitive process supposed to be measured) are confounded by the different underlying processes contributing to a RT composite.

Schweizer (2007) referred to this confounding effect of different underlying cognitive processes in cognitive performance measures as the *impurity problem*. In fact, research within experimental cognitive psychology showed that latency-based performance in any cognitive task is a composite measure of the time taken by a number of different cognitive processes involved in the completion of that given task (Jensen, 1982, 1998b; Luce, 1986; J. Miller & Ulrich, 2013; Van Zomeren & Brouwer, 1994). The *impurity problem* can be partly avoided by several provisions in the experimental design: control for movement times (Jensen & Munro, 1979), establishment of stimulus-response compatibility (Alluisi & Warm, 1990), or avoiding (motivational) feedback (Neubauer, Bauer, & Höller, 1992). However, these provisions are not sufficient enough to curtail all unintended sources of variance and, hence, a statistical approach is needed to dissociate variance caused by the experimental manipulation from residual variance independent of the experimental manipulation.

1.3.4 Fixed-links modeling

Schweizer (2006a, 2006b, 2008) introduced fixed-links modeling (FLM) as a statistical approach to cope with the *impurity problem* inherent in all cognitive performance measures. FLM is a kind of SEM and represents a special form of CFA for experimental repeated-measurement designs. As an advantage over manifest approaches, FLM exclusively considers the true variance shared by several manifest variables as represented by latent variables. Most FLM studies propose to decompose variance into two components: an experimental latent variable, representing individual differences in processes directly affected by the different levels of the experimental manipulation, and a non-experimental latent variable, representing individual differences in the processes that remain constant irrespective of the experimental manipulation (Schweizer, 2006b). Therefore, the experimental and non- experimental latent variable are expected to be independent. In order to extract these two latent variables from the same set of manifest variables, fixation of factor loadings is required. The factor loadings of the experimental latent variable are fixed in accordance to the theoretically expected trajectory caused by the experimental manipulation (e.g., an increasing trajectory across task conditions), whereas all factor loadings of the non-experimental latent variable are fixed to the same value indicating consistency across treatment levels (see Figure 3 for an example of a fixed-links model). Given that all factor loadings are fixed and not estimated, variance of a latent variable is set free and needs to reach statistical significance in order to be interpreted as psychologically meaningful. Insignificant fixed-links variables are removed from the model and the revised models are used for the further analyses (cf. Wang, Ren, Li, & Schweizer, 2015).

FLM has been successfully applied to decompose experimental from non-experimental variance for cognitive processes such as working memory- (Schweizer, 2007; Stankov & Schweizer, 2007; Thomas, Rammsayer, Schweizer, & Troche, 2015; Wang, Ren, Altmeyer, & Schweizer, 2013; Wang et al., 2015), memory- (R. Miller, Rammsayer, Schweizer, & Troche, 2010; Stauffer, Troche, Schweizer, & Rammsayer, 2014), and attention-related phenomena (Ren, Schweizer, & Xu, 2013; Wagner, Rammsayer, Schweizer, & Troche, 2014, 2015). For the present study, it is expected that experimentally caused variance representing the increased attentional demands can be decomposed from non-experimental variance representing all other residual processes not influenced by the experimental manipulation of complexity. Hence, the experimental latent variable is supposed to represent attention-paced speed variance, whereas the non-experimental latent variable is supposed to represent residual speed variance, which is a conglomerate of all process untouched by the experimental manipulation of complexity. Therefore, the non-experimental latent variable cannot be unambiguously identified and has to be interpreted in the context of the study’s results and its nomological network (Cronbach & Meehl, 1955).

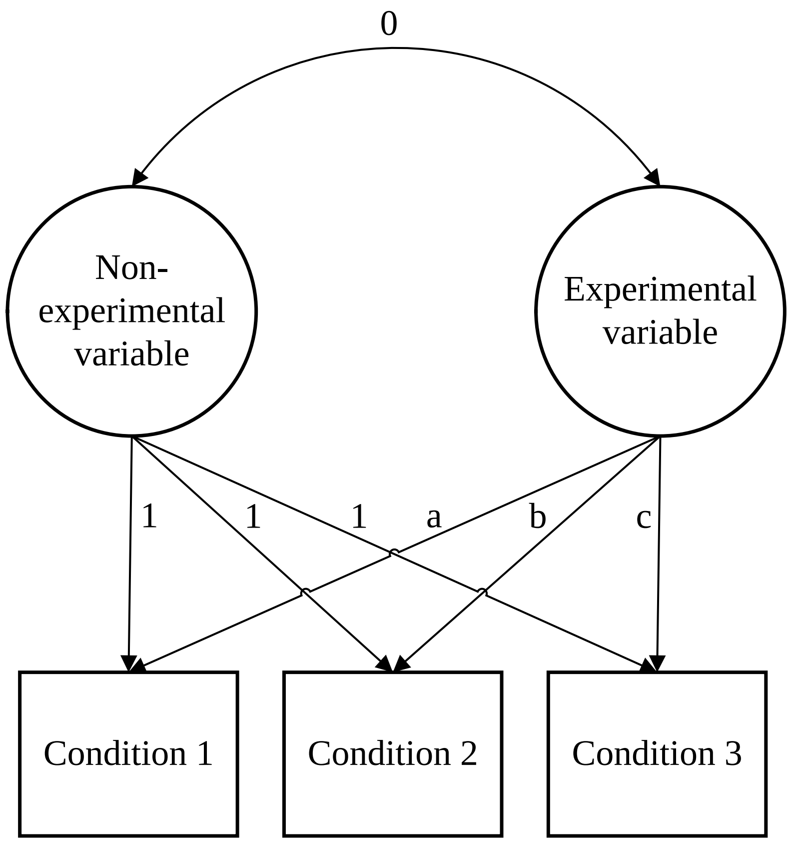

Figure 3. Illustration of an exemplary fixed-links model based on three manifest indicator variables (conditions 1 to 3). The non-experimental latent variable represents variance equally contained in all three conditions, hence, its factor loadings are fixed to the same value (i.e., 1). The experimental latent variable represents the variance caused by the experimental manipulation, hence, its factor loadings are fixed to the theoretically expected trajectory caused by the experimental manipulation. For example, an increasing trajectory would comprise the following fixation of factor loadings: a < b < c.

2 Research questions

The present study focuses on two research questions and the thereby associated necessary prerequisites. Research question 1 (RQ1) has a replicative character: can the relationship between TRP and *g* be replicated? Based on the previous findings of a robust relationship between TRP and *g* (e.g., Rammsayer & Brandler, 2007), it is expected that this relationship can be replicated in the present study. For the purpose of answering RQ1, two prerequisites have to be fulfilled. First, TRP needs to be successfully modeled based on the psychophysical timing tasks DDE, TG, and TOJ, as in the study by Troche and Rammsayer (2009b). Second, *g* needs to be successfully modeled based on a diverse set of cognitive ability tests provided by a modified short version of the Berlin Intelligence Structure (BIS) test (Jäger, Süss, & Beauducel, 1997; Wicky, 2014). However, both latent variables consist of three indicators, thus, represent perfect identified measurement models which yield a trivial fit (Kline, 2011). Therefore, the manifest indicators of each construct need to coercively show a *positive manifold* in order to be reducible to a single factor (Gignac, 2007; Jensen, 1998a).

Research question 2 (RQ2) is concerned with the role of perceptual attention in the context of the TRP hypothesis by clarifying its potential mediating role: is the relationship between TRP and *g* of genuine nature or does perceptual attention account for the formation of this relationship? For the purpose of answering RQ2, four prerequisites have to be fulfilled. First, the previous finding of a relationship between TRP and intelligence has to be replicated. That is, RQ1 has to be confirmed. Second, it has to be verified that the experimental manipulation of complexity worked. Third, a statistically significant experimental latent variable representing perceptual attention needs to be identified for each ECT by means of theory-driven FLM. For this purpose, the fixation of factor loadings for the experimental latent variable needs to be chosen in accordance with the expected increase of complexity across ECT conditions and the thereby associated increased attentional demands on the limited processing resources. For each ECT, the non-experimental latent variable is only considered for further analyses if statistically meaningful. Fourth, based on the three experimental latent variables identified for each ECT, a higher-order latent variable needs to be modeled representing the perceptual aspects of attention common to all ECTs. The same higher-order modeling approach will be conducted for the significant non-experimental latent variables (see Figure 4 for an illustration of the higher-order modeling of perceptual attention). However, as introduced, it has to be considered that the content of the higher-order non-experimental latent variable cannot be determined a priori due to its ambiguous conglomerate character. It is only known that the non-experimental latent variables represent a latency-based conglomerate of all processes independent of the experimental manipulation of complexity. Therefore, the exploratory results associated with the higher-order non-experimental latent variable are discussed cautiously. If all four prerequisites are fulfilled, RQ2 can be addressed by up to date bootstrapped mediation analysis (e.g., B. O. Muthén, L. K. Muthén, & Asparouhov, 2016) further described in chapter 4.4.3 of the results. Three potential findings might result from the mediation analysis. First, perceptual attention might fully mediate the relationship between TRP and *g*, which would strongly question the validity of the TRP hypothesis. Second, perceptual attention might not mediate the relationship, hence, the relationship between TRP and *g* can be considered genuine in nature. The third possibility is that the relationship between TRP and *g* is partially mediated by perceptual attention. Considering these three possible findings, the one found will be discussed in detail.

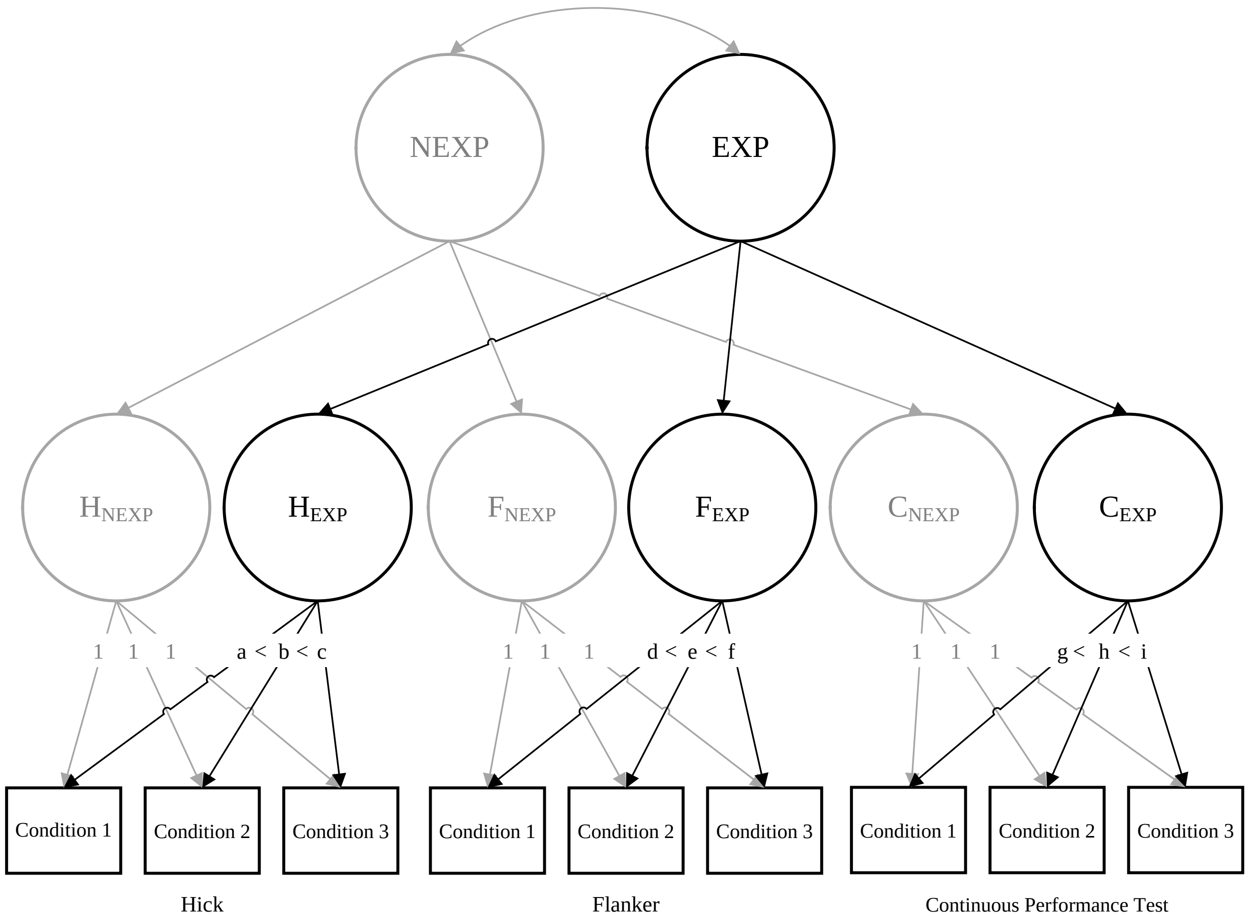

Figure 4. An illustration of the higher-order modeling approach to perceptual attention. For each ECT used (i.e., the Hick paradigm, the Flanker task, and the Continuous Performance Test) an experimental latent variable representing attention is dissociated from a residual non-experimental latent variable representing the non-experimental processes. For example, the factor loadings of the non-experimental Hick variable (H_{NEXP}) are all fixed to the same value (i.e., 1), whereas the factor loadings of the experimental Hick variable (H_{EXP}) are fixed to the theoretically expected increasing trajectory (i.e., a < b < c). Analog modeling is used for the other two ECTs. Based on all three experimental variables (i.e., H_{EXP}, F_{EXP}, and C_{EXP}) dissociated, a higher-order experimental variable (EXP) is modeled to represent perceptual attention. The non-experimental variables (H_{NEXP}, F_{NEXP}, and C_{NEXP}) are only modeled as a higher-order non-experimental variable (NEXP) if considered as statistically meaningful, hence, all variables and paths associated with the non-experimental variables are depicted in light grey within Figure 4.

3 Method

3.1 Subjects

A total of 243 subjects participated in the study. Ten subjects had to be removed due to incorrect test behavior, misunderstanding of the instructions, or exceeding the predefined age-range of 18 to 30 years (see Appendix A for details) and another five subjects were removed due to interindividual outlier correction as reported in the results (chapter 4.1). The sample used for the analyses consisted of 118 women and 110 men ranging in age from 18 to 30 years (mean and standard deviation of age: 22.03 ± 2.94 years). One hundred and thirty-one subjects were from an academic background and 97 subjects were from a vocational background (i.e., subjects with or in an apprenticeship, but without higher education). For a more detailed description of the sample see Appendix B. All subjects reported normal hearing and normal or corrected-to-normal vision. As gratification students received three participation credits for their Bachelor course "Methods II: Experimental Practice", whereas all other subjects were paid 45.00 Swiss franc. Each subject was informed about the study protocol and gave his/her written informed consent. The study was approved by the local ethics committee.

3.2 Assessment of psychometric intelligence

Psychometric intelligence was assessed with the BIS test (Jäger, Süss, & Beauducel, 1997) based on Jäger's (1984) BIS model of intelligence, which classifies cognitive abilities with respect to two facets: the mental operation (processing capacity, processing speed, memory, and creativity) required and the content (figural, verbal, and numeric) processed (see Figure 5). The cross-classification of the two facets (4 operations × 3 contents) results in 12 modal cells, one for every operation-content-combination and each represented by at least three subtests in the full version of the BIS test. The original BIS short version includes 15 of the full version's 45 subtests. For the present study, a modified short version was used based on an unpublished master thesis (Wicky, 2014). In comparison to the original short version, all creativity subtests were removed and one subtest was added to each processing speed and memory cell, otherwise processing capacity would have been overrepresented with two subtests for each content. A description of the 18 subtests used is given in Table 1, in which the abbreviations of the added processing speed and memory subtests are supplemented with the letter n (e.g., RZn). The six added subtests were selected based on reliability analyses and duration of completion. Wicky (2014) reported internal consistencies (Cronbach's α), test-retest reliabilities (r_{tt}), and composite reliabilities as measured with McDonald's (1999) omega (Ω) for processing capacity ($\alpha = .73$, $r_{tt} = .64$, and $\Omega = .79$), processing speed ($\alpha = .70$, $r_{tt} = .85$, and $\Omega = .58$), and memory ($\alpha = .69$, $r_{tt} = .86$, and $\Omega = .63$). The internal consistency for processing capacity reported in the original short version is $\alpha = .51$. Several studies showed that *g* can be extracted based on modified BIS short versions (Beauducel & Kersting, 2002; Süss et al., 2002; Valerius & Sparfeldt, 2014).

After a general instruction to get familiar with the whole procedure, the experimenter guided the subjects through the entire assessment according to the standardized guidelines of the BIS manual. The following working utensils were provided by the experimenter: the test booklet of the original short version with creativity subtests crossed out, a customized test booklet with the six added subtests, an envelope, and a pen. Subjects first solved the warm-up subtest *fragmentary words* (UW) followed by the 18 subtests used for the later analyses. In Table 1 all subtests are listed in order of administration with the process time allowed and the number of items contained. The raw scores were *z*-standardized since the number of items vary in a broad range from six items in the *Charkow* (CH) subtest to 130 items in the *crossing letters* (BD) subtest and, in addition, the BIS manual provides no norms for the modified short version as well as for the age range of the present sample.

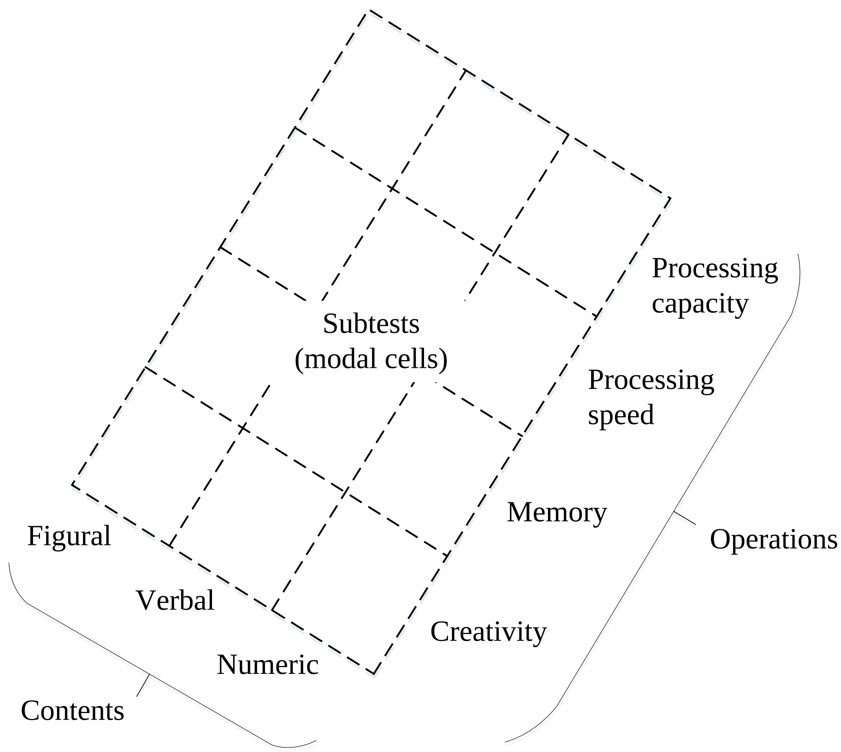

Figure 5. Berlin Intelligence Structure (BIS) model based on Jäger (1984), which classifies cognitive abilities with respect to two facets: mental operations (processing capacity, processing speed, memory, and creativity) and contents (figural, verbal, and numeric). The cross-classification of the two facets (4 operations × 3 contents) results in 12 modal cells, one for every operation-content-combination and each represented by at least three subtests in the full version of the BIS test.

Table 1

BIS subtests (with abbreviation) used in order of administration, supplemented by a brief description, the corresponding operation and content facet, the process time allowed, and the number of items contained

Subtest (abbreviation)	Description	Operation	Content	Process time allowed	Number of items
Fragmentary words (UV)	Complete missing letter in words	S	V	0:50	57
City map (OG)	Recall of buildings in a city map	M	F	1:30 + 1:40	27
Number sequences (ZN)	Completion of number sequences	C	N	3:50	9
Figural analogies (AN)	Geometric analogies of the form A:B = C:?	C	F	1:45	8
X-larger (XG)	Cross numbers that are x greater than the prior number	S	N	1:00	44
Verbal analogies (WA)	Completion of word analogies	C	V	1:30	8
Paired associates (ZP)	Memorize pairs of numbers	M	N	2:00 + 2:00	12
Fact-opinion (TM)	Decide whether fact or opinion	C	V	1:00	16
Crossing letters (BD)	Cross specific letter in line of letters	S	F	0:50	130
Estimation (SC)	Estimation of complex arithmetics	C	N	2:45	7
Story (ST)	Recall of story information	M	V	1:00 + 2:00	22
Charkow (CH)	Completion of figure sequences	C	F	3:00	6
Part-whole (TG)	Cross word in part-whole relation to prior word	S	V	0:40	22
Math operators (RZn)	Complete simple math equations	S	N	0:50	20
Word memory (WMn)	Memorize random words	M	V	0:40 + 1:30	20
Word classification (KWn)	Classification of words (flowers)	S	V	0:30	40
Two-digit numbers (ZZn)	Memorize set of two-digit numbers	M	N	1:00 + 0:50	16
Old English (OEn)	Cross letters of typeface Old English	S	F	0:30	56
Routes memory (WEn)	Memorize city route	M	F	0:30 + 0:40	31

Note. Memorizing time and maximal allowed completion time are given for all memory subtests (e.g., 1:30 + 1:40). English subtest names, abbreviations, and descriptions are based on Süss and Beauducel (2015). C = processing capacity; S = processing speed; M = memory; F = figural; V = verbal; N = numeric.

3.3 Experimental tasks: General apparatus, stimuli, and procedure

The following eight experimental tasks were administered: Hick, Flanker, CPT, SWAPS, DDE, TG, TOJ, and inspection time (IT). SWAPS (Stankov, 2000) and IT (Vickers, Nettelbeck, & Willson, 1972) were administered to answer future research questions not object of the present study, thus, these two tasks are not described in further detail.

Two working stations were used for the administration of the experimental tasks. Working station A was used for the administration of all tasks except TOJ, which was administered at working station B. At working station A, sitting distance to the 18" Samsung SyncMaster 900SL monitor was 55 cm. The display refresh rate was set to 75 Hz. A Dell OptiPlex 760 computer with E-Prime (Psychology Software Tools, 2012) installed was used for task administration. A Cedrus response pad (model RB-830) was used to record the responses, which were logged with an accuracy of ± 1 ms. Loud speakers (Dell model A225) or headphones (Sennheiser model HD 555) were used to present the auditory stimuli. All auditory stimuli and feedback tones were presented with 70 decibel (dB). All visual stimuli as well as all the instructions were presented white on black screen. In all tasks, the instructions had to be repeated to the experimenter. Task-specific information about apparatus and stimuli are reported in the respective task's chapter. Working station B is only used for the administration of TOJ, hence, apparatus and stimuli are reported in the TOJ chapter 3.3.6.

All subjects received a general instruction to get familiar with the apparatus and the overall procedure. The eight experimental tasks were combined into two blocks of administration, one block consisted of Hick, Flanker, CPT, and SWAPS, whereas the other block consisted of DDE, TG, TOJ, and IT. The task sequence within each block was balanced with a

Latin square to avoid position effects (Bradley, 1958). In addition, the block sequence was balanced as well, resulting in 32 different conditions. Breaks were administered after every two tasks in order to avoid fatigue effects.

3.3.1 Hick paradigm

Apparatus and stimuli

Working station A was used for task administration. Stimuli were rectangles (1.6 cm × 1.4 cm) and plus signs (0.5 cm × 0.5 cm). A feedback tone (1,000 Hz) with a duration of 200 ms was used. In the first condition (H0), one rectangle was presented. In the second condition (H1), two rectangles were presented 3 cm apart of each other. In the third condition (H2), four rectangles were used. The lower two rectangles were presented 1.1 cm apart of each other, while the upper two rectangles were presented 3.6 cm apart of each other. The space between the lower and upper two rectangles was 1.4 cm. Stimulus presentation, trial sequence, and response pad setup (with the corresponding finger placement) are presented in Figure 6.

Procedure

In H0, each trial started with the presentation of a rectangle in the center of the screen (except for the first trial, which started after a 1,000 ms black screen after the instructions). After a foreperiod varying randomly between 1,000 ms and 2,000 ms in steps of 333 ms, the imperative stimulus, the plus sign, was presented in the center of the rectangle. The rectangle and the plus sign remained on the screen until the subject pressed the designated response button. In case of a mistake (i.e., pressing the response button before the plus sign appeared) the feedback tone was presented through the loud speakers. The next trial started after an intertrial interval (ITI) of 1,100 ms. H1 was identical to H0, except that two rectangles were presented arranged in a row. After the variable foreperiod, the plus sign was presented in one of the two rectangles and remained on the screen until the subject pressed the designated response button. In case of a mistake (i.e., pressing the response button before the plus sign appeared or pressing the response button corresponding to the other empty rectangle) the feedback tone was presented through the loud speakers. Presentation of the plus sign was balanced. Thus, the plus sign appeared in each of the two rectangles in 50% of the trials. H2 was identical to H1, except that four rectangles arranged in two rows were presented. After the variable foreperiod, the plus sign was presented in one of the four rectangles and remained on the screen until the subject pressed the designated response button. In case of a mistake (i.e., pressing the response button before the plus sign appeared or pressing the response button corresponding to one of the other three empty rectangles) the feedback tone was presented through the loud speakers. The plus sign was presented equiprobably in one of the four rectangles.

The instructions emphasized responding as quickly as possible, but to avoid response errors. The conditions were presented in ascending order. Each condition consisted of 32 trials preceded by eight practice trials. The foreperiod and the position of the plus sign were pseudorandomized. That is, trial sequence in each condition was identical for all subjects. As indicators of individual performance, mean RT based on correct trials were computed separately for H0, H1, and H2. Intraindividual outlier correction is reported in chapter 4.1.

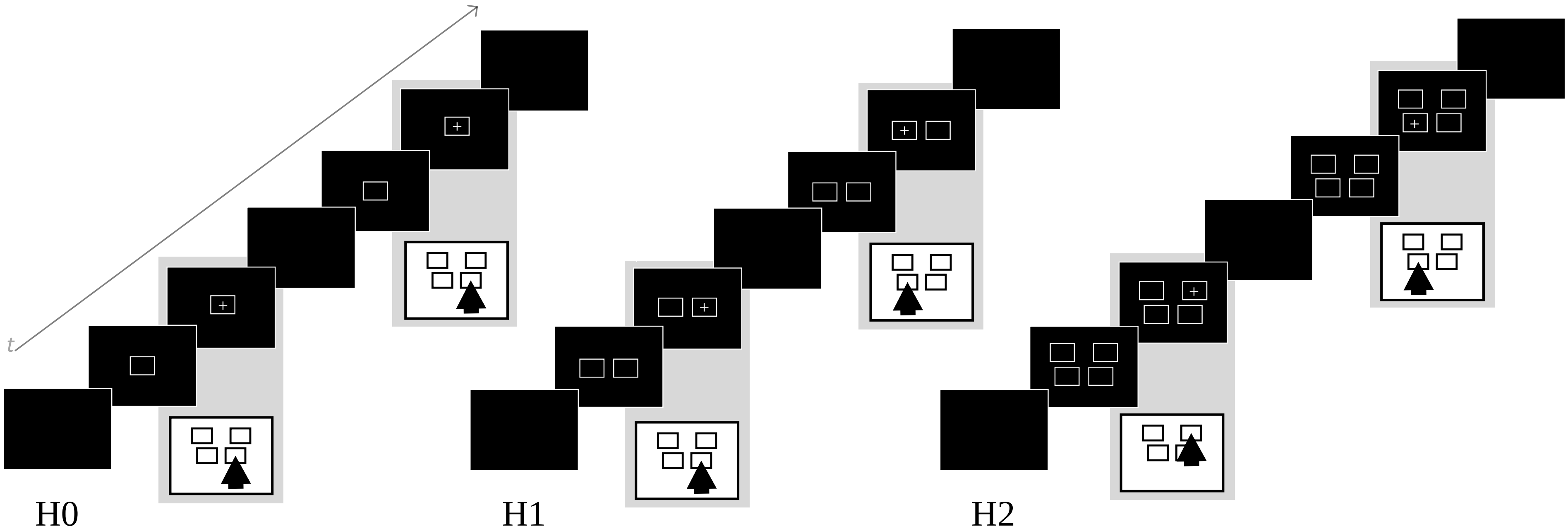

Figure 6. Stimulus presentation, trial sequence, and Cedrus response pad setup for all three Hick conditions H0 to H2. The temporal course of the trial sequence is delineated by the grey drawn-out arrow (*t*) above the trial sequence of condition H0. In H0, subjects were allowed to press the response button with the index finger of their preferred hand. In H1, subjects had to use the right index finger for the lower right response button and the left index finger for the lower left response button. In H2, subjects placed their index fingers as in H1 and, in addition, the right middle finger had to be used to press the upper right response button and the left middle finger had to be used to press the upper left response button. In all conditions, the fingers were placed directly onto the response buttons to avoid movement times. The black arrows indicate the correct answer in the respective exemplary trial.

3.3.2 Flanker tasks

Apparatus and stimuli

Working station A was used for task administration. Stimuli were arrows pointing either to the left (<) or to the right (>) with a height of 0.7 cm and width of 0.5 cm on the screen. The total length of the five equidistant presented arrows (<<<<<, >>>>>, >><>>, and <<><<) in the third condition (F3) was 3 cm. A feedback tone (1,000 Hz) with a duration of 200 ms was used. Stimulus presentation, trial sequence, and response pad setup (with the corresponding finger placement) are presented in Figure 7.

Procedure

In the first condition (F1), each trial started with the presentation of a fixation cross in the center of the screen lasting for 500 ms (except for the first trial, which started after a 1,000 ms black screen after the instructions). After a foreperiod varying randomly between 600 ms and 1,600 ms in steps of 333 ms, the imperative stimulus, an arrow pointing either to the left or to the right, was presented in the center of the screen. The arrow remained on the screen until the subject pressed the designated response button. In case of a mistake (i.e., pressing the response button before the arrow appeared) the feedback tone was presented through the loud speakers. Presentation of arrows pointing to the left and right was balanced. The next trial started after an ITI of 500 ms. The second condition (F2) was identical to F1, with the difference that subjects now had to indicate in what direction the arrow was pointing by pressing the left button if the arrow pointed to the left or the right button if the arrow pointed to the right. In case of a mistake (i.e., pressing the response button before the arrow appeared or indicating the wrong directional response) the feedback tone was presented through the loud speakers. Presentation of arrows pointing to the left and right was balanced. F3 was identical to F2, except that the imperative stimulus was now flanked by either congruent (<<<<< or >>>>>) or incongruent (>><>> or <<><<) distractor arrows. Subjects had to indicate in what direction the center arrow was pointing by pressing the left or right response button. In case of a mistake (i.e., pressing the response button before the arrow appeared or indicating the wrong directional response) the feedback tone was presented through the loud speakers. The presentation of the imperative stimuli with the according congruent or incongruent distractor arrows was balanced. That is, each of the four different trial types (<<<<<, >>>>>, >><>>, and <<><<) was presented in 25% of all trials.

The instructions emphasized responding as quickly as possible, but to avoid response errors. The conditions were presented in ascending order. F1 and F2 consisted of 32 trials preceded by eight practice trials. F3 consisted of 64 trials preceded by 16 practice trials. The foreperiod and the presentation of trials were pseudorandomized in each respective condition. That is, trial sequence in each condition was identical for all subjects. Before the computation of individual performance measures, F3 was split into F4* and F5*. F4* comprised all congruent trials and F5* comprised all incongruent trials. As indicators of individual performance, mean RT based on correct trials were computed separately for F1, F2, and F5*. Intraindividual outlier correction is reported in chapter 4.1.

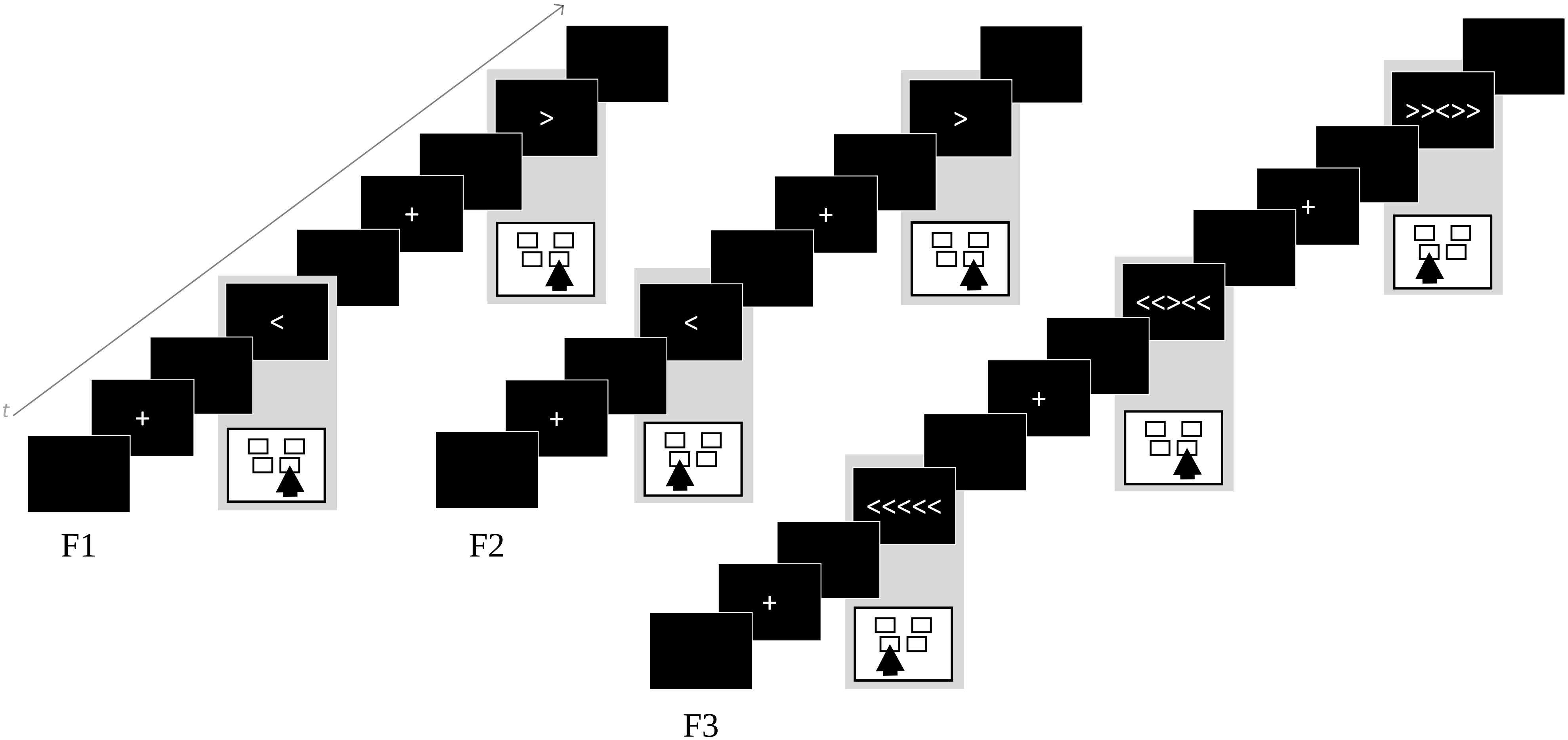

Figure 7. Stimulus presentation, trial sequence, and Cedrus response pad setup for all three Flanker conditions F1 to F3. The temporal course of the trial sequence is delineated by the grey drawn-out arrow (*t*) above the trial sequence of condition F1. In F1, subjects were allowed to press the response button with the index finger of their preferred hand. In F2 and F3, subjects had to use the right index finger for the right response button and the left index finger for the left response button. In all conditions, the fingers were placed directly onto the response buttons to avoid movement times. The black arrows indicate the correct answer in the respective exemplary trial. The upper two response buttons were inactive and not used for the administration of Flanker.

3.3.3 Continuous performance test

Apparatus and stimuli

Working station A was used for task administration. Imperative stimuli in the first (CPT1) and second condition (CPT2) were X's (0.9 cm x 0.6 cm). For the third condition (CPT3), the same X's were used, but in cursive typeface. The following distractor letters were used for CPT2: K, D, W, R, S, M, G, and A. For CPT3, a non-cursive X was added to the set of distractor letters. Stimulus presentation, trial sequence, and response pad setup (with the corresponding finger placement) are presented in Figure 8.

Procedure

In CPT1, each trial started with the presentation of the imperative stimulus (an X) for 200 ms in the center of the screen followed by a 1,000 ms black screen response window (during these 1,200 ms responses were logged). Subjects had to press the designated response button for each X that appeared. After a black screen ITI varying randomly between 0 ms and 1,000 ms in steps of 333 ms, the next X was presented. In each condition, the response window and the ITI were perceived as one continuous black screen (see Figure 8). In CPT2, each trial started with the presentation of a letter (one of the eight distractor letters) for 200 ms in the center of the screen followed by a 1,000 ms black screen response window (during these 1,200 ms responses were logged). Subjects had to press the designated response button only for each X that appeared. After an ITI varying randomly between 0 ms and 1,000 ms in steps of 333 ms, the next letter was presented. The presentation of distractor letters was balanced. In CPT3, each trial started with the presentation of a letter (one of the nine distractor letters, but not the newly added X) for 200 ms in the center of the screen followed by a 1,000 ms black screen response window

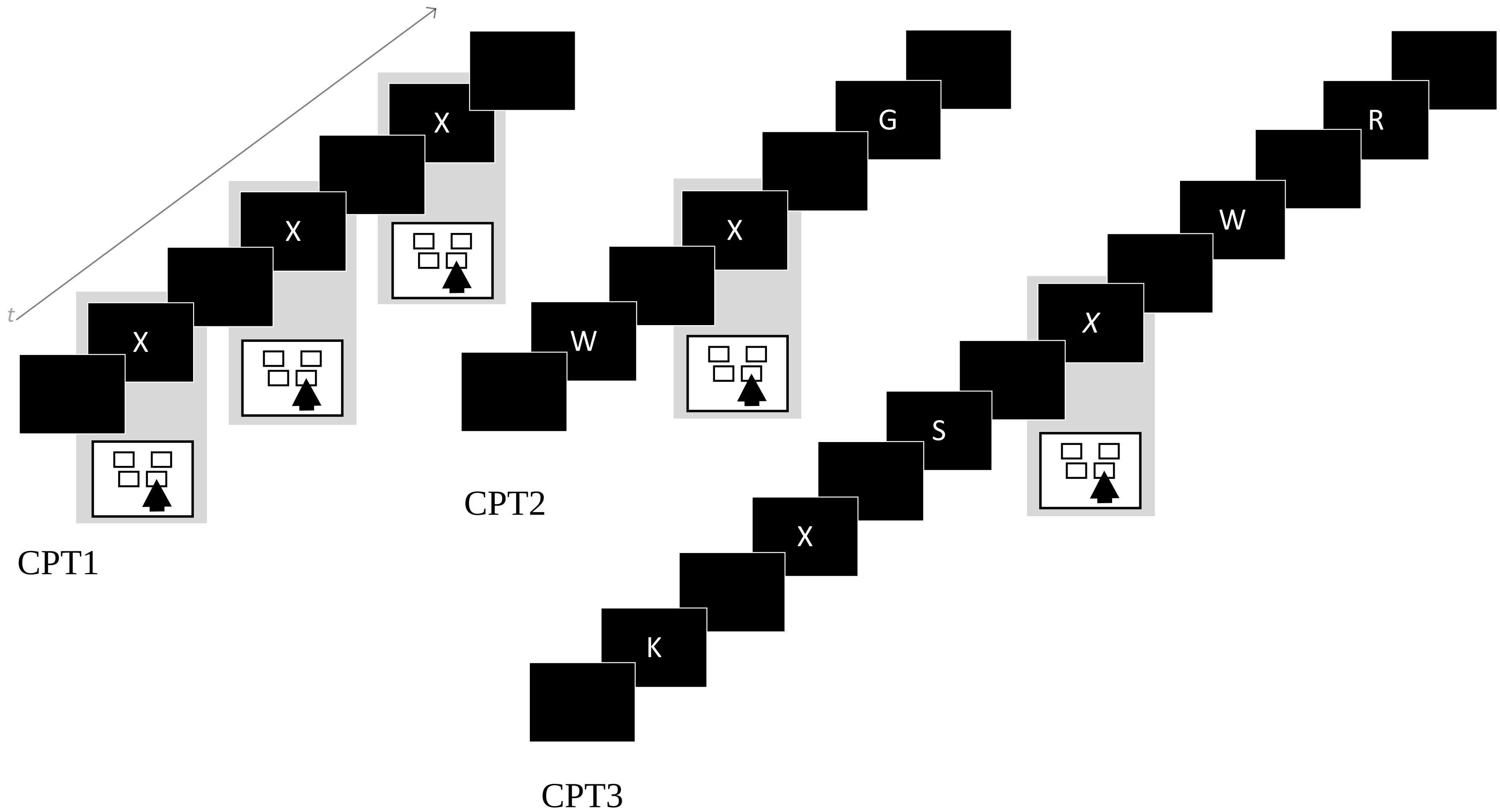

Figure 8. Stimulus presentation, trial sequence, and Cedrus response pad setup for all three CPT conditions CPT1 to CPT3. The temporal course of the trial sequence is delineated by the grey drawn-out arrow (*t*) above the trial sequence of condition CPT1. The response window and the intertrial interval are depicted as one continuous black screen between two presented letters. In all CPT conditions, subjects were allowed to press the response button with the index finger of their preferred hand. In all conditions, the finger was placed directly onto the response button to avoid movement times. The black arrows indicate the correct answer in the respective exemplary trial. The other three response buttons were inactive and not used for the administration of CPT.

(during these 1,200 ms responses were logged). Subjects had to press the designated response button only for each cursive X that appeared. After an ITI varying randomly between 0 ms and 1,000 ms in steps of 333 ms, the next letter was presented. The presentation of distractor letters was balanced.

The instructions emphasized responding as quickly as possible, but to avoid response errors. As in the Hick paradigm and the Flanker task, the first trial of each condition started after a 1,000 ms black screen after the instructions. The conditions were presented in ascending order. CPT1 consisted of 32 trials preceded by eight practice trials. CPT2 consisted 120 trials (24 imperative stimuli and 96 distractor letters) preceded by 10 practice trials (two imperative stimuli and eight distractor letters). CPT3 consisted of 240 trials (24 imperative stimuli and 216 distractor letters) preceded by 20 practice trials (two imperative stimuli and 18 distractor letters). The letter sequence and the ITI were pseudorandomized. That is, trial sequence in each condition was identical for all subjects. As indicators of individual performance, mean RT based on commissions were computed separately for CPT1, CPT2, and CPT3. Intraindividual outlier correction is reported in chapter 4.1.

3.3.4 Duration discrimination with empty intervals

Apparatus and stimuli

Working station A was used for task administration. Stimuli were auditory empty intervals presented through headphones. Each empty interval was marked by a 3 ms onset and a 3 ms offset click (i.e., a white noise burst). The duration of the standard interval was 50 ms, while the duration of the comparison interval varied according to the weighted up-down method (Kaernbach, 1991) as described in the procedure. Visual feedback stimuli were plus signs for correct answers and minus signs for incorrect answers. A pictorial example of a single trial was used to instruct the subjects (see Figure 9).

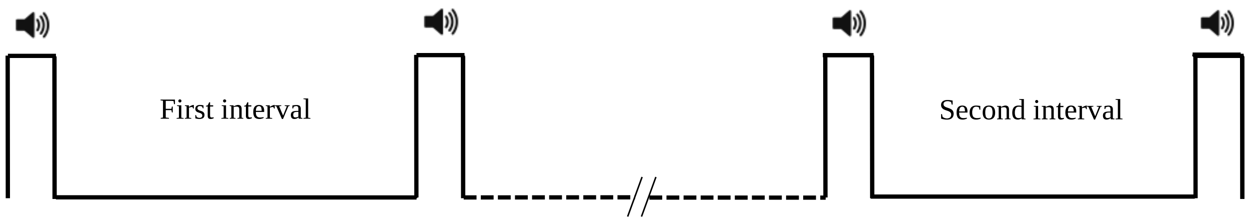

Figure 9. The pictorial example of a single trial used to instruct the subjects.

Procedure

A single trial consisted of one standard interval and one comparison interval separated by an interstimulus interval (ISI) of 900 ms. Subjects started the first trial by pressing the lower right button of the Cedrus response pad and the auditory presentation began 1,000 ms later. Subjects had to indicate whether the first or the second interval was longer by pressing the response button labeled “first interval longer” or “second interval longer”. The button “first interval longer” corresponded to the lower left button of the Cedrus response pad and had to be pressed with the left index finger, while the button “second interval longer” corresponded to the lower right button of the Cedrus response pad and had to be pressed with the right index finger. After a subject’s response, visual feedback was displayed on screen for 1,500 ms. The next trial started 600 ms after the presentation of the feedback.

DDE consisted of two randomly interleaved series with 32 trials each, resulting in a total of 64 trials. In each series, the duration of the comparison interval varied according to the weighted up-down method (Kaernbach, 1991) to estimate the 25%- and the 75%-difference-threshold of the individual psychometric function. That is, the 25%-difference-threshold, where the shorter interval was incorrectly judged to be the longer interval in 25% of the trials, and the 75%-difference-threshold, where the longer interval was correctly judged to be the longer interval in 75% of the trials. The duration of the first 25%-difference-threshold comparison interval was 15 ms shorter than the standard interval (i.e., 35 ms), while the duration of the first 75%-difference-threshold comparison interval was 15 ms longer than the standard interval (i.e., 65 ms). For trials 1 to 6 in the 25%-difference-threshold series, the duration of the comparison interval was increased by 3 ms when the subject correctly judged the standard interval to be longer and decreased by 9 ms when the shorter comparison interval was falsely judged to be longer. For trials 7 to 32, the comparison interval was increased by 2 ms if the standard interval was correctly judged to be longer and decreased by 6 ms if the shorter comparison interval was falsely judged to be longer. The opposite step sizes were employed for the estimation of the 75%-difference-threshold. Within each series, the order of presentation of the standard and the comparison interval was randomized, but with both intervals being presented first equiprobably.

The instructions emphasized accuracy and pointed out that there is no need to respond as quickly as possible. Subjects had to repeat the instructions to the experimenter with the help of the pictorial example (see Figure 9). The main block of 64 trials was preceded by five practice trials to ensure that subjects did understand the task. As indicator of individual discrimination performance, the mean difference between the standard and the comparison interval was computed for the last 20 trials of each series. Thus, estimates of the 25%- and 75%-difference-thresholds in relation to the 50 ms standard interval were obtained. Next, the difference limen (DL: Luce & Galanter, 1963) was computed for each subject, which is half of the interquartile range [(75%-difference-threshold value – 25%-difference-threshold value)/2]. A better performance is represented by a smaller DL. For the later analyses, all DL's were inverted, so that a higher DL represented a better performance. Interindividual outlier correction is reported in chapter 4.1.

3.3.5 Temporal generalization

Apparatus and stimuli

Working station A was used for task administration. Auditory stimuli were white-noise bursts presented through headphones. The duration of the standard stimulus was 75 ms, while the durations of the non-standard stimuli were 42 ms, 53 ms, 64 ms, 86 ms, 97 ms, and 108 ms. Visual feedback stimuli were plus signs for correct answers and minus signs for incorrect answers.

Procedure

During an initial learning phase, subjects were given five trials to memorize the duration of the standard stimulus. After the learning phase, subjects worked through eight experimental blocks. In each block, the standard stimulus was presented twice and each non-standard stimulus was presented once. The presentation of the eight stimuli was randomized within each block. For every presented stimuli, subjects had to decide whether or not the duration matched the duration of the previously memorized standard stimulus by pressing either the response button labeled "same duration as the standard stimulus" or "not the same duration as the standard stimulus". The button "same duration as the standard stimulus" corresponded to the lower left button of the Cedrus response pad and had to be pressed with the left index finger, while the button "not the same duration as the standard stimulus" corresponded to the lower right button of the Cedrus response pad and had to be pressed with the right index finger. After a subject's response, visual feedback was displayed on screen for 1,500 ms. The next trial started 700 ms after the presentation of the feedback.

The instructions emphasized accuracy and pointed out that there is no need to respond as quickly as possible. Subjects had to repeat the instructions to the experimenter before the learning phase. As indicator of individual discrimination performance, an index of response dispersion (IRD: McCormack, Brown, Maylor, Darby, & Green, 1999) was computed. For the present study, the IRD is the frequency of "same duration as the standard stimulus"-responses to the actual standard stimulus divided by the sum of relative frequencies of "same duration as the standard stimulus"-responses to all seven stimuli presented. The IRD would be 1.0 if all "same duration as the standard stimulus"-responses were given exclusively to the standard stimuli and none to the non-standard stimuli. Therefore, a higher IRD indicates a better discrimination performance. Interindividual outlier correction is reported in chapter 4.1.

3.3.6 Temporal order judgment

Apparatus and stimuli

Working station B comprised a black viewer box (30 cm × 21 cm × 26.5 cm) with a red light-emitting diode (LED) inside and a 17" Samsung SyncMaster 172 N flat screen. Sitting distance to the LED (with a diameter of 0.5 cm) was 78 cm. A Smart 100x computer was used to administer TOJ (programmed in Turbo Pascal) and a Cherry keyboard (model G81-300) was used to record responses. Headphones (Sennheiser model HD 555) were used to present the auditory stimuli, while the visual stimuli were presented with the LED. Visual feedback was given with the Samsung flat screen, which was placed on the right side of the black viewer box.

Auditory stimuli were 1,000 Hz square waves tones presented at an intensity of 70 dB. Visual stimuli were generated by the red LED. Visual feedback stimuli were plus signs for correct answers and minus signs for incorrect answers. Instructions were given on a separate sheet of paper.

Procedure

First, the subjects solved five practice trials followed by a single experimental block that consisted of two randomly interleaved series with 32 trials each. In one series, the light was preceded by the tone and in the other series, the tone was preceded by the light. In each trial of both series, subjects had to decide whether the light or the tone was presented first by either pressing the response button labeled “light first” or “tone first” (matched to the Enter and Plus key of the numeric keypad). Subjects were allowed to use the index finger of their preferred hand. In each trial, both stimuli simultaneously terminated 200 ms after the onset of the second stimulus. The instructions emphasized accuracy and pointed out that there is no need to respond as quickly as possible.

In both series, the initial stimulus onset asynchrony (SOA) was set to 70 ms and each subsequent SOA varied according to the weighted up-down method (Kaernbach, 1991), which converged to the level of 75% of correct responses. While a correct response decreased the SOA by 6 ms, each incorrect response increased the SOA by 18 ms. As indicator of individual discrimination performance, the mean SOA was computed for the last 20 trials of each series and then averaged across series. A better performance in TOJ is represented by a smaller value. For the later analyses, the individual performance values were inverted, so that a higher value indicated a better performance. Interindividual outlier correction is reported in chapter 4.1.

3.4 Time course of study and facility

The psychometric assessment of intelligence lasted approximately 70 minutes and was always in groups from two to six subjects in a 19 m^2 room with six working stations. The assessment of psychometric intelligence was separated from the administration of the experimental tasks by a minimum of three to a maximum of 13 days. The administration of all experimental tasks (including breaks) lasted approximately 90 to 100 minutes. The working stations A and B were placed in a 10 m^2 sound-attenuated chamber. In both sessions, room conditions were held constant for all subjects (i.e., constant lighting and aeration). The data collection lasted for 18 months.

3.5 Statistical analyses

All analyses were performed in R (R Core Team, 2016) and RStudio (RStudio Team, 2012) was used as editor. In addition to the base functions of R, the following packages were used: corrplot (Wei, 2013), dplyr (Wickham & Francois, 2014), lavaan (Rosseel, 2012), psych (Revelle, 2015), readxl (Wickham, 2015), reshape2 (Wickham, 2007), rprime (Mahr, 2015), and semPlot (Epskamp, 2014).

For SEM/CFAs, all models were examined by means of the chi-square (χ^2) test statistic and approximate fit indices. A non-significant χ^2-value is desired since it indicates that the implied model does not substantially differ from the empirical data (Kline, 2011). However, in complex models and big samples, the χ^2-value turns out to be significant even with minor differences between the implied model and the data (Barrett, 2007). Therefore, in addition to the χ^2-test statistic, the following fit indices were used to establish whether a model was acceptable or not: Comparative Fit Index (CFI; Bentler, 1990), the Root Mean Square Error of

Approximation (RMSEA; Steiger, 1990), and the Standardized Root Mean Square Residual (SRMR; Kline, 2011). A CFI ≥ .95 (Hu & Bentler, 1999), a RMSEA ≤ .08 (Browne & Cudeck, 1993), and a SRMR ≤ .08 (Hu & Bentler, 1999) are considered a good fit. The Akaike Information Criterion (AIC) was used to compare competing models in relation to parsimony. A model with a lower AIC is considered the more parsimonious model (Kline, 2011).

4 Results

4.1 Correction of outliers

The outlier correction for Hick, Flanker, and CPT was on an intraindividual basis, whereas the outlier correction for the psychophysical timing tasks DDE, TG, and TOJ was on an interindividual basis.

Intraindividual outlier correction for Hick, Flanker, and CPT

First, extreme outliers were identified by plotting all trials of all subjects within an ECT condition (Figure C.1 in the Appendix C depicts the intraindividual outlier correction described here). For all three ECTs, the lower bound was set to 100 ms, which is based on the approximate physiological limit of the speed of reaction (Luce, 1986). For Hick and Flanker, the upper bound was based on the visual inspection of all plotted trials, whereas for CPT, the upper bound was set by the fix duration of the response window (i.e., the 1,200 ms during which responses were logged). Second, after the removal of invalid trials exceeding the lower and upper bound, all responses exceeding the intraindividual mean RT by three intraindividual standard deviations were considered as outliers and removed (cf. Moosbrugger et al., 2006). The thereby removed mean number of trials for each ECT condition are reported in Table 2.

Table 2
The mean number of trials removed per subject based on intraindividual outlier correction for the Hick, the Flanker, and the CPT conditions

	H0	H1	H2	F1	F2	F5*	CPT1	CPT2	CPT3
Mean trials removed	0.57	0.49	0.96	0.60	1.28	2.19	0.70	0.18	0.18

Note . H0 to H1 = Hick conditions; F1 to F5* = Flanker conditions; CPT1 to CPT3 = CPT conditions.

Interindividual outlier correction for DDE, TG, and TOJ

For each psychophysical timing task, interindividual mean and standard deviation were computed for the performance measures. All subjects exceeding the mean by three standard deviations were considered as outliers and removed. This led to the removal of five subjects in total, four in DDE and one in TG (Figure C.2 in the Appendix C depicts the interindividual outlier correction for DDE, TG, and TOJ)

4.2 Descriptive statistics and correlations

Mean, standard deviation, minimum, maximum, skewness, kurtosis, and the Shapiro-Wilk normality test (SWT) for the 18 BIS subtests based on raw scores before *z*-standardization are reported in Table 3. The same descriptive statistics for the Hick, the Flanker, and the CPT conditions as well as for the psychophysical timing tasks are reported in Table 4. In addition, the Spearman-Brown corrected (Cortina, 1993) split-half reliabilities (based on the odd-even method) are provided for the Hick, the Flanker, and the CPT conditions. Descriptive statistics for the Hick and the Flanker error rates as well as the CPT omission and false alarm rates are reported in Table D.1 in Appendix D.

The SWT was computed for all variables, because the use of parametric tests requires normally distributed data. For 16 out of 18 BIS subtests (see Table 3) and 10 out of 12 experimental tasks (see Table 4) the SWT indicated a significant deviation from normality. However, as with any other test of significance, a large sample size increases the chance of significance, thus, skewness and kurtosis were inspected as well. According to Finney and DiStefano (2006), skewness values outside the range of -2.0 to 2.0 and kurtosis values outside the range of -7.0 to 7.0 indicate severely non-normal data. Other authors, such as Lienert and

Table 3

Descriptive statistics for the 18 BIS subtests based on raw scores before z-standardization

BIS subtest	*M*	*SD*	Range		Skewness	Kurtosis	SWT
			Min	Max			*p*-value
City map (OG)	15.35	4.36	4	26	- 0.05	- 0.56	.05
Number sequences (ZN)	4.11	2.58	0	9	0.35	- 1.07	< .001
Figural analogies (AN)	3.36	1.61	0	8	0.09	- 0.54	< .001
X-larger (XG)	19.87	8.07	1	44	0.33	0.28	< .001
Verbal analogies (WA)	3.58	2.02	0	8	0.09	- 0.86	< .001
Paired associates (ZP)	6.05	2.33	0	12	0.16	- 0.13	< .001
Fact-opinion (TM)	9.34	3.54	2	16	- 0.06	- 1.10	< .001
Crossing letters (BD)	53.70	9.22	28	82	0.38	0.28	< .01
Estimation (SC)	3.56	1.96	0	7	0.00	- 0.97	< .001
Story (ST)	8.42	3.51	1	20	0.47	- 0.03	< .001
Charkow (CH)	3.02	1.65	0	6	- 0.13	- 0.79	< .001
Part-whole (TG)	11.51	3.17	1	20	- 0.73	0.66	< .001
Math operators (RZn)	10.13	4.06	1	20	0.22	- 0.24	< .01
Word memory (WMn)	7.03	2.60	1	17	0.59	0.50	< .001
Word classification (KWn)	22.94	6.29	1	36	- 0.50	0.40	< .01
Two-digit numbers (ZZn)	6.86	2.78	0	19	0.67	1.05	< .001
Old English (OEn)	32.28	5.98	4	48	- 0.38	1.59	< .01
Routes memory (WEn)	18.86	5.65	1	31	- 0.18	- 0.03	.11

Note. BIS = Berlin Intelligence Structure; SWT = Shapiro-Wilk normality test; based on $N = 228$.

Table 4

Descriptive statistics for the performance measures of the Hick, the Flanker, and the CPT conditions as well as for the three psychophysical timing tasks DDE, TG, and TOJ

Performance measure	M (in milliseconds)	SD (in milliseconds)	Range Min (in milliseconds)	Range Max (in milliseconds)	Skewness	Kurtosis	Shapiro-Wilk p-value	r_{tt}
Hick								
H0	249	29	190	373	0.82	1.11	< .001	.91
H1	305	32	242	447	0.79	1.17	< .001	.92
H2	377	49	262	624	0.98	2.44	< .001	.94
Flanker								
F1	263	34	202	432	1.19	2.34	< .001	.96
F2	371	46	300	699	2.06	10.45	< .001	.94
F5*	589	146	360	1642	3.09	15.64	< .001	.97
CPT								
CPT1	223	18	179	299	0.47	1.15	< .01	.94
CPT2	378	35	269	481	0.20	0.11	.29	.91
CPT3	483	49	334	677	0.38	0.59	< .05	.92
PPT								
DDE	21.43	9.04	6.08	51.50	0.76	0.27	< .001	
TG [IRD]	.67	.09	.42	.86	- 0.28	- 0.03	.06	
TOJ	97.43	30.25	25.45	178.60	0.31	- 0.41	< .05	

Note. All M and SD values are in milliseconds except for TG which is the IRD; CPT = continuous performance test; H0-H2 = Hick conditions; F1-F5* = Flanker conditions; CPT1-CPT3 = CPT conditions; PPT = psychophysical timing tasks; DDE = duration discrimination with empty intervals; TG = temporal generalization; IRD = index of response dispersion; TOJ = temporal order judgment; SWT = Shapiro-Wilk normality test; r_{tt} = Spearman-Brown corrected (Cortina, 1993) split-half reliability (odd-even-method).

Raatz (1998), proposed a more conservative range for skewness (-0.5 to 0.5). Corresponding to the critical values of Finney and DiStefano, only F2 and F5* showed sever non-normality. According to Lienert and Raatz, all Hick and Flanker conditions were not normally distributed. In order to assure that the present analyses were not biased by deviations from normality, non-parametric tests were computed in addition to the parametric tests. Furthermore, the Satorra-Bentler scaling to correct the χ^2-values (SBχ^2) and the standard errors was used for SEM (Satorra & Bentler, 1994). The non-parametric tests are reported alongside to the parametric tests or with a reference to the respective Appendix. For correlations, the parametric Pearson's product-moment correlation coefficient (in the further course referred to as correlation) was used, since this coefficient showed to be robust and to withstand violations of normality (Bishara & Hittner, 2012).

The correlations of the BIS subtests are reported in Table 5. For the most part, the BIS subtest correlation matrix showed significant positive correlations with few exceptions. The two figural processing speed subtests *crossing letters* (BD) and *old English* (OEn), which were strongly correlated, $r = .53$, $p < .001$, showed rather low as well as several non-significant correlations with other BIS subtests. Only four other correlations were found to be non-significant: *figural analogies* (AN) and *word memory* (WMn), $r = .13$, $p = .055$, *Charkow* (CH) and WMn, $r = .11$, $p = .101$, *word classification* (KWn) and *estimation* (SC), $r = .09$, $p = .178$, SC and WMn, $r = .12$, $p = .075$. The BIS subtests scores were aggregated within their respective operation facet in order to provide the three manifest indicators for *g* modeling. Each aggregate score represented the mean of the six operation specific subtests (i.e., processing speed mean based on BD, OEn, TG, KWn, XG, and RZn; processing capacity mean based on AN, CH, WA,

Table 5

Correlations among the 18 BIS subtests

	AN	BD	CH	KWn	OEn	OG	RZn	SC	ST	TG	TM	WA	WEn	WMn	XG	ZN	ZP
BD	.13*																
CH	.52***	.08															
KWn	.25***	.25***	.17*														
OEn	.08	.53***	- .05	.31***													
OG	.26***	.15*	.33***	.21**	.11												
RZn	.44***	.26***	.49***	.33***	.18**	.31***											
SC	.32***	.10	.41***	.09	.02	.22***	.50***										
ST	.28***	.13[a]	.17*	.41***	.19**	.31***	.29***	.24***									
TG	.31***	.21**	.21**	.51***	.22***	.24***	.40***	.16*	.39***								
TM	.29***	.19**	.30***	.54***	.17*	.20**	.33***	.26***	.37***	.45***							
WA	.51***	.09	.43***	.38***	.04	.26***	.46***	.36***	.34***	.38***	.48***						
WEn	.21**	.11	.35***	.16*	.05	.38***	.37***	.23***	.29***	.22***	.17**	.19**					
WMn	.13[a]	.14*	.11	.37***	.20**	.25***	.19**	.12	.50***	.23***	.30***	.24***	.18**				
XG	.31***	.24***	.40***	.39***	.11	.22***	.59***	.44***	.35***	.43***	.38***	.37***	.30***	.21**			
ZN	.45***	.20**	.56***	.27***	.09	.30***	.57***	.46***	.26***	.34***	.32***	.44***	.33***	.14*	.62***		
ZP	.22***	.07	.22***	.20**	.09	.24***	.34***	.29***	.37***	.20**	.15*	.17**	.33***	.29***	.24***	.31***	
ZZn	.22**	.13[a]	.24***	.24***	.07	.29***	.31***	.28***	.34***	.24***	.29***	.18**	.36***	.25***	.40***	.38***	.36***

Note. For abbreviations of subtests see Table 3.

[a]Coefficients were rounded up to .13 and showed p -values > .05.

*p < .05. **p < .01. ***p < .001.

TM, ZN, and SC; memory mean based on OG, WEn, ST, WMn, ZP, ZZn). The positive strong correlations (see Table 6) among the aggregate scores indicated the presence of a *positive manifold*, a necessary requirement for a successful modeling of a *g* factor.

Table 6
Correlations among the three BIS aggregate scores processing speed, processing capacity, and memory

	speed	capacity
speed		
capacity	.59***	
memory	.51***	.52***

Note. Speed = processing speed; capacity = processing capacity
*** $p < .001$.

The correlations among the experimental performance measures are reported in Table 7. Each ECT showed moderate to strong correlations within its respective conditions. The lowest correlation was found between F1 and F5*, $r = .32$, $p < .001$, whereas the strongest correlation was found for H0 and H1, $r = .73$, $p < .001$. In addition, the conditions of the different ECTs showed moderate to strong correlations among each other, with one exception of a weak correlation between F5* and CPT2, $r = .26$, $p < .001$. The psychophysical timing tasks showed only weak correlations among each other, with the highest correlation found between DDE and TG, $r = .19$, $p = .004$, whereas the correlation between TG and TOJ was the lowest and just reached statistical significance, $r = .13$, $p = .046$. Furthermore, the correlations between the psychophysical timing tasks and the different ECT conditions were rather weak and most of them were non-significant. Most of the significant correlations between the psychophysical timing tasks and the ECT conditions were found in relation to the Flanker conditions (see Table

7). DDE correlated only with CPT1, $r = .17$, $p = .011$, whereas TG correlated only with H0, $r = .19$, $p = .004$, and H1, $r = .15$, $p = .019$.

The correlations of all performance measures with intelligence are presented in the two bottom rows of Table 7. A similar picture is shown in relation to the mean of all *z*-standardized BIS subtests (denoted as *z*-score in Table 7) and the *g* factor scores (denoted as *g*-score in Table 7). All ECT conditions were weakly correlated with both measures of intelligence, except for some CPT conditions. CPT1 did not correlate with the *z*- and the *g*-score, whereas CPT2 just failed to reach statistical significance in relation to the *z*-score ($p = .051$). For the three ECTs, a tendency for stronger correlations with intelligence is shown for more complex conditions. The psychophysical timing tasks correlated weakly with both intelligence measures. The *z*- and the *g*-scores showed a perfect correlation ($r = .99$, $p < .001$).

4.3 Research question 1: Temporal resolution power and intelligence

The latent variables TRP and *g* are based on three indicator variables each, thus, represent perfect identified measurement models which cannot be analyzed meaningfully by means of a χ^2-test or fit indices (Kline, 2011). However, based on the *positive manifold* depicted in the BIS correlation matrices (see Table 5 or Table 6) and the positive, albeit low, correlations among the psychophysical timing tasks (see Table 7), it was expected that the necessary prerequisite of a *positive manifold* was met for both constructs. In addition, to validate the *g* model used in the present study, its *g* factor scores were correlated with *g* factor scores of different *g* models (as e.g. suggested by Beaujean, 2015). The *g* factors of the different models were virtually identical (see Appendix E for details).

Table 7

Correlations among the conditions of the three elementary cognitive tasks, the three psychophysical timing tasks, a manifest intelligence score (z-score), and the g factor score

	H0	H1	H2	F1	F2	F5*	CPT1	CPT2	CPT3	DDE	TG	TOJ	*z*-score
H1	.73***												
H2	.60***	.70***											
F1	.60***	.47***	.40***										
F2	.52***	.59***	.55***	.50***									
F5*	.35***	.39***	.49***	.32***	.63***								
CPT1	.55***	.48***	.52***	.41***	.46***	.33***							
CPT2	.44***	.41***	.42***	.34***	.50***	.26***	.49***						
CPT3	.43***	.47***	.41***	.31***	.43***	.31***	.35***	.68***					
DDE	.11	.03	.10	.14*	.16*	.07	.17*	.03	.04				
TG	.19**	.15*	.09	.09	.21*	.12	.10	.09	.10	.19**			
TOJ	.11	.13[a]	.12	.12	.15*	.16*	.12	.09	.12	.18**	.13*		
z-score	-.18**	-.18**	-.24***	-.19**	-.24***	-.28***	-.05	-.13[a]	-.20**	-.23***	-.19**	-.23***	
g-score	-.20**	-.19**	-.26***	-.21**	-.25***	-.30***	-.07	-.14*	-.20**	-.23***	-.20**	-.23***	.99***

Note. CPT = continuous performance test; H0-H2 = Hick conditions; F1-F5* = Flanker conditions; CPT1-CPT3 = CPT conditions; DDE = duration discrimination with empty intervals; TG = temporal generalization; TOJ = temporal order judgment; *z*-score = the mean of all *z*-standardized BIS subtests; *g*-score = *g* factor scores derived from the *g* measurement model used in the present study.

[a]Coefficients were rounded up to .13 and showed *p*-values > .05.

*$p < .05$. **$p < .01$. ***$p < .001$.

The relationship between TRP and *g* was modeled as predictive path from TRP to *g* as depicted in Figure 10. A good model fit was observed, $SB\chi^2(8) = 3.034$, $p = .932$, CFI = 1.000, RMSEA = .000, SRMR = .015, with a significant path coefficient, $\beta = .60$, $p = .002$, indicating substantial predictive strength of TRP explaining 36.48% of variance in *g*. All standardized factor loadings and error scores presented in Figure 9 were significant (at least $p < .01$).

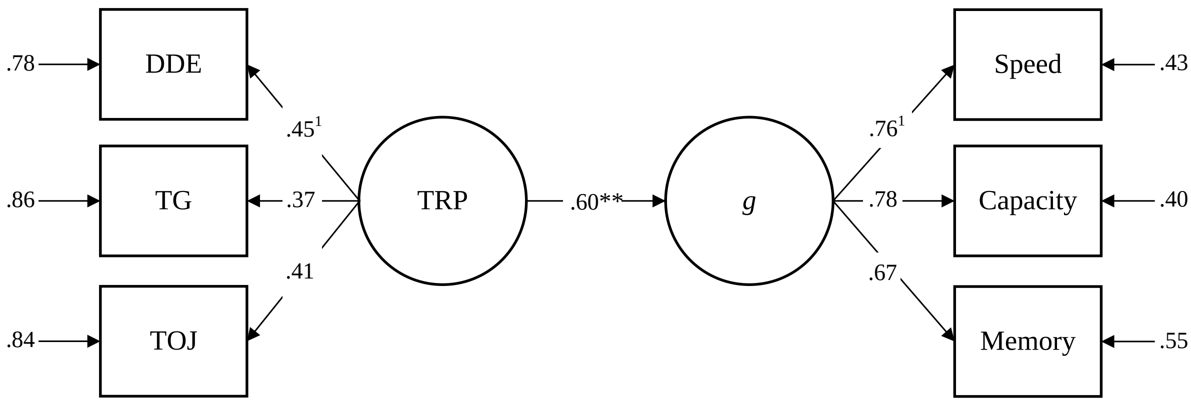

Figure 10. The structural model of the relationship between TRP and *g*. TRP is based on the three psychophysical timing task used, whereas *g* is based on the BIS aggregate scores of processing speed (Speed), processing capacity (Capacity), and memory (Memory). All depicted factor loadings and errors were significant with at least $p < .01$. The marker loadings were DDE for TRP and Speed for *g* (as indicated by the superscript 1).

4. **$p < .01$.

intelligence

The present chapter is divided in three subchapters. First, the manipulation check of complexity is presented. Second, the two steps of isolating perceptual attention from the non-experimental processes are presented followed by the third subchapter presenting the mediation analysis.

4.4.1 Manipulation check: complexity

The descriptive statistics showed that the mean RTs increased across conditions in each ECT (see Table 4). Therefore, one-way repeated measures analyses of variance (ANOVAs) were used to test whether RTs were influenced by the experimental manipulation of complexity. Mauchly's test of sphericity was violated for Hick, $\chi^2(2) = 82.44$, $p < .001$, for Flanker, $\chi^2(2) = 336.58$, $p < .001$, and for CPT, $\chi^2(2) = 62.27$, $p < .001$, thus, the degrees of freedom (*df*) of the *F*-Tests were adjusted according to the Greenhouse-Geisser-method (Greenhouse & Geisser, 1959). The ANOVAs revealed that the mean RTs differed significantly between the Hick conditions, $F(1.54, 349.58) = 1692.26$, $p < .001$, the Flanker conditions, $F(1.12, 254.24) = 1039.62$, $p < .001$, and the CPT conditions, $F(1.62, 367.74) = 5326.63$, $p < .001$. Furthermore, the Tukey post-hoc tests determined that all conditions differed significantly from each other in each ECT (all pairwise comparisons at $p < .001$). In addition, the non-parametric Friedman rank sum tests and its according post-hoc tests also showed that the experimental manipulation of complexity worked for each ECT (see Appendix F).

4.4.2 Isolating attention with fixed-links modeling

In order to examine the interplay between TRP, perceptual attention, and *g*, fixed-links measurement models had to be identified for each ECT. Therefore, variance caused by the experimental manipulation of complexity was disentangled from variance independent of the experimental manipulation of complexity (i.e., the non-experimental processes constant across ECT conditions) by means of FLM. For the non-experimental variable, the unstandardized factor loadings were all fixed to 1. For the experimental variable, the unstandardized factor loadings had to be identified first, since there is no standard approach in fixing factor loadings of an experimental variable in FLM. For this purpose, different increasing trajectories were modeled based on the rationale that complexity was increased across ECT conditions. In all fixed-links measurement models, the experimental and the non-experimental variable were forced to be independent by fixing their correlation to zero. For the further course of this dissertation, the experimental and the non-experimental variable for the fixed-links measurement models are abbreviated with the respective ECT's first letter and a lower case letter indicating the respective fixed-links variable. As an example, the experimental variable of the Hick paradigm is abbreviated as H_{EXP} and the non-experimental variable as H_{NEXP}. The process of identifying appropriate factor loadings for each ECT is described in the following three paragraphs. Table 8 shows the tested factor fixations and the fit statistics of all models referred to in the rest of this chapter.

Hick: Fixed-links measurement models

Four theory-driven trajectories were modeled for H_{EXP}: an increasing trajectory according to the bits of information contained in each condition (model 1), a linear increase (model 2), a monotonic increase based on the number of possible stimulus locations (model 3), and a quadratic increase (model 4). Out of these four models, model 3 was selected since it fitted the data best, $SB\chi^2(1) = 0.096$, $p = .756$, CFI = 1.000, RMSEA = .000, SRMR = .008. The variance of H_{EXP}, $z = 7.41$, $p < .001$, and H_{NEXP}, $z = 3.51$, $p < .001$, were both significant. In addition, model 3 was the most parsimonious model (AIC = 226.182) compared to the models 1, 2, and 4 (see Table 8). Model 3 is depicted in Figure 11 with the Flanker and the CPT fixed-links measurement models.

Table 8

Fixation of factor loadings and fit statistics for the fixed-links measurement models of Hick, Flanker, and CPT

ECT	Model	Fixed factor loadings	$SB\chi^2$	*df*	*p*	CFI	RMSEA	SRMR	AIC
Hick	1	0,1,2	3.677	1	.055	.989	.108	.057	232.206
	2	1,2,3	0.682	1	.409	1.000	.000	.021	227.029
	3	1,2,4	0.096	1	.756	1.000	.000	.008	226.182
	4	1,4,9	1.745	1	.186	.997	.057	.036	228.718
Flanker	5	0,1,3	5.631	1	.018	.876	.143	.075	1120.570
	6	1,2,4	0.609	1	.435	1.000	.000	.027	1112.797
	7	1,2,6	1.277	1	.259	1.000	.035	.046	1115.379
	8	1,4,16	0.333	1	.564	1.000	.000	.014	1111.842
CPT	9	0,1,2	0.004	1	.950	1.000	.000	.001	176.080
	10	1,2,3	19.761	1	< .001	.894	.287	.095	196.659
	11	1,2,4	28.603	1	< .001	.844	.348	.121	207.346
	12	1,4,9	9.275	1	.002	.953	.191	.060	185.346

Note. The column "fixed factor loadings" indicates the factor loadings of the respective experimental latent variable. ECT = elementary cogntive task; $SB\chi^2$ = Satorra-Bentler scaled χ^2; CFI = Comparative Fit Index; RMSEA = Root Mean Square Error of Approximation; SRMR = Standardized Root Mean Square Residual; AIC = Akaike Information Criterion; CPT = Continuous Performance Test.

Flanker: Fixed-links measurement models

The identical fixations of factor loadings were used as for Hick, but with the difference that the trajectory was based on four conditions (F1, F2, F4*, and F5*), but only three conditions (F1, F2, and F5*) were used as indicators. As an example, a linear trajectory based on four conditions would result in the according fixation of factor loadings: 1, 2, 3, and 4. However, condition F4* was omitted and, hence, the following fixation of factor loadings resulted for a linear trajectory: 1, 2, and 4. Evaluating the models presented in Table 8, only model 8 represented the data well, $SB\chi^2(1) = 0.333$, $p = .564$, CFI = 1.000, RMSEA = .000, SRMR =

.014. Both, the variance of F_{EXP}, $z = 4.75$, $p < .001$, and F_{NEXP}, $z = 2.13$, $p = .034$, were significant. Model 5 did not represent the data well, $SB\chi^2(1) = 5.631$, $p = .018$, CFI = .876, RMSEA = .143, SRMR = .075. Model 6 showed a negative and non-significant estimated variance of F_{NEXP}, $z = -.70$, $p = .483$. In addition, model 8 was the most parsimonious model (AIC = 1111.842) compared to the models, 5, 6, and 7 (see Table 8). Model 8 is depicted in Figure 11 with the Hick and the CPT fixed-links measurement models.

CPT: Fixed-links measurement models

The identical fixations of factor loadings were used as for Hick. Model 9 represented the data best, $SB\chi^2(1) = 0.004$, $p = .950$, CFI = 1.000, RMSEA = .000, SRMR = .001 and was the most parsimonious model (AIC = 176.080) compared to the models 10, 11, and 12. In addition, the variances of C_{EXP}, $z = 6.62$, $p < .001$, and C_{NEXP}, $z = 6.39$, $p < .001$, were both significant. Model 10 showed a negative and non-significant estimated variance of C_{NEXP}, $z = -1.08$, $p = .282$. Model 11 did not fit the data well, $SB\chi^2(1) = 28.603$, $p < .001$, CFI = .844, RMSEA = .348, SRMR = .121. Furthermore, model 12 did not fit the data well, $SB\chi^2(1) = 9.275$, $p = .002$, CFI = .953, RMSEA = .191, SRMR = .060. Model 9 is depicted in Figure 11 with the Hick and the Flanker fixed-links measurement models.

Modeling the higher-order latent variable of perceptual attention and the higher-order latent variable of the non-experimental processes

Based on the fixed-links measurement models identified for Hick, Flanker, and CPT, a higher-order experimental latent variable (EXP) representing perceptual attention and a higher-order non-experimental latent variable (NEXP) representing the non-experimental processes

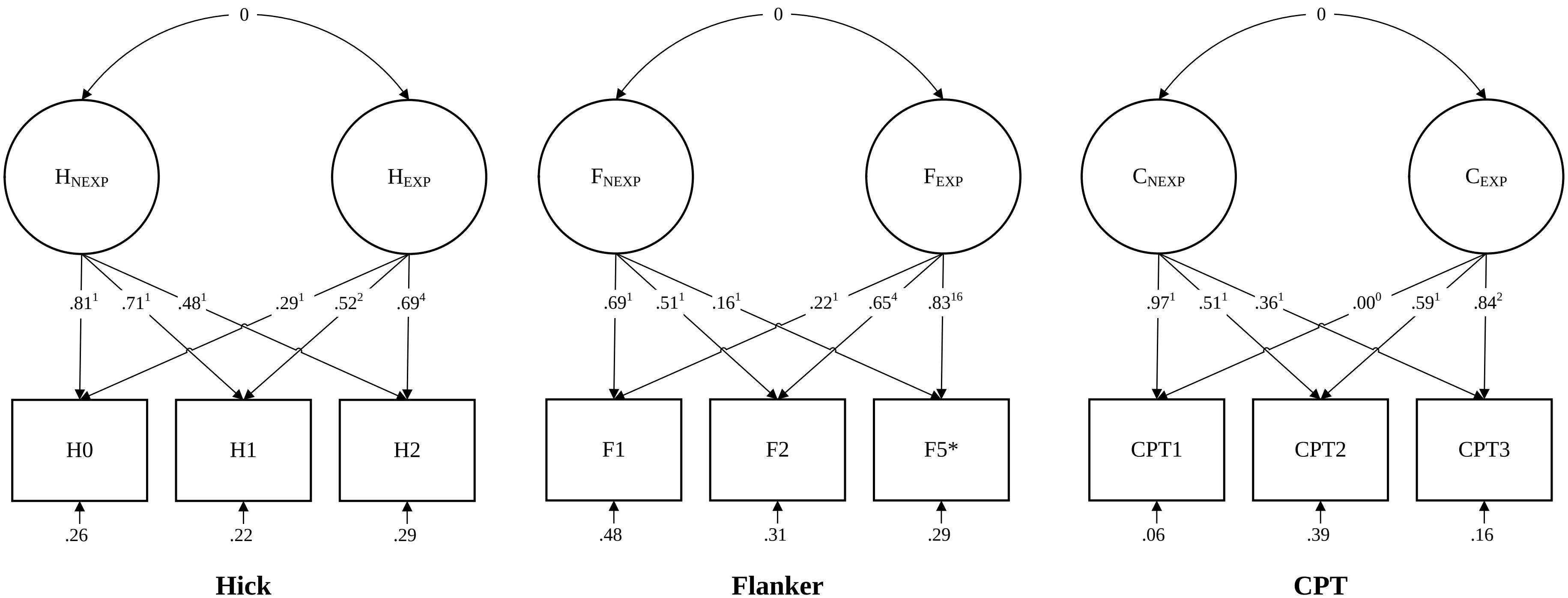

Figure 11. An illustration of the Hick, Flanker, and CPT fixed-links measurement models selected for the further analyses of the present study. The superscript numbers above the standardized factor loadings indicate the unstandardized factor loadings used for fixation. For each ECT, an experimental latent variable (e.g., H_{EXP} for Hick) was dissociated from a non-experimental latent variable (e.g., H_{NEXP} for Hick). The latent variables were forced to be independent. All errors were significant at least with $p < .05$, except for CPT1 ($p = .643$).

were modeled (see Figure 12). The EXP was based on H_{EXP}, F_{EXP}, and C_{EXP}, whereas the NEXP was based on H_{NEXP}, F_{NEXP}, and C_{NEXP}.

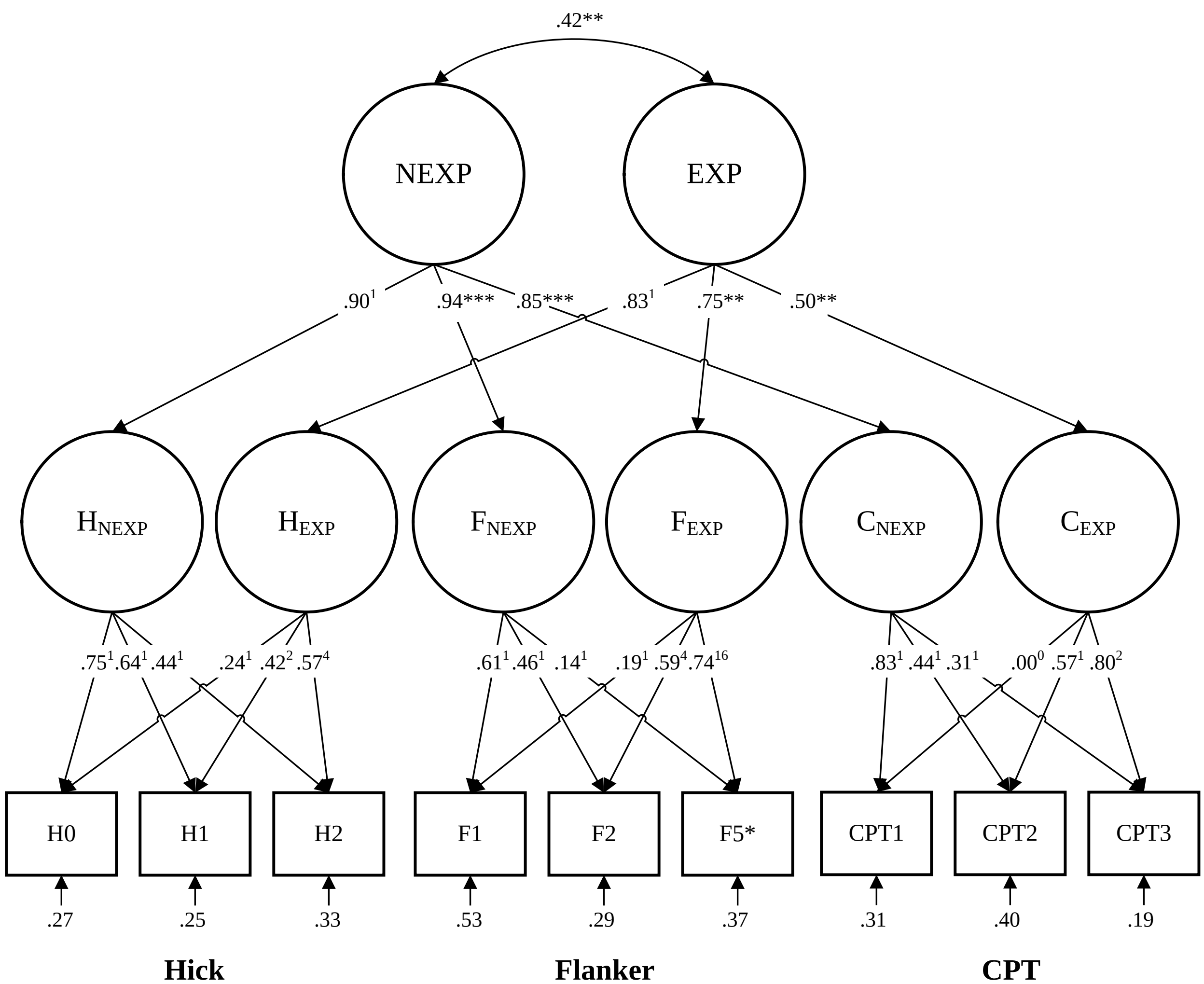

Figure 12. An illustration of the higher-order structural model based on the three fixed-links measurement models derived for Hick, Flanker, and CPT. Considering the fixed-links measurement model, the superscript numbers above the standardized factor loadings indicate the unstandardized factor loadings used for fixation. For the higher-order experimental (EXP) and non-experimental latent variable (NEXP) the marker loadings were H_{NEXP} for NEXP and H_{EXP} for EXP (as indicated by the superscript 1). All errors were significant at least with $p < .01$.
$^{**}p < .01$. $^{***}p < .001$.

The higher-order model showed a satisfactory fit, $SB\chi^2(23) = 50.972$, $p < .001$, CFI = .953, RMSEA = .073, SRMR = .039. The freely estimated factor loadings of EXP and NEXP were all significant (at least with $p < .01$) and the variance of EXP, $z = 2.64$, $p = .008$, as well as of NEXP, $z = 3.83$, $p < .001$, was significant. The EXP and NEXP significantly correlated, $r = .42$, $p = .006$. If the correlation between EXP and NEXP was fixed to 0, a worse model fit resulted, $SB\chi^2(24) = 60.093$, $p < .001$, CFI = .939, RMSEA = .081, SRMR = .086. A $SB\chi^2$-difference test (Satorra & Bentler, 2001) showed that the model with the correlation fixed to 0 was significantly worse than the model with the freely estimated correlation, $SB\chi^2(1) = 11.135$, $p < .001$.

4.4.3 Mediation analysis

First, the principle of mediation and the appropriate mediation method to be used are introduced. Second, the correlations among the four constructs are reported followed by the two predictor models used to evaluate the predictive power of TRP in EXP and NEXP as well as the predictive power of EXP and NEXP in *g*. Third, the mediation model is presented.

The principle of mediation

A simple mediation model evaluates how a predictor variable *x* exerts its effect on a criterion *y*, but with an intervening variable *z* located casually between *x* and *y*. Baron and Kenny (1986) introduced the *causal steps approach*, which helps to illustrate and explain the principle of mediation. The *causal steps approach* is supposed to help researchers decide whether a variable *z* functions as a mediator for the two variables *x* and *y* by casually interpreting a set of four regression hypotheses about these three variables. In a first step, it is investigated whether there is evidence for a statistical significant regression of the predictor *x* on criterion *y* (denoted as total effect β_c in Figure 13). In a second step, it is investigated whether predictor *x* predicts the potential mediating variable *z* (β_a path in Figure 13), followed by the third step, in which it is investigated whether the potential mediating variable *z* predicts the criterion *y* (β_b path in Figure 12) controlled for the predictor *x*. In the fourth step, it is investigated how the mediator *z* influences the prediction of the criterion *y* through the predictor *x* ($\beta_{c'}$ in Figure 13). If all four steps are fulfilled and $\beta_{c'}$ is close to zero, then *z* is deemed as a mediator. If $\beta_{c'}$ is not zero, but significantly weakened compared to β_c, then it is spoken of a partial mediation.

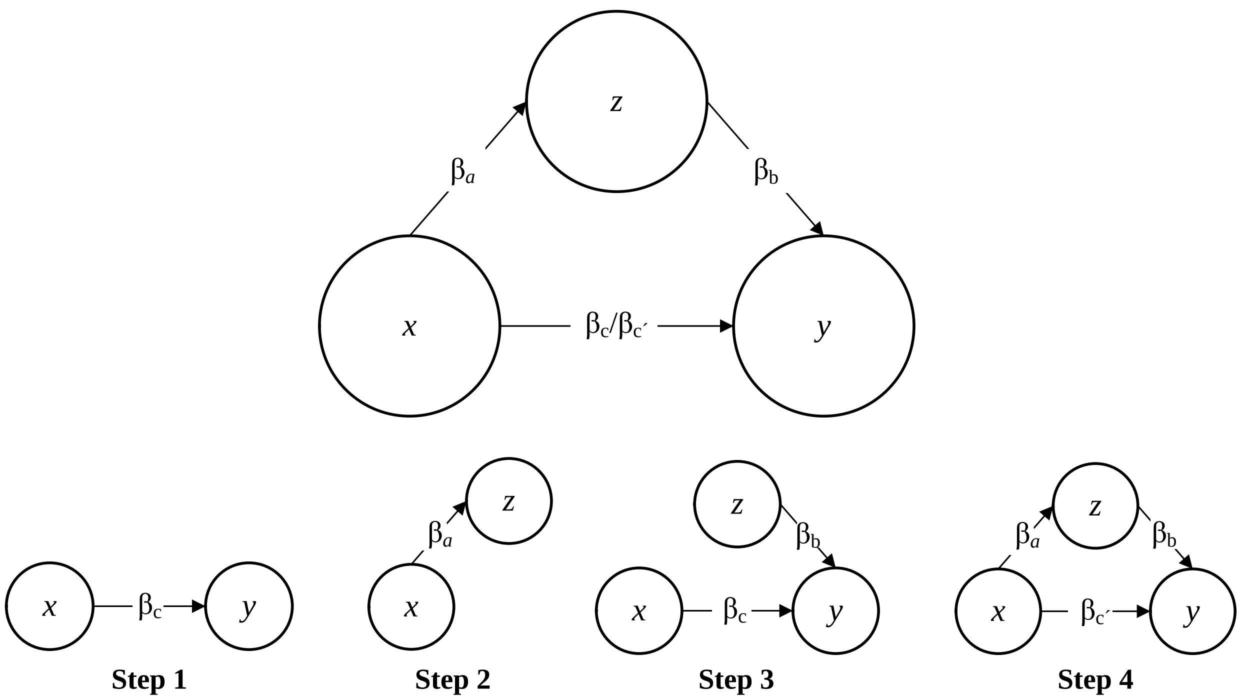

Figure 13. An illustration of the *causal steps approach* introduced by Baron and Kenny (1986). The lower part of Figure 13 depicts each step separately, whereas the upper part of Figure 13 depicts the integrated mediation model. For the present study, the *causal steps approach* is only used to illustrate the principle of mediation.

Despite being used in virtually all fields of social sciences, the *casual steps approach* was heavily criticized (Hayes, 2009; Hayes, Preacher, & Myers, 2011; LeBreton, Wu, & Bing, 2009). For example, Hayes (2009) remarked that the *casual steps approach* is not statistically testing an indirect effect β_{ab} (product term of the two paths β_a and β_b as presented in Figure 13) per se, the one thing it is supposed to "test", but rather infers its existence from the set of four hypotheses. Further major points of criticism came from simulation studies, which showed that the *casual steps approach* had low statistical power compared to other tests of mediation (Fritz & MacKinnon, 2007; MacKinnon, Lockwood, Hoffman, West, & Sheets, 2002). For detailed overview on the criticism and the statistical shortcomings of the *casual steps approach* see LeBreton and colleagues (2009).

Inferences about β_{ab} need to be drawn based on an empirically derived bootstrap sampling distribution of β_{ab} (Hayes, 2009; Preacher & Hayes, 2004). That is, the original sample is resampled with replacement in order to generate a new sample of the exact same sample size as the original sample. This process is repeated k-times with at least k = 1000 (MacKinnon, 2008), but it is recommended to obtain up to k = 5000 (Hayes, 2009) bootstrap samples. For each of these k bootstrap samples, β_{ab} is estimated. To test whether β_{ab} is statistically different from zero, the bootstrapped sampling distribution has to be rearranged so that the k estimates of β_{ab} are sorted from the lowest to the highest estimate. Based on this rearranged distribution, the 95% confidence interval is computed by identifying the values that correspond to the 2.5% and 97.5% percentiles. Based on this 95% percentile confidence interval (pCI), the null hypothesis (i.e., β_{ab} = 0) can be rejected with 95% confidence, if the zero does not fall between the lower and upper bound of the pCI. There are several variations of bootstrapped CI (see Davison & Hinkley, 2005). However, recent simulation studies showed that the pCI method outperforms other types of bootstrapped CI considering type I error rates, statistical power, and coverage rates (Biesanz, Falk, & Savalei, 2010; Falk, 2016; Falk & Biesanz, 2015; B. O. Muthén et al., 2016).

Correlations among temporal resolution power, perceptual attention, intelligence, and the non-experimental processes

First, all four latent variables (TRP, EXP, *g*, and NEXP) were combined as correlation model (see Figure 14), which showed a satisfactory fit, $SB\chi^2(81) = 132.190$, $p < .001$, CFI = .951, RMSEA = .053, SRMR = .051. The highest correlation was found between TRP and *g*, $r = .60$, $p < .001$. TRP also correlated significantly with the EXP, $r = -.31$, $p = .026$, and the NEXP, $r = -.41$, $p = .003$. Additionally, EXP and NEXP were significantly correlated, $r = .42$, $p = .003$. In relation to *g*, both, the EXP, $r = -.50$, $p < .001$, as well as the NEXP, $r = -.16$, $p = .043$, were significantly correlated.

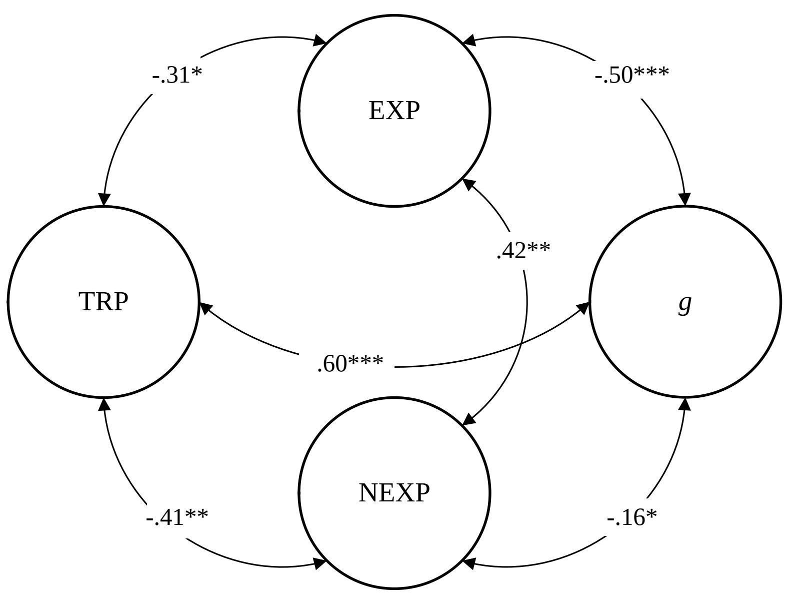

Figure 14. Correlations among the four latent variables TRP, *g*, EXP, and NEXP. Indicator variables and lower levels of the higher-order EXP/NEXP-model were omitted.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Predictive models of temporal resolution power, perceptual attention, intelligence, and the non-experimental proc

The predictive power of TRP in relation to EXP and NEXP (left model in Figure 15 denoted as TRP-predictor model) as well as the predictive power of EXP and NEXP in relation to *g* (right model in Figure 15 denoted as mediator-predictor model) were evaluated. The TRP-predictor model showed a satisfactory fit, $SB\chi^2(48) = 74.622$, $p = .008$, CFI = .964, RMSEA = .049, SRMR = .038. TRP was a significant predictor of EXP, $\beta_{a1} = -.31$, $p = .039$, and NEXP, $\beta_{a2} = -.41$, $p = .017$. The residual correlation between EXP and NEXP was not significant, $r = .34$, $p = .078$. The mediator-predictor model showed a satisfactory fit, $SB\chi^2(48) = 104.243$, $p < .001$, CFI = .939, RMSEA = .072, SRMR = .056. EXP and NEXP were significantly correlated, $r = .42$, $p = .003$, but only EXP was a significant predictor of *g*, $\beta_{b1} = -.52$, $p = .001$, while NEXP did not significantly predict *g*, $\beta_{b2} = .05$, $p = .728$. In addition, Figure 15 also reports the correlations (in brackets below the β-values) for both models when specified as correlation models instead of predictive models.

Bootstrap mediation analysis

The two mediators EXP and NEXP were modeled as parallel mediators in the relationship between TRP and *g* (see Figure 16). The model showed a satisfactory fit, $SB\chi^2(81) = 132.190$, $p < .001$, CFI = .951, RMSEA = .053, SRMR = .051. TRP significantly predicted *g*, $\beta_{c'} = .57$, $p = .005$, as well as EXP, $\beta_{a1} = -.31$, $p = .034$, and NEXP, $\beta_{a2} = -.41$, $p = .009$. Only EXP significantly predicted *g*, $\beta_{b1} = -.43$, $p = .010$, while NEXP did not significantly predict *g*, $\beta_{b2} = .26$, $p = .079$. In addition, the residual correlation between EXP and NEXP was not significant, $r = .34$, $p = .053$.

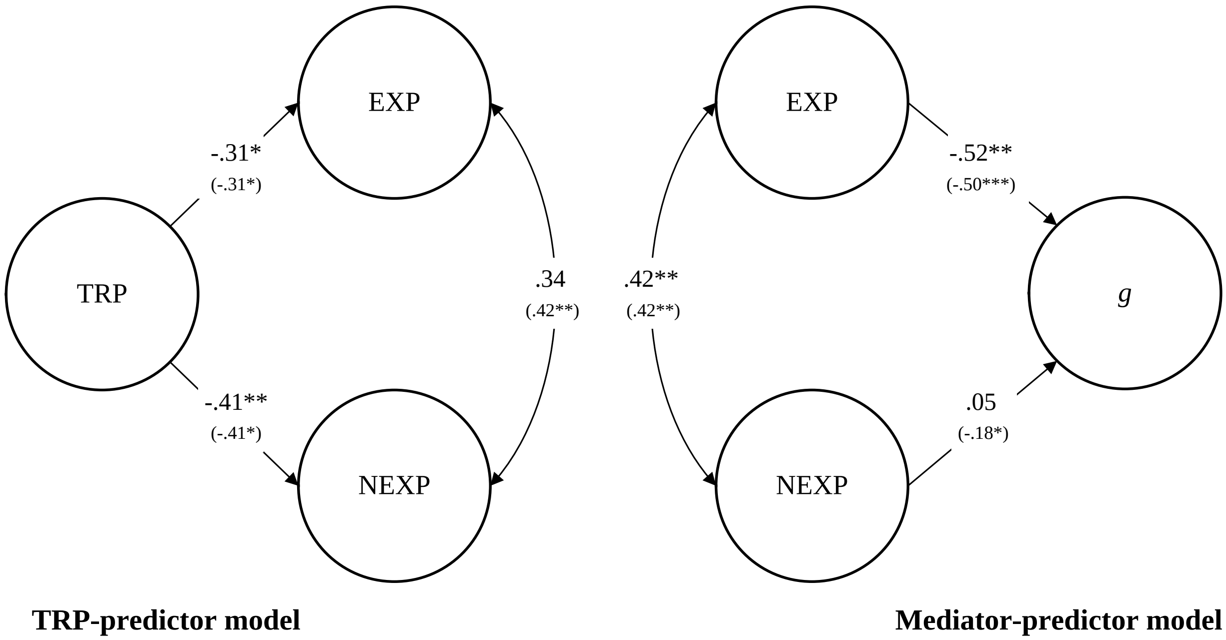

Figure 15. The predictive power of TRP in relation to EXP and NEXP (TRP-predictor model) and the predictive power of EXP and NEXP in relation to g (mediator-predictor model). Correlations are reported in brackets below the β-values.
$^{*}p < .05$. $^{**}p < .01$.

The standardized indirect effect *ab1*, $\beta_{ab1} = .13$, is the product term of the TRP-EXP prediction, $\beta_{a1} = -.31$, and the EXP-g prediction, $\beta_{b1} = -.43$. The standardized indirect effect *ab2*, $\beta_{ab2} = -.11$, is the product term of the TRP-NEXP prediction, $\beta_{a2} = -.41$, and the NEXP-g prediction, $\beta_{b2} = .26$. In order to test the significance of β_{ab1} and β_{ab2}, $k = 5000$ bootstrap samples were generated of which 99.5% (i.e., 4975 samples) converged successfully. For both indirect effects, the 95% pCIs were computed. The pCI [-.06, .57] of β_{ab1} did include the zero, thus, it can be concluded that β_{ab1} was not significantly different from zero at $p < .05$ (two-tailed). For β_{ab2}, the pCI [-.95, .01] indicated that β_{ab2} was not significant either. The bootstrapped distributions of the 4975 estimated indirect effects *ab1* and *ab2* are displayed in Figure G.1 in Appendix G.

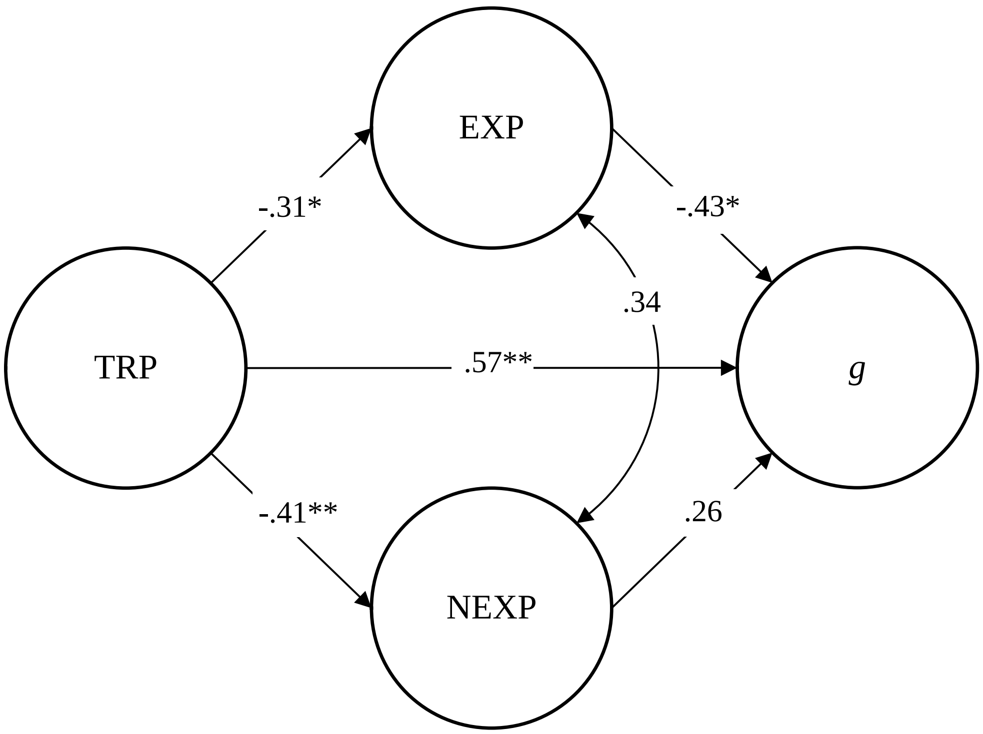

Figure 16. The parallel multiple mediator model with EXP and NEXP specified as mediators of the TRP-*g*-relationship.
*p < .05. **p < .01.

5 Discussion

The TRP hypothesis refers to the idea that temporal acuity of the central nervous system accounts for speed and efficiency of information processing and, thus, underlies individual differences in intelligence (e.g., Helmbold et al., 2007). The functional relationship between TRP and intelligence has been reported repeatedly (Haldemann et al., 2012; Helmbold & Rammsayer, 2006; Helmbold et al., 2007; Rammsayer & Brandler, 2007). Because attention is involved in both, temporal as well as non-temporal information processing (Brown, 2008b; Carroll, 1993; Schweizer et al., 2005), the relationship between TRP and intelligence could alternatively be explained by attention as common source of variance. However, the influence of attention on the relationship between TRP and intelligence has never been systematically examined. Therefore, the present study aimed to arrive at a better understanding of the role of attention in the context of the TRP hypothesis. In the following, the two research questions RQ1 and RQ2 are answered and discussed, followed by study limitations and future directions of research.

5.1 Temporal resolution power and intelligence

In RQ1 it was examined whether the relationship between TRP and *g* can be replicated. As a necessary prerequisite, it had to be evaluated whether the identification of the measurement models of TRP and *g* was acceptable.

5.1.1 Measurement models of temporal resolution power and intelligence

The latent variables TRP and *g* were both modeled based on three indicators. For TRP, the three psychophysical timing tasks DDE, TG, and TOJ were used, whereas *g* was modeled based on the three aggregate scores of processing speed, processing capacity, and memory, as measured with a modified short version of the BIS test (cf. Wicky, 2014). The goodness of fit of the two measurement models had to be determined based on alternative criteria than the typically used χ^2-test statistic and fit indices, because measurement models based on three indicators are perfectly identified models, which are not testing any hypothesis and yield a trivial fit (Kline, 2011). The following criteria were used instead. First, TRP and *g* were modeled based on indicators that were already successfully used in previous TRP studies (Stauffer et al., 2014; Troche & Rammsayer, 2009b). In addition, DDE, TG, and TOJ were previously proven to be valid indicators of TRP (Rammsayer & Brandler, 2004) and the three *g* indicators covered the most frequently suggested components of intelligence (e.g., Carroll, 1993). Second, the correlation matrix of the three indicators of each construct had to depict a *positive manifold* in order to be reduced to a single latent variable. The psychophysical timing task showed low, nonetheless significant positive correlations among each other (see Table 7), whereas the BIS aggregate scores showed strong positive correlations among each other (see Table 6). Consequently, the criterion of a *positive manifold* was fulfilled for both constructs. Third, the present *g* model was compared to more complex *g* models to ensure that the chosen basic model did indeed measure *g*. This was especially important since the current literature presents different suggestions of *g* modeling (cf. Beaujean, 2015). For this purpose, the *g* factor scores of the present model were correlated with *g* factor scores of more complex higher-order or bi-factorial models of *g* (Appendix G). The high correlations among the *g* factor scores indicated that the present *g* factor was virtually identical to the *g* factors derived from more complex models. Furthermore, in line with Jensen and Weng (1994), *g* showed to be remarkably robust and rather invariant across different approaches of modeling. Consequently, despite not being able to evaluate the goodness of fit of the identified TRP and *g* measurement models by means of the χ^2-

test statistic or the fit indices, the alternative criteria presented provided evidence for a valid measurement of both constructs. Additional evidence for a valid modeling of TRP and *g* comes from the χ^2-test statistic and the fit indices of the combined model presented next.

5.1.2 The relationship between temporal resolution power and intelligence

Within the framework of the model that specified TRP as predictor of *g* (see Figure 10), a strong relationship between TRP and *g* was confirmed. As a matter of fact, the relationship (β = .60) was among the strongest found throughout the entire TRP literature. So far, the strongest relationship (β = .67) was found in Helmbold, Troche, and Rammsayer (2007). In the present study, TRP accounted for 36.48% of overall variability in *g*. This is in line with previous studies, in which TRP accounted for a substantial portion of overall variability in intelligence (Haldemann et al., 2011, 2012; Helmbold & Rammsayer, 2006; Helmbold et al., 2006, 2007; Rammsayer & Brandler, 2007). As initially proposed by Rammsayer and Brandler (2002, 2007), the present finding confirms that TRP is a reliable and substantial determinant of individual differences in general intelligence.

5.2 The interplay between temporal resolution power, attention, and intelligence

In RQ2 it was examined whether the relationship between TRP and *g* is of genuine nature or if perceptual attention represents a common source of variance and, hence, accounts for the formation of the as hitherto considered genuine relationship. In order to find an answer to RQ2, four necessary prerequisites had to be fulfilled. First, the relationship between TRP and *g* had to be replicated as confirmed in RQ1. Second, the experimental manipulation of complexity had to be successful. That is, the increase of complexity across ECT conditions should lead to increased attentional demands put on the limited processing resources, which, in turn, should lead to prolonged RTs across ECT conditions. That way, the experimental manipulation of complexity is directly linked to Kahneman's (1973) theory of limited processing resources. Third, for each ECT, the experimentally caused variance had to be successfully dissociated from the non-experimental variance by means of FLM in order to obtain a pure measure of the respective type of attention. Fourth, a higher-order latent variable of perceptual attention (as represented by the EXP) had to be modeled based on the three experimental latent variables (i.e., H_{EXP}, F_{EXP}, and C_{EXP}) derived in each ECT. In cases where the non-experimental latent variables (i.e., H_{NEXP}, F_{NEXP}, and C_{NEXP}) were significant, the same higher-order modeling approach was used to derive a NEXP.

5.2.1 Manipulation of complexity

The present study aimed to increase task complexity according to Jensen's (2011) means of information load. That is, the experimental manipulation of complexity aimed to increase the cognitive demands based on the rationale that more complex task conditions require higher cognitive demands in information processing (Stankov & Schweizer, 2007). Hence, more complex tasks require more of the limited processing resources, which in turn, lead to prolonged RTs. In that context, the term complexity is often used synonymously with task difficulty, but these two terms should be distinguished carefully (Spilsbury et al., 1990). The difficulty of a task can be increased without increasing its complexity. As an example, a task can be made more difficult by presenting the stimuli in smaller print, while the amount of information to be processed remains the same (Jensen, 2006; Spilsbury et al., 1990). In the present study, the manipulation of complexity in the respective ECT aimed to trigger specific attentional processes. For the Hick paradigm, the number of elements (i.e., possible stimulus locations) a subject had to attend to was systemically increased across conditions in order to increase the demands on the selective aspect of selective-focused attention.

For the Flanker task, selective-focused attention was manipulated across conditions with an emphasis on the aspect of focusing, since only one possible stimulus location was presented and subjects had to ignore the irrelevant information. In F1, subjects had to ignore the directional response of the imperative stimuli, whereas in F2, subjects had to focus on the specific directional response indicated by the respective imperative stimulus. In F3, complexity was additionally increased by adding flankers aside of the imperative stimuli, which either indicated a congruent or an incongruent directional response. For the incongruent trials (<<><< or >><>>), the subject had to inhibit the automatically activated false directional response induced by the incongruent flankers. Consequently, the demands of focusing on the relevant were systematically increased across ECT conditions. F5* showed the longest mean RT (see Table 4) and the highest error rate (see Appendix D) of all ECT conditions suggesting that F5* was the most complex condition of all ECT conditions.

For the CPT, CPT1 consisted of targets only, whereas CPT2 and CPT3 consisted of targets and distractor stimuli. Hence, for CPT1, complexity was kept at a minimum level so that a subject's limited processing capacity was challenged only marginally. This low degree of complexity suggests that only a minimum number of cognitive processes are involved in obtaining a correct response. As a matter of fact, CPT1 showed the shortest mean RT of all ECT conditions (see Table 4) suggesting that CPT1 was a rather simple RT condition (cf. Schweizer, 1996). In contrast to CPT1, the two other CPT conditions were more complex. In these two conditions, a subject had to sustain its attention in order to search for and respond to an imperative stimulus in a rapid sequence of multiple distractor stimuli. In comparison to CPT2, CPT3 was even more complex by increasing information processing demands by means of inhibitory control. That is, the previously used imperative stimulus of CPT2 was used as additional distractor stimulus in the set of distractor stimuli in CPT3. Therefore, the previously habituated response had to be inhibited during CPT3, which put additional attentional demands on the human information processor.

For each ECT, the repeated measures ANOVA revealed a significant effect of complexity, meaning that the RTs increased substantially across ECT conditions. Furthermore, the post-hoc tests revealed that the RTs of the three conditions differed significantly from each other in all ECT used. The same effect was found when non-parametric tests were used. Therefore, it can be concluded that the manipulation of complexity did work and that demands on the limited information processing resources were systematically increased across the respective ECT conditions. Further evidence for a successful manipulation of complexity comes from the finding that more complex ECT conditions showed a tendency to correlate higher with intelligence than less complex ECT conditions. This is in line with the *complexity hypothesis* (e.g., Vernon & Jensen, 1984) and the assumption that attention is the main driver of the correlation between latency-based performance measures and intelligence (Heitz et al., 2005; Schweizer, 2010). The more attention an ECT condition requires, the higher its correlation with intelligence. However, the attention-paced speed variance has to be dissociated from the residual speed variance in order to obtain a pure measure of latency-based perceptual attention.

5.2.2 Isolating attention from the non-experimental processes

The process of isolating the experimentally induced variance from the non-experimental variance was conducted by means of FLM. For each ECT, the factor loadings of the experimental variable were fixed according to the theoretically expected trajectory caused by the respective experimental manipulation of complexity. However, no standard approach for the fixation of factor loadings exists. Therefore, different increasing trajectories representing the complexity increase were modeled. For the non-experimental variables, the factor loadings were always fixed to 1. These different fixed-links measurement models derived were analyzed by means of χ^2-test statistic and fit indices.

Hick: Fixed-links measurement models

Model 3 with the factor loadings of the H_{EXP} fixed to 1, 2, and 4 represented the data best. This trajectory represented the increased information processing demands of selective-focused attention caused by the number of possible stimulus location presented in each condition. That way, the H_{EXP} and the H_{NEXP} were successfully dissociated. The variance of both latent variables was significant and, hence, statistically meaningful. The H_{EXP} represented the increased demands associated with the selective aspect of selective-focused attention, whereas the H_{NEXP} represented all other residual processes not associated with selective-focused attention. The discarded fixed-links measurement models either showed worse fit indices or were less parsimonious.

Flanker: Fixed-links measurement models

The third condition was split into two conditions, one representing the congruent (F4*) and the other representing the incongruent trials (F5*). Only F5* was modeled in combination with F1 and F2, because only the incongruent trials represented the effect of inhibitory control, whereas the congruent trials were only used to intensify the complexity manipulation in F3. That is, a subject did not know in advance if a congruent or incongruent trial was presented and, hence, had to flexibly switch between the execution and the inhibition of the automatically triggered directional responses induced by the flankers. Model 8 with the factor loadings of the F_{EXP} fixed to a quadratic increase of 1, 4, and 16 fitted the data best. This trajectory represented the increased information processing demands of selective-focused attention caused by the increased need to focus on the relevant. That way, the F_{EXP} and the F_{NEXP} were successfully dissociated. The variance of both latent variables was significant and, hence, statistically meaningful. The F_{EXP} represented the increased demands associated with the focusing aspect and the perceptual process associated with the inhibitory aspect of selective-focused attention. The F_{NEXP} represented all other residual processes not associated with selective-focused attention. The discarded fixed-links measurement models either showed a significant χ^2-test statistic, worse fit indices, were less parsimonious, or showed further deficiencies such as negative variances.

CPT: Fixed-links measurement models

The three CPT conditions differed not only in complexity, but also in the function of the conditions. All Hick and Flanker conditions showed qualitative similarities, whereas CPT1 showed qualitative differences to CPT2 and CPT3. That is, CPT1 was a rather simple RT condition with a very low level of complexity, whereas CPT2 and CPT3 were classical measures of sustained attention putting increased attentional demands on the human information processor. Therefore, model 9 with the factor loadings of the C_{EXP} fixed to 0, 1, and 2 was chosen in order to represent the qualitative difference between CPT1 and the other two CPT conditions. That way, the C_{EXP} and the C_{NEXP} were successfully dissociated and this model represented the data best. The variance of both latent variables was significant and, hence, statistically meaningful. The C_{EXP} represented the increased demands associated with sustained attention, whereas the C_{NEXP} represented all other residual processes, most likely simple speed processes. The other CPT measurement models examined, which did not indicate a functional difference between CPT1 and the other two conditions, had to be discarded due to a significant χ^2-test statistic, bad fit indices, or further deficiencies such as negative variances.

5.2.3 Higher-order modeling of attention and non-experimental processes

H_{EXP}, F_{EXP}, and C_{EXP} as well as H_{NEXP}, F_{NEXP}, and C_{NEXP} were all significant and, consequently, statistically meaningful. Therefore, the non-experimental variables were included in the further process of modeling. The H_{EXP}, F_{EXP}, and C_{EXP} were combined to a higher-order latent variable EXP, whereas the non-experimental variables H_{NEXP}, F_{NEXP}, and C_{NEXP} were combined to a higher-order NEXP. Both, the higher-order EXP and NEXP, were statistically meaningful. The EXP represented the common variance of H_{EXP}, F_{EXP}, and C_{EXP}. As in line with previous research on the structure of attention, such higher-order variables of attention most likely represent what is common to all measures of attention, hence, the EXP can be considered as a measure of perceptual attention (Moosbrugger et al. 2006; Schweizer, 2010; Schweizer et al., 2005).

In contrast, the NEXP did represent a conglomerate of the time taken by the residual processes not influenced by the experimental manipulation of complexity. Based on the circumstance of being a conglomerate, it was difficult to determine the content of the NEXP. In previous fixed-links studies, the NEXP was referred to as the auxiliary processes or the constant processes representing individual differences in basic (i.e., task-independent) processing speed

(Schweizer, 2007; Stauffer et al., 2014; Wang et al., 2015). In the study by Schweizer (2007), the latency-based Exchange Test - a test measuring the speed with which a certain number of cognitive elements can be exchanged and temporarily stored - was fixed-links modeled. Schweizer stated that the EXP represented the speed with which cognitive exchange and storage processes are executed, whereas the NEXP represented the speed with which basal perceptual and motor processes are executed. Furthermore, Schweizer saw the effect of the latency-based NEXP on intelligence as evidence for the mental speed approach to intelligence. However, due to being a conglomerate of multiple residual processes, the content of the NEXP can hardly be determined, hence, the NEXP is open for interpretation within the nomological network (Cronbach & Meehl, 1955) of the respective study.

Thomas and colleagues (2015) noted that the NEXP might represent aspects of an individual's current mental state such as fatigue or motivation. The notion of the NEXP as a container of constant processes such as motivation or fatigue seems to be reasonable, because these two processes are intended to be held constant in an experimental setting by applying breaks or providing the identical motivational basis for all subjects. However, for prolonged testing it might be possible that variations in fatigue or motivation increase/decrease the performance in latency-based assessment of information processing (Humphreys & Revelle, 1984; Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Lisper & Kjellberg, 1972). If so, these processes might be alternatively explained by an increasing or a decreasing trajectory according to FLM. On all accounts, the content of the NEXP remains a conglomerate of several cognitive processes and further research is necessary to clarify its content by curtailing processes captured by it. Therefore, the results related to the NEXP are of an explorative character and cautiously discussed in the context of the nomological network of the present and previous studies.

5.2.4 Mediation analysis

Within the framework of the mediator model, the EXP and NEXP were specified as parallel mediators in between the relationship of TRP and *g* (see Figure 16). Considering the intricacy of this higher-order model with two parallel mediators, the model fit was satisfactory. All predictive paths were substantial, except the predictive path from the NEXP to *g* was not significant. Furthermore, the residual correlation between the EXP and the NEXP was also not significant.

Both indirect effects were not significant, since the bootstrapped pCIs did include the zero. As a result, the EXP representing perceptual attention as well as the NEXP representing the non-experimental processes did not mediate the relationship between TRP and *g*. In addition, when comparing the direct path of the mediation model ($\beta_{c'}$) to the direct path of the single predictor model (β_c) with no mediators contained, the direct effect from TRP to *g* remained a strong effect (β_c = .60 versus $\beta_{c'}$ = .57). As a matter of fact, the relationship between TRP and *g* within the mediation model ($\beta_{c'}$ = .57) was still among the strongest found throughout the TRP literature (Helmbold, Troche, & Rammsayer, 2007). This finding demonstrates the genuine and robust nature of the relationship between TRP and *g*. Therefore, the present finding supports the notion that TRP represents a basic property of the central nervous system that accounts for individual differences in intelligence.

Indirect effect ab1 – the interplay between TRP, perceptual attention, and g

According to Michon (1985), temporal processing of brief intervals is of perceptual nature and supposedly not accessible to cognitive control. Therefore, the most likely type of attention to mediate the relationship between TRP and *g* is of perceptual nature as operationalized with the EXP. Furthermore, on the correlational level, the EXP showed to be moderately correlated with TRP and strongly with *g* (see Figure 14). These correlational findings were in line with previous research, which suggested that attention is involved in temporal information processing (Brown, 2008b) as well as non-temporal information processing (Carroll, 1993; Schweizer et al., 2005). In addition to the correlation analysis, TRP showed to be a substantial predictor of EXP, whereas EXP showed to be a substantial predictor of *g*, suggesting that there might be a potential mediating effect as by the rationale of the *casual steps approach* (Baron & Kenny, 1986). However, as reported and discussed, the EXP did not mediate the relationship between TRP and *g*. Consequently, perceptual attention does not account for the relationship between TRP and *g*, even though the results from the correlation analysis and the predictor models suggested that this might be the case.

The finding of non-mediation does only clarify the role of perceptual attention in the context of the TRP hypothesis. However, as shown in previous research, WM conceptualized as general capacity-limited system mediated the relationship between TRP and speed-related as well as capacity-related aspects of intelligence (Troche & Rammsayer, 2009b). As presented in the introduction, WM is described as attention-controlled cognitive processing and most prevalent models of WM contain some form of attentional WM component amongst other WM components such as short-term memory or storage components (Baddeley & Hitch, 1974;

Conway et al., 2002; Engle et al., 1999; Süss et al., 2002). Therefore, it might be possible that top-down executive attention derived from capacity-limited WM measures might account for the relationship between TRP and *g*. The efficiency of controlled attention or the ability to successfully inhibit interfering information might be of key importance for the perception of durations and their comparisons. Furthermore, the comparison of different durations might involve WM-specific short-term memory functions, especially in the case of TG, in which the standard duration has to be actively maintained in WM. However, to the present state of knowledge, no studies exist on the influence of executive attention on TG or TOJ. Additionally, a systematic examination of WM-based executive attention and efficiency of short-term memory in the context of the TRP hypothesis is missing.

Indirect effect ab2 – the interplay between TRP, the non-experimental processes, and g

The content of the non-experimental variables of the ECTs as well as the content of the NEXP cannot be determined unambiguously, because these variables represent a conglomerate of all non-experimental processes, that is, the variability in RTs not caused by the experimental manipulation of complexity. Previous literature suggested that the non-experimental variable represents general (i.e., task-independent) processing speed (Schweizer, 2007; Stauffer et al., 2014). The nomological network of the present study conveys some evidence for the notion that the NEXP might represent a general SIP variable. First, the NEXP showed a small correlation to *g* (see Figure 14), which is in line with previous results within the mental speed approach to intelligence showing that correlations between simple RTs and intelligence are rather low (e.g., Neubauer et al., 1997; Sheppard & Vernon, 2008). Second, the insignificant indirect effect *ab2* fits with the results presented in the mediational analysis by Helmbold and colleagues (2007), which suggested that TRP is the more important predictor of *g* than a general latent variable of SIP (derived from several Hick parameters). In the present study and the study by Helmbold and colleagues, TRP appeared to be sufficient to account for the effects relating SIP to *g*. However, as explained before, the interpretation of the NEXP as a general SIP variable has to be taken with caution, because a multitude of different unidentified cognitive processes contribute to the variance of the NEXP.

5.3 General conclusion: integration of the research questions

The results of the present study showed that the relationship between TRP and *g* is robust and of genuine nature. The single predictor model (RQ1) showed that the TRP hypothesis was reproducible. Furthermore, the mediation analysis (RQ2) showed that perceptual attention as well as the conglomerate of all non-experimental processes were not capable of mediating the relationship between TRP and *g*. In addition, despite that two parallel mediators were used, one of them representing a manifold conglomerate of potential mediating processes, the relationship between TRP and *g* was not mediated and remained a strong relationship. In summary, the present findings confirm that TRP is a reliable and substantial determinant of individual differences in general intelligence.

5.4 Study limitations

Several potential limitations of the present study were identified. First, it was not possible to examine whether perceptual attention (or the NEXP) exerted a different mediating effect for high and low intelligent individuals. Unfortunately, the sample of the present study was too small to perform the mediation analysis for these two subsamples separately. Furthermore, even if the present sample would have been big enough to be split, there are no norms provided for the modified short version of the BIS test to determine the validity of the sample split (cf. Jäger et al., 1997).

Second, FLM is a promising approach to dissociate experimentally manipulated variance from non-experimental variance. However, despite the theory-driven fixation of factor loadings, the fixation of factor loadings within the theoretically expected trajectory remains somehow arbitrary. For example, an increasing trajectory might vary in many different ways and there is no standard procedure in the fixation of factor loadings. Therefore, the theoretically expected trajectory has to be modeled repeatedly with different factor fixations in order to identify the appropriate factor loadings.

Third, the psychophysical timing task used as indicators of TRP were primarily in the auditory modality, except for the bimodal TOJ, whereas all measures of perceptual attention were in the visual modality. There is considerable evidence for faster and more accurate information processing in the auditory compared to the visual domain (as discussed by Stauffer, Haldemann, Troche, & Rammsayer, 2012). Therefore, the auditory-based assessment of TRP might have been more accurate than the visual-based assessment of perceptual attention.

5.5 Future directions

In the present study, attention was conceptualized as limited information processing resource depending on perceptual processes. As presented in the introduction and the discussion on the indirect effect *ab1*, Troche and Rammsayer (2009b) showed that the relationship between TRP and capacity- as well as speed-related aspects of intelligence was mediated by WM capacity, of which executive attention can be considered a subcomponent (e.g., Kane et al., 2004; Miyake & Shah, 1999). Therefore, it would be interesting to examine what specific WM subcomponent (e.g., executive attention and/or short-term memory) accounted for the mediation found in Troche and Rammsayer to further elucidate the role of (executive) attention in the context of the TRP hypothesis.

Furthermore, it would be interesting to examine whether perceptual attention also exerts no effect in mediation analyses for different subsamples (e.g., different sexes, age groups, or for low and high intelligent individuals). The idea of subsampling has also to be considered when investigating the potential mediating role of executive attention in the context of the TRP hypothesis so that sufficiently big samples can be accomplished.

A further topic to be examined, which has been discussed in the presented study and in previous work using FLM (e.g., Thomas et al., 2015), is the content of the NEXP. It has never been systematically examined what the NEXP represents or what the NEXP does not represent. For latency-based FLM designs, it would be important to evaluate whether the NEXP can be considered a general SIP variable or if this consideration has to be withdrawn. For this purpose, the fixed-links variables derived from classical ECTs, will have to be related to variables representing basal speed measures as well as variables representing current mental states such as fatigue or motivation. It would be of advantage for the individual differences research on intelligence, mental speed, and attention, if the processes contained in the NEXP can be curtailed.

6 Summary

Previous research showed repeatedly that individual differences in the temporal resolution power (TRP) of the central nervous system are related to individual differences in general intelligence. This relationship became to be known as the TRP hypothesis. However, the TRP hypothesis was challenged by the fact that temporal as well as non-temporal neural information processing afford considerable attentional resources and, hence, the relationship between TRP and general intelligence might be explained alternatively by attention as common source of variance. Therefore, the present study aimed to arrive at a better understanding of the interplay among TRP, attention, and general intelligence. For this purpose, a latent variable approach was used to dissociate attention-paced speed variance in latency-based measures of attention from all residual-based, non-experimental speed variance. That way, two potential mediators were derived, one representing a pure measure of perceptual attention and the other representing a conglomerate of the non-experimental processes not associated with the experimental manipulation of attention. A bootstrapped mediation analysis revealed that both mediators were not capable of mediating the relationship between TRP and general intelligence, hence, the present finding confirmed that TRP is a reliable and substantial determinant of individual differences in general intelligence. Future studies have to clarify the potential mediating role of more executive aspects of attention in order to elucidate the role of attention as an integral phenomena in the context of the TRP hypothesis.

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Appendix

Appendix A: Subjects removed from the initial raw sample

From the initial raw sample of 243 subjects, 10 subjects were removed due to the following reasons. One subject was removed due to insufficient knowledge of the German language, even though the subject reported to be a native speaker. Three subjects reported to exceed the predefined age range of 18 to 30 years. Subjects younger than 18 years and older than 30 years were not admitted since age-related changes in cognitive and motor processes can affect RTs (Fry & Hale, 1996; Kramer & Madden, 2008; Sleimen-Malkoun et al., 2013). One subject reported to have misunderstood the instructions of the BIS memory subtest *paired associates* (ZP) and therefore marked random answers in that subtest. Five subjects showed incorrect test behavior during testing session such as confusing response buttons.

Appendix B: A detailed description of the sample

Seventy-three subjects out of the 131 subjects with an academic background were women (mean and standard deviation of age: 22.44 ± 3.05 years) and 58 were men (22.91 ± 2.72 years). Most of the academic subjects studied psychology (64%). The other most frequently mentioned fields of studies were teacher education (6%), economics (6%), and law (6%). Forty-five subjects out of the 97 subjects with a vocational background were women (20.93 ± 2.68 years) and 52 were men (21.42 ± 2.89 years). The most frequently mentioned vocational backgrounds were merchant (8%), gastronomy employee (8%), and nurse (6%). The remaining jobs were manifold: flight attendant, polygraph, hair dresser, optician, fashion adviser, photographer, dental care, mechanic, and many more. Out of all 228 subjects, 207 subjects reported to be right-handed, 20 subjects reported to be left-handed, and one subject reported to be both.

Appendix C: Intraindividual outlier correction for Hick, Flanker, and CPT, and interindividual outlier correction for DDE, TG, and TOJ

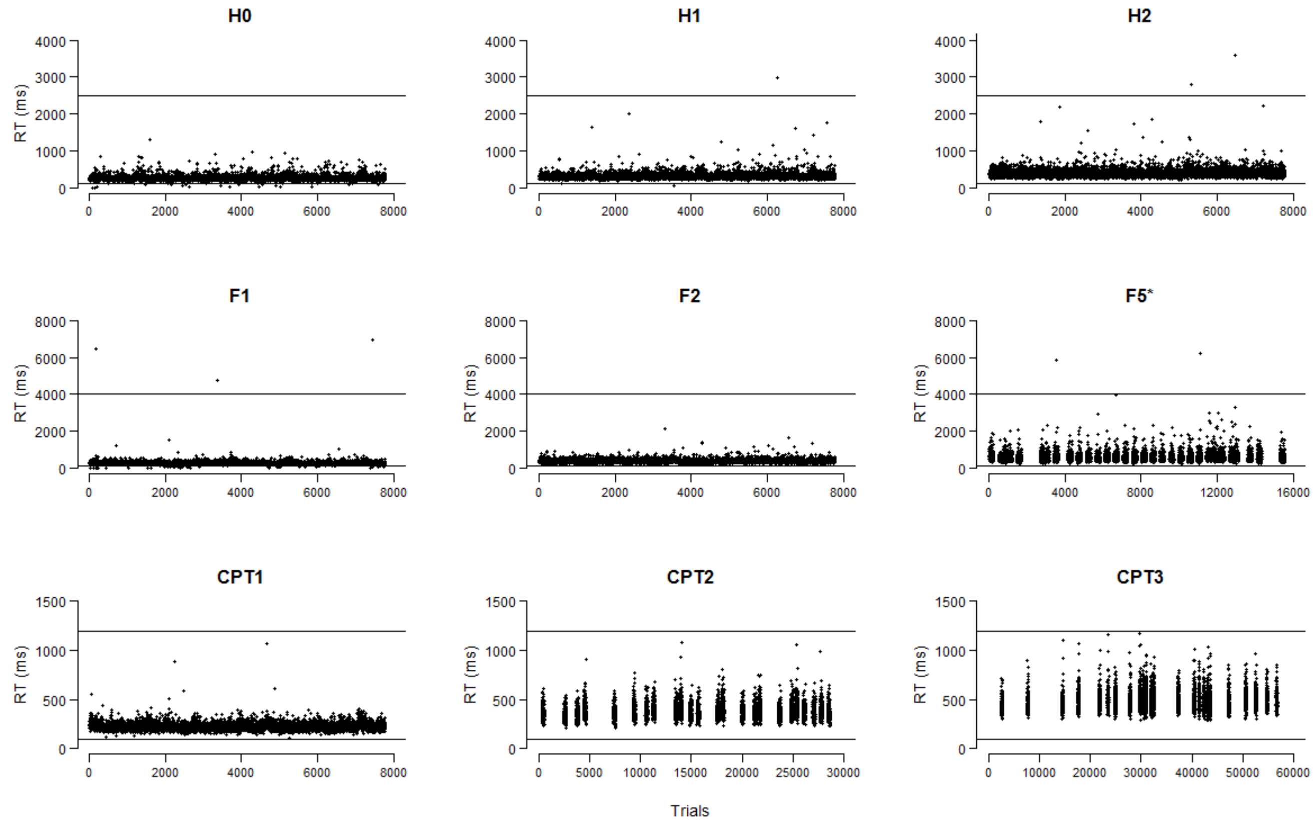
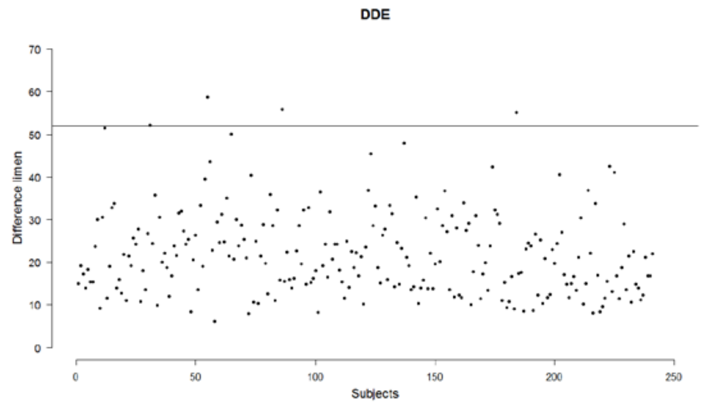
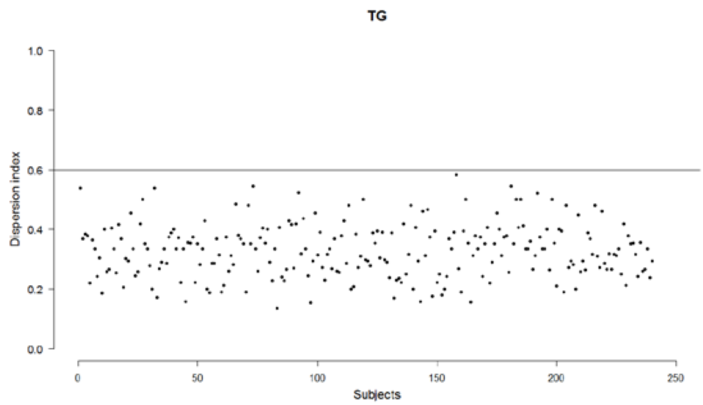


Figure C.1. Intraindividual outlier correction as reported in chapter 4.1 for the Hick, the Flanker, and the CPT conditions. Within each scatter plot, all correct trials of all subjects are plotted. The x-axis indicates all these trials, whereas the y-axis indicates the RT of each trial. The lower horizontal line in each scatter plot is the 100 ms physiological limit of the speed of reaction, whereas the upper horizontal line is the visually identified upper limit. For each Hick condition, the upper limit was 2,500 ms. For each Flanker condition, the upper limit was 4,000 ms. For each CPT condition, the upper limit was 1,200 ms. All trials below the lower limit and all trials above the upper limit were removed before the further outlier correction described in chapter 4.1. In F5*, CPT2, and CPT3, all congruent/distractor trials were removed before the outlier inspection, thus, the empty space between the target trials.





TOJ

Figure C.2. Interindividual outlier correction as reported in chapter 4.1 for DDE, TG, and TOJ. The x-axis indicates the subject, whereas the y-axis indicates the respective performance measure: difference limen for DDE, dispersion index for TG, and mean SOA for TOJ. Subjects exceeding the interindividual mean by three interindividual standard deviations (indicated by the horizontal line) were considered as outliers and removed from the further analyses.

Appendix D: Error rates for Hick and Flanker as well as omission and false alarm rates for CPT

Table D.1

Error rates for the Hick and the Flanker conditions as well as the omission and the false alarm rates for the CPT conditions

		Percentage						
Performance measure	Trials	*Mean*	*SD*	min	max	Skewness	Kurtosis	Shapiro-Wilk *p*-value
Hick								
H0	32	-	-	-	-	-	-	-
H1	32	0.00	0.01	0	0.06	3.30	10.78	< .001
H2	32	0.02	0.02	0	0.12	1.14	1.84	< .001
Flanker								
F1	32	-	-	-	-	-	-	-
F2	32	0.03	0.04	0	0.22	1.74	3.97	< .001
F5*	32	0.06	0.06	0	0.32	1.40	1.79	< .001
CPT omission								
CPT1	32	0.01	0.03	0	0.16	2.56	8.40	< .001
CPT2	24	0.00	0.01	0	0.08	5.02	25.60	< .001
CPT3	24	0.02	0.05	0	0.38	3.96	20.26	< .001
CPT false alarm								
CPT1	32	-	-	-	-	-	-	-
CPT2	96	0.01	0.01	0	0.05	1.91	4.96	< .001
CPT3	216	0.01	0.01	0	0.12	3.61	24.84	< .001

Note . The second column "Trials" indicates the number of trials on which the error percentage is based on. Errors (i.e., pressing the wrong response button) were not possible in H0 and F1. The CPT omission rate indicates the missed imperative stimuli. The CPT false alarm rate indicates the distractor stimuli falsely identified as imperative stimulus. CPT = continuous performance test; H0-H2 = Hick conditions; F1-F5* = Flanker conditions; CPT1-CPT3 = CPT conditions; SWT = Shapiro-Wilk normality test.

Appendix E: A comparison of the *g* factors scores of different *g* models

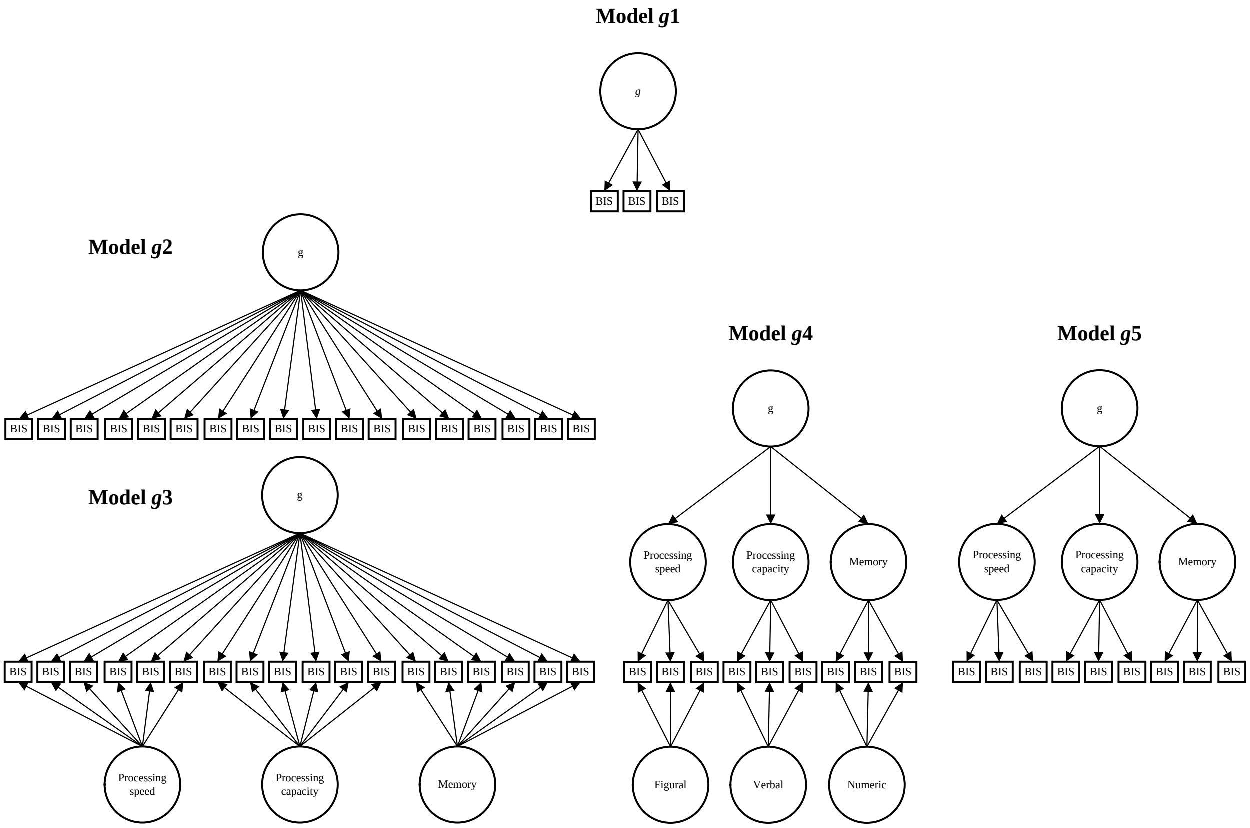


Figure E.1. For validity reasons, the *g* model used for the present study based on the three aggregate scores of processing speed, processing capacity, and memory (Model *g*1) was compared to more complex *g* models. Therefore, *g* factor scores were extracted from all models presented in Figure E.1 and correlated. The content of the indicators used varied from model to model: the 18 indicators of Model *g*2 and *g*3 are based on the 18 *z*-standardized subtest scores, whereas the nine indicators of Model *g*4 and *g*5 are based on operation cell means. The models depicted in Figure E.1 are greatly simplified.

Table E.1
Correlations among the g factor scores of the different g models and the z-score

	Model *g*2	Model *g*3	Model *g*4	Model *g*5	*z*-score
Model *g*1	.98***	.91***	.92***	.96***	.99***

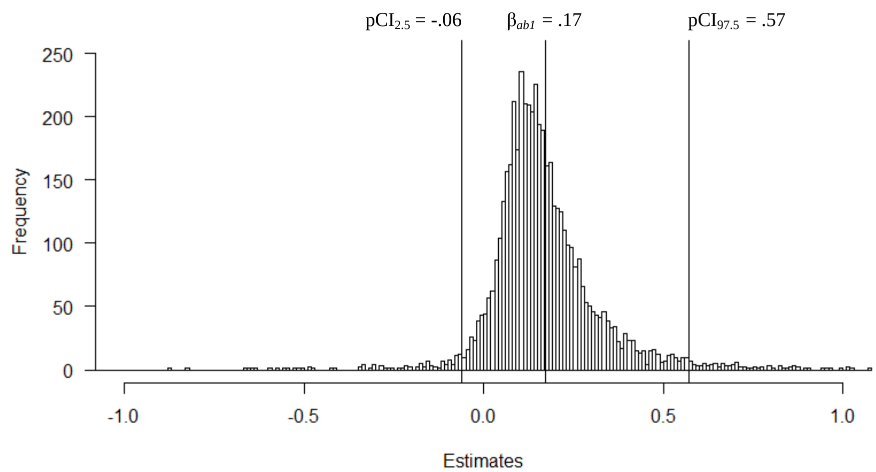
Note. Models are explained in the caption of Figure E.1. *z*-score = the mean of all *z*-standardized BIS subtests.
***p < .001.

Appendix F: Non-parametric manipulation check of complexity

For the Hick paradigm, the Friedman rank sum test revealed a significant total effect of complexity, $\chi^2(2) = 452.04$, $p < .001$. The Friedman post-hoc tests (Galili, 2010) showed that all three Hick conditions differed significantly from each other ($p < .001$). For both, the Flanker and the CPT task, the Friedman test showed that the manipulation of complexity worked as well, $\chi^2(2) = 456$, $p < .001$. The identical χ^2-values for both ECTs are due to the identical RT-courses for each of the 228 subjects (i.e., all subjects showed the same increasing trajectory of RTs across conditions in Flanker and CPT: mean RT of condition 1 < mean RT of condition 2 < mean RT of condition 3). The Friedman post-hoc tests revealed that all three Flanker and all three CPT conditions differed significantly from each other ($p < .001$). Therefore, the non-parametric manipulation check revealed the same result as the parametric manipulation check.

Appendix G: Bootstrapped distributions of the indirect effects

The bootstrapped distribution of the 4795 estimates of β_{ab1} and β_{ab2} are displayed in Figure G.1. The lower ($pCI_{2.5}$) and upper bound ($pCI_{97.5}$) of the pCI and the unstandardized estimate of β_{ab1} and β_{ab2} are depicted within the respective histogram



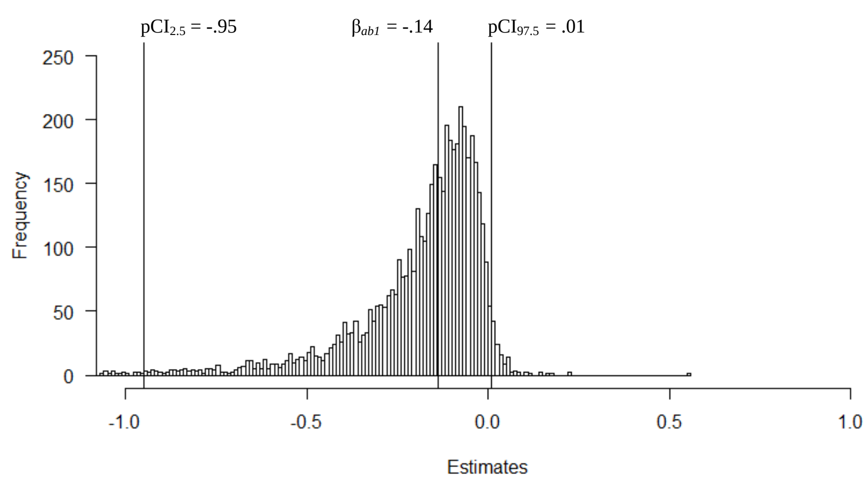


Figure G.1. The bootstrapped distributions of the unstandardized indirect effects β_{ab1} (upper histogram) and β_{ab2} (lower histogram). For both indirect effects the upper and lower bound of the percentile CI (pCI) is depicted within the histogram.