Elucidating Different Aspects of Speed of Information processing: A Comparison of Behavioral Response Latency and P300 Latency in a Modified Hick Reaction Time Task

Inauguraldissertation der Philosophisch-humanwissenschaftlichen Fakultät der Universität Bern zur Erlangung der Doktorwürde

Sarah Merks (Furrer)
von Bürchen VS

Bern, September 2016

Acknowledgements

I would like to thank my supervisors, Professor Thomas Rammsayer and Professor Stefan Troche, for their support, inputs and thoughtful discussions during this research project. Another big thanks goes to Professor Michael Houlihan who contributed significantly to my knowledge and understanding of electrophysiological data.

I am very grateful to Maggie Ward, Annkathrin Müller, Christine Krebs and Dominic Freitag for their help with data collection.

A special thanks to Michael Merks, Dominique Imesch, Natalie Borter and Norbert Furrer for their endless patience and support.

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Introduction

Faster information processing is related to higher levels of intelligence (Jensen, 2006). This finding was confirmed in a large amount of studies and is the general assumption of the so called mental speed approach of intelligence. The most common approach to measuring speed of information processing has been the use of response time (RT) in elementary cognitive tasks (ECTs) (Jensen, 2006; Neubauer, 1995). The Hick reaction time task is one of the classic and most investigated ECTs. It is usually conducted under different complexity conditions and a linear increase of RT across conditions can be observed. The complexity is manipulated by adding response alternatives and therefore increasing the uncertainty of the stimulus' position and thus the complexity of response selection (Frith & Done, 1986). The linear increase of RT depends on the amount of binary decisions that have to be made in order to successfully solve the task and is known as Hick's law (Hick, 1952). Furthermore, in accordance with the mental speed approach, an inverse relation of Hick RT with general intelligence is typically observed (Jensen, 2006; Neubauer, 1995). Another index of speed of information processing is the latency of the event-related potential (ERP) component P300 (Kutas, McCarthy, & Donchin, 1977; McCarthy & Donchin, 1981). P300 latency is often considered as a measure of stimulus evaluation time that is relatively independent of response-related processing stages like response selection and execution (Donchin, 1979; Doucet & Stelmack, 1999; Duncan-Johnson & Donchin, 1982; Kutas et al., 1977). However, there has been studies showing that P300 latency is sometimes also sensitive to experimental manipulations that focus on response selection, especially in choice reaction time tasks (Falkenstein, Hohnsbein, & Hoormann, 1994a; Pfefferbaum, Christensen, Ford, & Kopell, 1986; Verleger, 1997). The use of P300 latency as a measure of stimulus evaluation time is not compatible with the finding of a P300 latency sensitivity to response selection. However, choice reaction time tasks are often not only varying the complexity of response selection, but also the complexity of stimulus evaluation. Thus, the functional significance of P300 latency remains unclear. P300 latency has been used as a speed of information processing index in mental chronometry studies before, but, to my knowledge, never in the Hick paradigm. The Hick paradigm, however, is an excellent task to investigate the influences of an increase in response alternatives without increasing the complexity of stimulus evaluation. By using both, RT and P300 latency, as measures of speed of information processing in the Hick paradigm, the present work intended to get a more detailed understanding about the functional significance of P300 latency. Furthermore, by contrasting the two speed measures as predictors of intelligence, it was aimed to elucidate specific stages of information processing that account for individual differences in intelligence. Before introducing the research questions in more detail, the main concepts of the present work will be presented in the following sections in a deductive way. These include intelligence, the Hick paradigm, event-related potential technique, and, eventually the P300 component of the event-related potential.

Intelligence

Since the work of Sir Francis Galton (1869, 1879, 1883) in the late nineteenth century, the investigation of intelligence and its underlying processes has been of great interest in psychology and especially in differential psychology (Jensen, 1998). With his research, Galton has developed a basic idea of intelligence for all following research in this field. He stated that the human mind consists of a general component and specific components. Furthermore he hypothesized that the general component has much more influence on individual differences than the specific components (Galton, 1879, 1883). Galton was also the first researcher that tried to assess intelligence with simple sensory discrimination tasks by using RT to simple visual and auditory stimuli (J. M. Cattell & Galton, 1890). Due to overly simple tasks and the lack of knowledge about specific statistical procedures at that time, his efforts were not fully successful and an empiric prove of his ideas was not possible (Jensen, 1998). Nevertheless, various psychologists after Galton adopted his ideas and extended them.

Binet (1905) for example, created the first valuable and practical useful intelligence test using some of Galton's tasks like memory span or weight discrimination. Furthermore, Galton's idea of a general and a specific component of the human mind is the foundation for the factor models of intelligence.

Factor models of intelligence. It was not until the work of Charles Spearman (1904, 1927) and his statistical inventions like factor analysis that allowed for an empiric confirmation of Galton's idea of general and specific components of intelligence. Spearman (1904) initially developed the two-factor theory of intelligence, as he observed that all tasks that require some kind of cognitive effort correlate with each other. Using factor analysis, Spearman (1904) extracted this common variance and simply called this factor "g". He described g as "mental energy" which "enters into the measurement of ability of all kinds, and is thought to be constant for any individual, although varying greatly for different individuals" (Spearman, 1904, p. 411). Spearman (1904) also discovered that g is a strong predictor of general intelligence. The second factor of Spearman's theory is called "s" and represents the variance of each manifest variable that is left after extracting g, namely the test-specific variance plus the measurement error. By comparing high g-loading tests with low g-loading tests, Spearman (1904, 1927) found that g especially affects the performance in tasks that require reasoning and problem solving, and not so much in tasks that require the use of fact knowledge. Another discovery of Spearman (1904, 1927) was that more complex tasks have higher g-loadings compared to simpler tasks. This implies that more complex tasks are better predictors of g than simpler tasks. Later, R. B. Cattell (1971), a student of Spearman, described general intelligence using a hierarchical structure model. In his theory, g is replaced by two second-order general factors, namely fluid intelligence (Gf) and crystallized intelligence (Gc). While Gf affects the performance in tasks that require reasoning or problem solving, Gc is affecting the performance in tasks that require fact knowledge, culture-specific knowledge and scholastic knowledge. However, the division of general intelligence into Gf and Gc is not always that clear and is not conclusively established. Gc cannot always be found, especially not when the investigated sample is very homogenous. Furthermore, Gf often correlates almost perfectly with g, so that one could state that Gf is very similar to g (Gustafsson, 1984, 1988). Similar to Cattell's theory, Carroll (1993) proposed a three level structure of general intelligence. The three levels describe classes of relationships between various abilities that reflect individual differences in intelligence. In this so called three-stratum theory of cognitive abilities, the first, lower-order stratum consists of 50-60 linearly independent abilities that are very narrow, e.g. perceptual speed, spatial relations and visualisation. The second-order stratum is constituted by eight to ten broader abilities that summarize the abilities from the first-order stratum, e.g. broad visual perception. The third-order stratum contains one single ability that is named general intelligence or g. Carroll's (1993) theory can be used as a map of existing cognitive abilities and how they are related to each other.

Despite the differences in details about the structure of general intelligence, the empiric evidence of the above mentioned theories all suggest the concept of g as the basis of general intelligence. The concept of a general factor of intelligence that underlies all kinds of cognitive effort is widely accepted and is also the applied construct of the present thesis. The short version of the Culture Fair Test Scale 20-R (CFT 20-R; Weiss, 2006) was applied as indicator of reasoning performance and general fluid intelligence.

Besides the study of the structure of intelligence, research has also focused on cognitive underpinnings of intelligence. In this branch of research, the concept of g is not denied, but rather understood as biological feature of the brain (Anderson, 1995). g is not seen as a concept that corresponds to one single cognitive process or one single brain region, but as a corollary of a biological foundation that underlies all cognitive performance. The performance on cognitive tasks is, like every other behavior, the result of brain activity and the level of performance mirrors the efficiency of the brain (Anderson, 1995). The biology of intelligence is mainly investigated with functional brain activation correlates from measures like electroencephalography (EEG), functional magnetic resonance imaging (fMRI), position emission tomography (PET) etc., while cognitive research on intelligence mainly investigates speed of information processing measured by reaction time as a correlate of intelligence. The following section will introduce a main approach to the cognitive foundations of intelligence, the mental speed approach.

Mental speed approach. The basic assumption of the mental speed approach is that faster information processing leads to higher general intelligence. Indeed, a negative correlation between RT as an index of speed of information processing and intelligence, especially Gf measures, has been found in a large amount of studies. Sheppard and Vernon (2008) reviewed 172 studies and reported a correlation of r = -.24 in average between intelligence and mental speed. Mental speed is usually investigated with so called elementary cognitive tasks (ECTs). ECTs are defined as very simple tasks, simple in terms of low cognitive demands, which can be typically solved by any individual if unlimited processing time is provided (Carroll, 1980). However, ECTs are usually conducted under time pressure, meaning that they need to be accomplished as fast as possible. Therefore, RT is typically used as performance indicator in ECTs instead of the error rate that is usually very low due to the low difficulty of the tasks. Due to the low cognitive requirements of ECTs, the use of strategy and previous experiences are only minimally influencing the individual performance and RT of ECTs is therefore interpreted as an index of speed of information processing (Jensen, 2006). ECTs are typically presented under different complexity conditions. Complexity is hereby defined as the amount of information a participant has to process in one trial or in other words the cognitive load. The more information a stimulus contains, the higher the complexity level of the task. The idea behind the application of different complexity levels goes back to Donders' subtraction method (Snodgrass, Levy-Berger, & Haydon, 1985). Assuming that the different conditions only vary in the complexity of a specific elementary cognitive process, e.g. response selection by increasing the number of response alternatives, the change in RT across conditions is interpreted as an index of the information processing time, or in other words, of speed of information processing. The inverse relation between RT and intelligence is typically higher under more complex conditions (Sheppard & Vernon, 2008), indicating that more complex tasks are differentiating better between more and less intelligent individuals. Furthermore, similar to the g factor models mentioned earlier, different ECTs are often highly correlated with each other and a single speed of information processing factor can be extracted from a variety of speed tests or ECTs. In accordance with the relation between g and general intelligence, this speed factor is also correlated with both, general intelligence and g (Danthiir, Wilhelm, Schulze, & Roberts, 2005; Neubauer & Bucik, 1996). One of the most frequent investigated ECTs is the Hick reaction time task. The following section will introduce the Hick paradigm and give an overview of previous findings.

Hick Paradigm

The Hick task is a simple and choice reaction time task that requires participants to decide in which particular position a stimulus appears and to press the corresponding button on a response pad. The arrangement of possible stimulus positions is matching the arrangement of buttons on the response pad. The Hick task is typically conducted under different conditions varying in their complexity, as it is usual for ECTs. In the Hick paradigm, complexity is manipulated by adding response alternatives and therefore making the response selection more complex (Frith & Done, 1986). The presented imperative stimulus, however, remains always the same. The complexity of stimulus evaluation is therefore minimally and constant across conditions. The complexity conditions are named in bits according to the amount of binary decisions participants need to make in order to successfully solve the task

(Deary, 2000). For example, if there is only one possible stimulus position, no binary decision has to be made in order to determine the positon of the imperative stimulus and the condition is called 0 bit condition. This 0 bit condition corresponds to a simple reaction time task. If there are two possible stimulus positions, participants have to make one binary decision to successfully solve the task and it will be called 1 bit condition. 1 and all higher bit conditions are choice reaction time tasks. Participants typically react slower across complexity levels, or in other words, RT is increasing the more information has to be processed (Hick, 1952; Jensen, 1982, 2006). The slope of RT across bit conditions is linear until the 2 or 3 bit condition. In higher bit conditions the slope usually flattens. This linear increase of RT in dependence of the amount of bit of information a stimulus contains is known as Hick's law (Hick, 1952). Furthermore, the slope is steeper for less intelligent individuals compared to individuals higher in intelligence (Jensen, 1982, 2006; Roth, 1964). Accordingly, the correlation between Hick RT and intelligence is negative and increases across complexity, approximately between $r = -.10$ and $r = -.30$ (Neubauer, 1995). As noted earlier, RT is used as an index of speed of information processing and therefore, the inverse relation between Hick RT and intelligence is considered as confirmation of the mental speed approach (Danthiir, Roberts, Schulze, & Wilhelm, 2005; Deary, 2000; Jensen, 2006; Neubauer, 1995).

Information processing in the Hick paradigm. RT is a behavioral measure that summarizes the time of several sensory, cognitive, motoric, and also strategic underlying processes (Jensen, 1982; Schweizer, 2006). Neubauer and Knorr (1997) suggested that in choice reaction time tasks, like the Hick paradigm, the following information processing stages can be differentiated: stimulus perception, stimulus discrimination, response choice and motoric response. Carroll (1981) described a similar differentiation of processes involved in the Hick paradigm: stimulus apprehension, encoding, converting, response selection, and execution. This model of information processing is illustrated in Figure 1 and is the assumed model for the present thesis. Carroll (1981) suggested that in order to solve a choice reaction time task participants are required to go through this series of contingent processing steps. First, the stimulus has to be apprehended before it is encoded, which means the stimulus is perceived and identified. The encoded stimulus is then converted to an action plan, which means that the stimulus is categorized. The stimulus evaluation ends here and in paradigms with decision and movement time measuring, this would mark the end of the decision time (Carlson & Widaman, 1987). Decision and movement time will be explained in more detail in the next section. The cognitive response is followed by the response-related processing stages. Meaning that after the stimulus has been evaluated, the response is selected and executed.

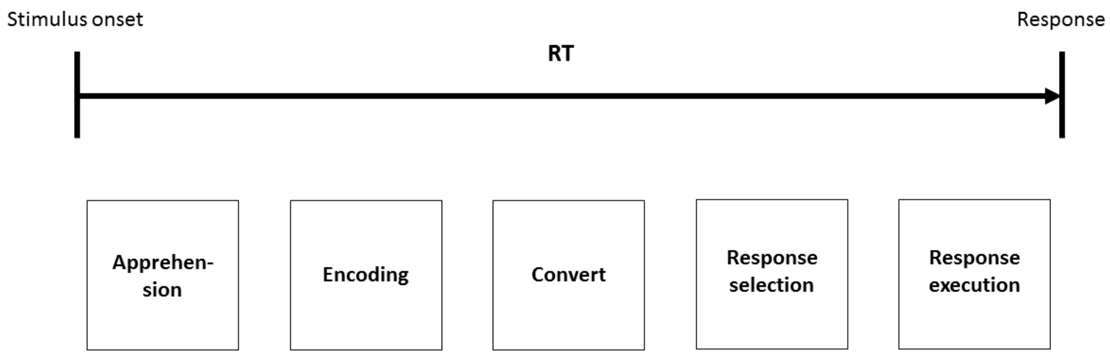

Figure 1. Illustration of the information processing stages involved in the Hick paradigm adapted from Carroll (1981). The time of these information processing stages is summarized in RT as depicted by the arrow.

There have been various ways in order to isolate different stages of information processing to get a better understanding of general information processing in the Hick paradigm. A lot of research has been done by splitting up overall RT into different subparts or by using other parameters of RT instead of its mean or median. The following sections will give an overview of the main findings.

Movement and decision time. One way to isolate the cognitive from the motoric response in the Hick paradigm is to split overall RT up into decision time (DT) and movement time (MT) (Jensen, 2006; Jensen & Munro, 1979). For this purpose, the response pad typically has an additional button, the so called home button, which participants have to hold down as a default, which means whenever they are not reacting to the target stimulus. DT is defined as the time from stimulus onset to the time the participant leaves hold of the home button. MT on the other hand is defined as the time from leaving the home button to the time the target button is pressed. The idea behind this division of RT is to have a cognitive measure, DT, and a motoric measure, MT, for speed of information processing in order to see if there is a difference between these two measures across complexity and between the correlations of intelligence with both, DT and MT. Generally, the same results for DT were found as they were for overall RT (Jensen, 1982). DT is linearly increasing across bit conditions and is negatively correlated with intelligence. Furthermore, MT does not increase across complexity and is, in fact independent of DT over single trials within an individual. Interestingly though, DT and MT do positively correlate interindividually about r = .40 (Jensen, 1982). MT, however, is always much shorter than DT. To investigate the relevance of MT for information processing in the Hick paradigm, Jensen (1982) conducted the Hick task under two different conditions. First, under the “single response” condition, the instructions were to only leave hold of the home button when the stimulus appeared without actively execute a response. This condition was conducted in order to reveal if the cognitive manipulation of the task, namely the increase of uncertainty of the stimulus’ position per se is responsible for the increase in RT across conditions. Second, under the “double response” condition, the task was conducted as per usual. Participants had to remove their finger from the home button and press the button corresponding to the stimulus' position. This condition was conducted to see if the motoric component of the experimental manipulation, namely the response execution is the source of Hick's law. Under both conditions, single and double response, DT was measured. DT of both, single and double response conditions was increasing across bit conditions. However, DT of the double response condition was about 30 milliseconds (ms) slower than DT of the single response condition. Furthermore, the correlation between intelligence and DT was about the same size under both, the single and double response condition. Jensen (1982) attributed this delay in time of about 30 ms under the double response condition compared to the single response condition to the ballistic movement programming. Since response selection and execution were not engaged under the single response condition, but the intelligence-DT correlation was still found, Jensen (1982) concluded that the correlation between Hick RT and intelligence is more likely caused by the uncertainty of the stimulus' position involving stimulus apprehension, encoding and converting than by response selection and execution. The results also suggests that although the motoric response adds to RT across complexity, it is a constant amount of time that can be attributed to the ballistic movement.

Intraindividual variability. Another approach to get a more detailed understanding of information processing in the Hick paradigm is the investigation of intraindividual variability in RT or MT using its standard deviation (SD) (Jensen, 1982, 1992). Although intraindividual variability in RT is not as widely used as is the mean RT, DT and MT, Jensen (1982) points out that it is the measure showing the highest correlation with intelligence. An explanation for this high correlation with intelligence has been the physical lower limit of RT (Jensen, 1982). While the shortest RT of participants with higher intelligence is about the same as the shortest RT of participants with lower intelligence, the slowest RT varies largely between intelligence groups. The SD of participants with lower intelligence is therefore typically much higher than the SD of participants with higher intelligence. A recent meta-analysis that investigated 24 studies, however, reported only small to moderate average correlations between intelligence and SD of RT and did not confirm that the relation between SD of RT and intelligence was consistently larger than between mean RT and intelligence (Doebler & Scheffler, in press). Nevertheless, SD of RT and also DT is increasing in a positive accelerated curve across complexity levels (Jensen, 1982). However, SD of MT is completely unaffected by complexity. Even though intraindividual variability in MT is about 1.7 times larger than in DT, it has the lowest correlation with intelligence among all measures derived from RT in the Hick paradigm.

Intercept and slope. A further approach to investigate information processing within the Hick paradigm is the use of a more holistic measure of the task, namely the intercept and slope of the linear regression line of RT in dependence of bit conditions. Intercept and slope are considered to be more holistic measures to the effect that they account for all conditions of the task at once. When using other measures like RT, DT, MT and also intraindividual variability, the different bit conditions are usually independently considered by themselves. Jensen (2006) describes that intercept and slope are both measuring different subsets of processes. While the intercept captures the time of stimulus apprehension, perceptual encoding, response preparation, and muscle lag, the slope reflects the rate of information gain, meaning the time a participant needs to process one bit of information. Both, intercept and slope are negatively correlated with intelligence, whether they are calculated over groups of individuals with different ability levels or individually within a sample (Jensen, 1982). Nevertheless, the slope seems to differentiate better among individuals with higher ability levels and the intercept among individuals with lower ability levels. However, slope and intercept often have poor psychometric characteristics (e.g. test-retest reliability of Hick slope: r = .39) and the relation to intelligence is therefore oftentimes very low (Deary, 2003).

Nevertheless, the correlation between intelligence and the intercept suggests that the relationship of RT and intelligence is probably determined by very basic cognitive processes, even though interindividual differences in RT get amplified by the complexity of the task requirements, indicated by the correlation between the slope and intelligence (Neubauer, 1995).

All of the introduced approaches for a better understanding of Hick's law and generally of information processing and intelligence have been applied by using RT or other measures that are derived from RT. The comprehensive investigation of reaction time measures in the Hick paradigm, broadly done by Jensen (1982; 2006), revealed strong hints that the typical course of RT across complexity according to Hick's law as well as the inverse relation of RT and intelligence have their source in cognitive underlying processing stages rather than in the response execution. Another measure of speed of information processing is the event-related potential (ERP) that is derived from the continuous EEG. The latencies of particular ERP components represent some distinct aspects of speed of information processing and are considered to be less confounded by the motoric response than RT. The event-related potential technique will be introduced in the following sections.

Event-related Potential Technique

An ERP is the product of averaged segments of one channel of the continuous EEG signal. It consists of a series of peaks, either positive or negative, that are evoked by a stimulus. The different peaks that are also called components can be defined or described by their latency and amplitude. The latency is the time interval from stimulus onset to a specific point of the particular component depending on the method it is calculated. Usually this latter time point is the maximum peak of the component. Since latencies are time intervals, they are measured in milliseconds. The amplitude of an ERP is the intensity of the component. It is a measure on how much the peak is deflecting, again, either positive or negative. Since it is electrical currency that is measured, the measuring unit of amplitudes is micro Volts (µV). The different components are named after their positivity/negativity (P or N) and the approximate time of their peaks (Luck, 2005). For example, the negative peak that occurs around 80 to 120 ms after stimulus onset is called N100. It is elicited by an unexpected stimulus without any task requirements. Such early ERP components are reflecting the sensory response to a stimulus and are considered to be exogenous due to their dependence on external determinants (Luck, 2005). Later ERPs, e.g. the P300 component, are determined rather by an individual's task performance than by the external characteristics of a stimulus and are therefore called endogenous components (Luck, 2005). One of the most useful characteristics of ERPs is their excellent temporal resolution that allows for the assessment of the timing of sensory or cognitive processes in a millisecond range (Woodman, 2010). This makes ERP technique very useful in the study of early cognitive processing, and especially in the study of the timing of cognitive processing (Rugg & Coles, 1995).

Interpretation of ERP data. The interpretation of ERP data can be challenging. A full understanding of the determinants of a lot of components could not be achieved yet (Luck, 2005, 2012). Nevertheless, knowledge from psychophysiological research has led to some general rules for drawing conclusions about the functional significance of particular ERP components. In the following sections some of these rules will be described. The first part will be about the general interpretation of ERPs without any a priori knowledge of a specific component. The second part will be about the interpretation of ERP data including a priori knowledge about the particular component.

Interpretation of ERP data without a priori knowledge. Even without having any knowledge or assumptions about a particular component, it is possible to draw some conclusions about the timing, degree of intensity and functional equivalence of cognitive processes using ERP data. General conclusions about the timing can be drawn by looking at the peak latency, onset time, rise time and overall duration of the different peaks (Otten & Rugg, 2005). The onset time, which is the starting point of a component, is giving an idea about the time when different cognitive processes begin to distinguish themselves. If there are two different onset times of a particular ERP component under two different conditions, it is clear that the underlying cognitive process of this component is affected by the experimental condition at least from that moment on. It is only an “at least” assumption because it is possible that the underlying cognitive process was affected by the experimental condition before the onset time change, but that the ERP was not sensitive for it (Otten & Rugg, 2005). By looking at the amplitude, general conclusions can be drawn on what degree an experimental condition influences cognitive processing. Differences in amplitudes under different conditions point to a quantitative change in the underlying cognitive processes. It can be interpreted that the same cognitive process(es) is/are involved, since the same component was elicited under both conditions, but to a different degree (Otten & Rugg, 2005). To learn more about functional equivalence of ERPs and cognitive processes, the scalp distribution of both, latencies and amplitudes of different EEG channels are very informative (Otten & Rugg, 2005). Scalp distributions represent different patterns of neural activity and how they change under different experimental conditions. They also contribute to the knowledge about the underlying biological determinants or sources of the ERPs.

Interpretation of ERP data with a priori knowledge. One of the most important general rules to keep in mind when interpreting ERP data, and drawing conclusions about the functional significance of a component, is to be aware of the purpose of using ERP data in the first place (Luck, 2005; Otten & Rugg, 2005). Since ERPs are elicited by a stimulus and/or the participants’ performance on a task, it is necessary to have the information the particular ERP can reveal in mind. If different conditions of a task only vary in the complexity of a specific process, and the investigated ERP component is sensitive to this manipulation, it can be concluded that this component is a functional equivalent of this manipulated process. Additional information about cognitive processing can be gained by looking at systematic relationships between ERP components and specific experimental conditions or manipulations.

Interpretation of the peak latency of ERPs. Psychophysiological research has come up with some standardized rules about interpreting peak latencies of ERP components. Meyer, Osman, Irwin, and Yantis (1988) made a review about modern mental chronometry that includes a description of these rules. The following will give an overview of those rules that are relevant for the present work.

Functional significance. If the peak latency of an ERP is dependent on an experimental manipulation that is known to have an influence on a particular cognitive process, it can be concluded that this ERP is a manifestation of this cognitive process or of a following subprocess. N100, for example, is known to vary in tasks that manipulate spatial attention processes (Hillyard, Vogel, & Luck, 1998; Luck, Woodman, & Vogel, 2000). It can therefore be concluded that N100 latency represents the time of some early sensory processes linked to spatial attention.

Locus of the experimental effect. This rule can only be applied if the functional significance of an ERP is known. By comparing ERPs and RT measured in the same task, a few inferences about where the experimental effect within the information processing is located can be made (Meyer et al., 1988). Because RT typically summarizes the time of more processes than ERPs do, the differences in the delay of RT and ERP across experimental conditions reveal some information about the locus of the experimental effect. For example, it is known that in a particular, hypothetical task P300 latency is reflecting the time of stimulus classification, whereas RT additionally captures the time of response selection and the motoric response in the same task. If the peak latency and RT are equally affected in this hypothetical task, it can be concluded that only stimulus classification or a preceding process is involved in the experimental effect. However, if there is a larger delay in RT across conditions than in the peak latency, the experimental effect must happen at a following process of stimulus classification. This following process is affecting the open response to a stimulus but not the generation of the ERP. Furthermore, if in this hypothetical task a delay in the peak latency of P300 across conditions is observed but not on its onset time, it can be concluded that stimulus classification is the first processing stage that is affected by the experimental manipulation (Meyer et al., 1988).

The P300 component that was used in the example is a well investigated ERP component often used as a measure and correlate in the study of information processing (Donchin, 1979; Duncan-Johnson & Donchin, 1982; Rugg & Coles, 1995). It is also the ERP component that was investigated in the present work. After the general overview about the use and the interpretation of ERP components in the prior sections, the following part will therefore give a summary about specifics of the P300 component.

The P300 Component

The P300 component of the event-related potential (ERP) is linked to decision confidence (Mars et al., 2008), uncertainty (Duncan-Johnson & Donchin, 1977), context-updating (Donchin & Coles, 1988; Polich, 2007), or stimulus classification (Kok, 2001), depending on the ERP evoking task requirements. Although a full understanding of the determinants of this component could not be achieved yet, there is general consensus regarding the functional significance of the P300 component. It is considered as an index of the cognitive response to a stimulus (Duncan-Johnson & Donchin, 1982; Johnson, 1988; Polich, 2007; Pritchard, 1981). Polich (2007) characterizes this functionality as context-updating in the working memory. The incoming stimulus is compared to the current mental representation in the working memory, for example the representation of the previous stimulus. If the new stimulus is the same as the previous one, there will be no update of the current representation and the electrophysiological response will be the typical series of sensory ERPs (N100, P200, N200). However, if the incoming stimulus is different to the previous one, the mental representation in the working memory needs to be updated and this update leads to the P300 component as the electrophysiological response. Johnson (1988) describes variation in P300 amplitude using three dimensions: subjective probability, stimulus meaning and information transmission. Subjective probability describes how often a target stimulus is presented among other distractor stimuli. It is the relative frequency that a target is presented within a sequence of stimuli. The less a target is expected from an individual, the more cognitive effort is required to process the stimulus and therefore, a larger P300 amplitude is elicited. The second dimension, stimulus meaning, describes the significance of the stimulus for the specific individual. However, the meaning of the stimulus is seen as independent of the relative frequency of the stimulus. Stimulus meaning is more about the complexity of the task and stimulus as well as about the value of the stimulus. Generally, increased task and/or stimulus complexity requires greater effort in information processing and leads therefore to an increased P300 amplitude. The value of a stimulus accounts for the P300 amplitude in a motivational way. Meaning that the more a stimulus is catching an individual's attention, the larger the elicited P300 amplitude will be. The final dimension in Johnson's (1988) triarchic model of P300 amplitude is information transmission. It refers to the subjective accuracy or the received amount of information coming from a stimulus. This means that the variation of P300 amplitude depends on how confident the individual is about the accuracy of its own performance. If an individual cannot figure out the correct response of a task, e.g. due to lack of attention or ambiguity of a stimulus, no or a relatively small P300 amplitude is elicited. This leads to a decrease in P300 amplitude, if the stimuli are getting too complex or ambiguous. Basically, if the attentional resources of information processing have to be divided or are overloaded by a task, it will show in a decreased P300 amplitude (see Figure 2).

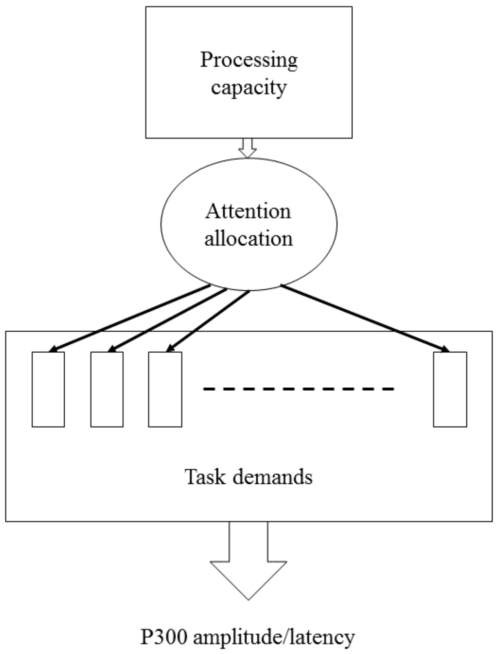

Figure 2. Illustration of the effect of attentional resources on P300 measures. Adapted from Polich (2007)

Besides the amplitude of the P300 component, there is another parameter often used in the study of cognitive processing, namely the P300 latency (Duncan-Johnson & Donchin, 1982; Kutas et al., 1977). P300 latency is a temporal measure for the context-updating process and is the central electrophysiological parameter for the present work. In the following sections P300 latency will therefore be introduced as a measure of speed of information processing, and in relation with RT and intelligence, respectively.

P300 latency as a measure of speed of information processing. The latency of the P300 component is considered to index the time of different underlying processes of the cognitive response to a stimulus, respectively the time that an individual needs to evaluate a stimulus and update the mental representation in the working memory (Kutas et al., 1977; Polich, 2007). However, P300 latency is not considered to be a more immediate measure of cognitive processing time than RT. Duncan-Johnson and Donchin (1982) rather suggest that

P300 latency is an additional index of speed in the study of information processing. The brain response has to be seen as another kind of behavior that can reveal some additional information in the study of information processing and its timing (Duncan-Johnson & Donchin, 1982). Stimulus evaluation hereby describes a subset of processing stages, namely apprehension, encoding and converting of a stimulus. Stimulus evaluation can be dissociated from the response-related processing stages response selection and execution (Duncan-Johnson, 1981). This interpretation of P300 latency as stimulus evaluation time came up with the discovery of the dependence of P300 amplitude on stimulus probability (Johnson, 1988). Because the probability of a stimulus cannot be determined until it is categorized, P300 latency is most likely at least as long as it takes to evaluate a stimulus (Duncan-Johnson & Donchin, 1982). This view is also in accordance with the context-updating theory of P300 (Polich, 2007). P300 is only elicited, if the representation in the working memory is updated. To do so, the incoming stimulus has to be evaluated, more specifically, compared to the current mental representation. P300 latency is therefore often used as a measure of stimulus evaluation time or of speed of information processing (Kutas et al., 1977; McCarthy & Donchin, 1981). Confirmation of the stimulus evaluation view of P300 latency was found by showing that P300 latency generally increases in dependence of the complexity of a stimulus and is often independent of response selection and always of response execution (Kutas et al., 1977; Pritchard, 1981; Verleger, 1997). The complexity of stimulus evaluation was hereby manipulated by reducing the discriminability of stimuli, which makes the stimulus categorization more difficult. McCarthy and Donchin (1981), for example, tested the influences of stimulus discriminability and stimulus-response compatibility on both, RT and P300 latency. In accordance with the stimulus evaluation time view, both manipulations had an additive effect on RT, but only the manipulation of stimulus discriminability delayed P300 latency. Similarly, Smulders, Kok, Kenemans, and Bashore (1995) investigated RT, P300 latency and the lateralized readiness potential (LRP) in a choice reaction time task manipulating stimulus degradation and response complexity. The LRP is used as a measure for the activation of the central response system (Eimer, 1998). Again, RT was delayed by both manipulations, stimulus degradation and response complexity, while P300 latency was only affected by the increase of stimulus degradation but not by response complexity. This makes the P300 latency a useful measure to assess the timing of the cognitive response to a stimulus, which is compared to RT, unaffected of response execution and often also of response selection. However, there are also studies that showed that P300 latency is sometimes sensitive to manipulations of response-related processing, especially in studies that manipulated response selection with a response incompatibility instruction or by increasing response alternatives. Christensen, Ford, and Pfefferbaum (1996), for example, investigated P300 latency and RT in a discrimination task in which participants had to respond to the words “left” and “right” either based on the meaning of the word, the case of the word, or both, meaning and case. Each task was furthermore conducted with intact and degraded stimuli and for half of the trials participants were given a response incompatibility instruction. The degradation of the stimuli was a manipulation on stimulus evaluation, while the response incompatibility instruction increased the complexity of response selection. Both measures, RT and P300 latency were delayed by the stimulus degradation and the stimulus-response incompatibility. However, incompatibility only affected P300 latency when participants had to respond based on the meaning of the word, but not based on the case of the word. Falkenstein et al. (1994a) reported a delay in P300 latency in a choice reaction time task, in which the complexity of response selection was manipulated by adding response alternatives. Participants had to react on one letter at a time, either out of two or four alternatives. The findings of a sensitivity of P300 latency to response-related processes are not compatible with the stimulus evaluation view of P300 latency. However, in a lot of studies that report this response-related sensitivity of P300 latency, the requirements of stimulus evaluation are affected as well, even though they mainly focus on response selection. Thus, a sensitivity of

P300 latency to response selection, independent of stimulus evaluation, is not confirmed. In the study of Christensen et al. (1996), for example, response incompatibility did only affect P300 latency when participants responded based on the meaning of the words. This means that the stimuli had to be evaluated first, and, more importantly, the imperative stimulus was not the same in each trial. It was either the word “left” or the word “right”. Similarly, in the study of Falkenstein et al. (1994a), the stimulus evaluation requirements were not to be neglected. Participants had to categorize either one out of two or one out of four letters before they had to select the corresponding response. Doucet and Stelmack (1999) even suggest that response incompatibility only affects P300 latency if the incompatibility is cued by an implicit part of the stimulus, but not if incompatibility is explicitly instructed prior to the target presentation.

Taken together, it can be said that the functional significance of P300 latency is not fully clear yet. While various studies confirm the stimulus evaluation time view of P300 latency (Donchin, 1979; Duncan-Johnson, 1981; Duncan-Johnson & Donchin, 1982; Kutas et al., 1977; McCarthy & Donchin, 1981), there are findings that are not compatible with this view (Christensen et al., 1996; Falkenstein et al., 1994a; Falkenstein, Hohnsbein, & Hoormann, 1994b; Pfefferbaum et al., 1986; Verleger, 1997). However, a sensitivity of P300 latency to response-related processes independently of stimulus evaluation has not been investigated yet. In order to illustrate the sensitivity of P300 latency to different information processing stages, the following section will elaborate P300 latency as a measure of speed of information processing relative to RT.

The relation of P300 latency and reaction time. P300 latency and RT are both used as measures of speed of information processing and thus it is very intuitive that a positive correlation between P300 latency and RT is often observable (Duncan-Johnson & Donchin, 1982). A positive correlation indicates that they measure the time of at least some common underlying processes. However, the direction and size of this correlation can be modified or even eliminated depending on the emphasis of specific characteristics of a task such as stimulus discriminability or response selection (Kutas et al., 1977; McCarthy & Donchin, 1981). Both, the size and the direction of the correlation between RT and P300 latency is highly dependent on task requirements and what set of processes are affected by the experimental manipulation. While RT is representing the time of and therefore delays in sensory, cognitive, and motoric processing, P300 latency is only representing the time of and delays in sensory and cognitive processing prior to response execution (Doucet & Stelmack, 1999; Luck, 2005; Pfefferbaum, Ford, Johnson, Wenegrat, & Kopell, 1983). Accordingly, if a task requires mostly stimulus evaluation, one can expect that P300 latency and RT are measuring mostly the same underlying processes and their correlation will be large and positive. Tasks that are determined by response selection or response execution, however, will largely only have an impact on RT but not or only minimally on P300 latency (Doucet & Stelmack, 1999; Duncan-Johnson & Donchin, 1982). In those tasks, P300 latency and RT might be representing the time of some common processes, e.g. stimulus evaluation, but RT will be affected by other processes as well that are not affecting P300 latency, like response execution. In tasks with a focus on response selection or execution, only a small or no correlation at all is expected between P300 latency and RT (Doucet & Stelmack, 1999).

Callaway (1983) introduced a different approach than the correlational analyses to investigate the relation between P300 latency and RT. Callaway (1983) defined a sensitivity measure that is the ratio between the delay in P300 latency and the delay in RT across experimental conditions. Under the assumption that information processing is a serial sequence of processing stages, this sensitivity measure contains information about the stage of information processing that is affected by the experimental manipulation. If the ratio is zero, P300 latency was not affected by the experimental manipulation. This means RT is increasing across conditions whereas P300 latency is not. In that case, the experimental effect takes place at a very late, response-related stage of information processing, e.g. response execution. Medium ratios imply that P300 latency was affected by the experimental manipulation, but to a smaller degree than RT. This means the experimental effect has an impact on some processing stages that are represented by both, P300 latency and RT, e.g. stimulus evaluation, but also on some processing stages that are only captured by RT, e.g. response execution. At last, if the ratio is one, the experimental effect happens at very early stages, like encoding or stimulus evaluation, and has therefore the same effect on both, P300 latency and RT. Verleger (1997) used this ratio of delay in P300 latency and RT in a review about P300 latency comparing a variety of different tasks to get a better understanding of the functional significance of P300 latency. He defined three sensitivity categories. P300 latency/RT ratios ranging between zero and 0.33 were considered as low/no sensitivity, ratios between 0.33 and 0.67 as medium sensitivity, and ratios between 0.67 and 1.0 or above 1.0 as high sensitivity. This thorough review of P300 latency sensitivities over a large variety of tasks revealed the following main findings. P300 latency is always high in sensitivity in tasks that are focussing on encoding, an early stage in information processing. This is not very surprising considering the stimulus evaluation view of the P300 latency. A rather unexpected finding in terms of the stimulus evaluation view, was that P300 latency showed high sensitivity in some tasks with focus on response selection (e.g. Simon effect). Additionally, the sensitivity of P300 latency in the Eriksen-Flanker task that requires both, encoding and response selection, was high as well. Response selection was also the focus of two tasks in which P300 latency had medium sensitivity. Experimental effects at intermediate stages of information processing, meaning in stages in between early and late stages, also seem to have a medium impact on P300 latency relative to RT. For example, P300 latency showed medium sensitivity in a Sternberg memory task that requires mostly a search in short-term memory. Low sensitivity in P300 latency was found in two kind of tasks: in one that mainly required response selection, and one in which the experimental manipulation was a speed instruction. There were also some task variations that had an effect on RT, but no effect on P300 latency. In accordance with the stimulus evaluation view of the P300 component, one of those tasks focused on response execution. The other tasks affected intermediate processing stages between encoding and response selection, e.g. mental rotation. Summarizing Verleger's (1997) findings, it can be concluded that relative to RT, P300 latency is very sensitive to manipulations taking place at early stages of information processing, e.g. encoding, but not to manipulations that affect late stages of information processing, e.g. response execution. Experimental manipulations that affect intermediate stages of information processing, especially response selection, have very different effects on P300 latency depending strongly on the type of task. While stimulus-response compatibility has no significant influence on P300 latency (Duncan-Johnson, 1981; Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981), variation in choice complexity affects P300 latency (Falkenstein et al., 1994a; Pfefferbaum et al., 1983; Ragot, 1984). Lastly, P300 latency is typically low in sensitivity in tasks with speed instructions (Pfefferbaum et al., 1983).

The relation of P300 latency with intelligence. Since P300 latency is considered as an index of speed of information processing, the relation of P300 latency with intelligence has been investigated within the mental speed approach. The findings are not conclusive, and seem to be strongly dependent on the task that was used to elicit the P300 component (Schulter & Neubauer, 2005). A large amount of studies that investigated the relation between P300 latency and intelligence used the classic oddball paradigm. The classic oddball task consists of infrequently occurring target stimuli that are presented in a stream of more frequently occurring standard stimuli. The stimuli are presented in both ways, either visually or auditory. Under both modalities a negative correlation of about r = -.30 between the oddball P300 latency as a measure of speed of information processing and intelligence could be demonstrated (De Pascalis, Varriale, & Matteoli, 2008; Jaušovec & Jaušovec, 2000;

Stelmack & Houlihan, 1995). De Pascalis et al. (2008) found a negative correlation between P300 latency in an auditory oddball task with backward masking and Raven Standard Progressive Matrices (RSPM) scores, a measure for reasoning performance. Jaušovec and Jaušovec (2000) also reported negative correlations between P300 latency of an auditory and visual oddball task and Wechsler Adult Intelligence Scale (WAIS) scores, a measure for general intelligence. There were several other studies that reported negative correlations between P300 latency in mostly auditory oddball paradigms and different intelligence measures (Bazana & Stelmack, 2002; McGarry-Roberts, Stelmack, & Campbell, 1992; Stelmack & Houlihan, 1995). However, there has been studies that used other tasks with different, often more complex task requirements than the oddball task that revealed no or in one study even a positive correlation between P300 latency and intelligence (Barrett & Eysenck, 1992; Egan et al., 1994; Houlihan, Stelmack, & Campbell, 1998; Widaman, Carlson, Saetermoe, & Galbraith, 1993). Widaman et al. (1993), for example, reported very inconsistent and low correlations between average auditory evoked potentials and intelligence measures that included general, fluid and crystallized intelligence. A positive correlation was reported in a study that used a Sternberg memory task (Houlihan et al., 1998). The Sternberg memory task is an ECT in which participants have to memorize a set of stimuli (memory set), usually letters. Afterwards, one single stimulus (probe stimulus) is presented and the participant has to decide as fast as possible if the probe stimulus was part of the memory set or not. The difficulty of this task increases with the size of the memory set that usually varies between one and five stimuli. In the study of Houlihan et al. (1998), the P300 component was measured to both, the memory set and the probe stimulus. While the P300 latency to the probe stimulus did not differ between higher-ability and lower-ability participants, the P300 latency to the memory set was actually longer in higher-ability than lower-ability participants. The authors explained this result with the possibility of a longer and more precise encoding and planning strategy in higher-ability individuals for tasks that require more than just a simple discrimination or classification as it is the case in the oddball task. Despite this unexpected relation of P300 latency with intelligence, the known inverse relation of RT with intelligence was confirmed in Houlihan et al.'s (1998) study. This finding suggests that the RT-intelligence relation might partly be mediated by response-related components. This means that the RT-intelligence relation is not completely explained by cognitive processing stages, but also by response-related processes like response selection and execution. To sum up, previous research on the relation between P300 latency used as a measure of speed of information processing and intelligence does not provide a consistent outcome. The relation between P300 latency and intelligence seems to depend highly on the specific processes that P300 latency is reflecting and therefore on the requirements of the task.

Conclusions and Research Questions

The goal of the present work was to investigate P300 latency in the Hick paradigm in order to get more clarity about its sensitivity to manipulations focusing on response selection and thus about its functional significance. P300 latency has been used in mental speed studies as an index for speed of information processing before (Donchin, 1979; Duncan-Johnson, 1981), but, to my knowledge, never in the Hick paradigm. The Hick reaction time task is one of the most frequently applied ECTs within the mental speed approach. Compared to other choice reaction time tasks, response selection is systematically manipulated across conditions while stimulus evaluation is kept constant and minimally. This makes the Hick paradigm an excellent tool to investigate the sensitivity of P300 latency towards manipulations on response selection. By taking this one step further and contrasting RT and P300 latency as predictors of intelligence, it was aimed to gain some additional information about the relation of the measures of speed of information processing. In the following sections, the research questions will be elaborated step by step. The structure of the research questions will be adopted for the method and result sections. Results will be discussed on the basis of the present data first, before they will be integrated in previous literature.

RT in the Hick paradigm

RT has been used as a measure of speed of information processing in the Hick paradigm in a large amount of studies. Hick's law describes the linear increase of information processing time in dependence of bits of information that have to be processed. This dependency has often been replicated and is widely accepted and established (Jensen, 2006). In the current study, it was therefore expected to find a linear increase of RT across bit conditions.

P300 latency in the Hick paradigm

P300 latency has not yet been investigated in the Hick paradigm. P300 latency has been used, however, as an index of speed of information processing complementary to RT (Kutas et al., 1977; McCarthy & Donchin, 1981; Verleger, 1997) and often considered as a measure of stimulus evaluation time. Nevertheless, P300 latency is not sensitive to all experimental manipulations that have an impact on RT or not to the same degree (Verleger, 1997). Relative to RT, P300 latency is always sensitive to manipulations in encoding processes, has moderate sensitivity to manipulations that impact intermediate processing stages and is only slightly sensitive to tasks with speed instructions (Verleger, 1997). P300 latency shows very variable, from low to high, sensitivity to manipulations that affect response selection and is not sensitive to manipulations of response execution. Previous studies that investigated P300 latency in choice reaction time tasks sometimes found a delay in P300 latency as response selection got more complex (Falkenstein et al., 1994a; Pfefferbaum et al., 1983). A sensitivity of P300 latency to response selection manipulations is not compatible with the stimulus evaluation view of the P300 latency. However, a lot of choice reaction time tasks do not only manipulate response selection, but have also an increase of complexity in stimulus evaluation. The Hick paradigm, on the other hand, is a choice reaction time task that increases the complexity of response selection by adding response alternatives, while maintaining the complexity of stimulus evaluation constant and minimally, since it is always the same stimulus. The Hick paradigm is therefore a qualified task to investigate if the P300 latency is sensitive to response selection. However, since P300 latency was never explicitly investigated in the Hick paradigm, the course of P300 latency was investigated in an explorative manner in order to get a better understanding of the functional significance of the P300 latency.

The relation of P300 latency and RT in the Hick paradigm

Previous findings showed that the correlation between RT and P300 latency is varying in both, size and direction, depending on the task demands (Duncan-Johnson & Donchin, 1982; Kutas et al., 1977; McCarthy & Donchin, 1981). In tasks with an emphasis on stimulus evaluation the correlation of RT and P300 latency is usually large and positive. On the other hand, in tasks that focus on response selection, RT and P300 latency do either correlate negatively or not at all. Furthermore, correlations are usually smaller when participants are instructed to respond as fast as possible and higher when participants are instructed to focus on accuracy (Pfefferbaum et al., 1983). Since the complexity manipulation in the Hick task is the addition of response alternative and the focus of the task therefore lies on response selection, the correlation between P300 latency and RT was expected to be small and negative. Furthermore, delays in P300 latency and in RT across bit conditions were compared with the purpose of gaining information about the sensitivity of P300 latency to the increase of response alternatives.

The relation of RT and intelligence

Faster information processing is related to higher levels of intelligence (Jensen, 2006). This finding was established in a large amount of studies using Hick RT as an indicator of speed of information processing (Deary, Der, & Ford, 2001; Neubauer, 1995; Vernon, 1987). Furthermore, the negative correlation between RT and intelligence is increasing across complexity, meaning that RT under higher bit conditions is correlating higher with intelligence than RT under the 0 bit condition (Neubauer, 1995). In the present study it was therefore expected to find the same negative, across complexity increasing relation between RT and intelligence.

The relation of P300 latency and intelligence

The results on the relation of P300 latency and intelligence are ambiguous and it is not fully established yet (Schulter & Neubauer, 2005). It is likely that this relation is hugely determined by the type of task that P300 latency was elicited from, or in other words, by the task demands. Studies that found a negative correlation mostly used the very simple oddball task in which P300 latency is representing stimulus evaluation (Bazana & Stelmack, 2002; McGarry-Roberts et al., 1992; Stelmack & Houlihan, 1995). The study that found the positive correlation was using the Sternberg task that is a little more complex and requires a retrieval from the short-term memory (Houlihan et al., 1998). There were also studies that did not find a correlation between P300 latency and intelligence (Barrett & Eysenck, 1992; Egan et al., 1994; Widaman et al., 1993). Because of the non-conclusive previous findings, the investigation of the relation between P300 latency in a Hick reaction time task and intelligence was also explorative. Based on the results of previous studies that investigated this relation, it highly depends on the localization of the experimental effect in the Hick task, and if this affected stage(s) is/are represented by P300 latency.

Contrasting P300 latency and RT as predictors of intelligence

In a last step, P300 latency and RT are contrasted as predictors of intelligence. Both, RT and P300, are used as indices of speed of information processing. Nevertheless, both measures are each representing different aspects or stages of information processing. While RT is impacted by all processing stages and is a measure of the summarized time of all processes, P300 latency is not influenced by all processing stages or not to the same degree (Verleger, 1997). It is very sensitive to encoding and intermediate stages, but not to response execution. The influence of manipulations in response selection on P300 latency is not conclusive. However, it is not clear if the covariance of RT and intelligence and the covariance of P300 latency and intelligence are largely overlapping or if RT and P300 latency explain mostly unique parts of variance in intelligence. If RT and P300 latency are correlating, P300 latency would most likely be representing the same processes of information processing as RT and therefore explain mostly the same parts of variance in intelligence. Nevertheless, if P300 latency and RT are not correlating, the both measures are probably representing different aspects of speed of information processing and also explain different parts of variance in intelligence. Therefore, P300 latency and RT were exploratory examined as predictors of intelligence.

Study 1

Method

Participants. Recruitment was ensued by the online psychology experiment management system of St. Thomas University, Fredericton, Canada. Participants were not eligible for the study if they were taking any centrally acting medication or if they had an underlying neurological disorder. Participants were also rejected from the investigation if they suffered from eczema or had any known skin related allergies or sensitivities to cosmetics or lotions. 159 female undergraduate students from St. Thomas University, Fredericton, Canada participated in Study 1. Only female participants were recruited in order to control for reported sex differences indicating larger P300 components in females than in males (Hoffman & Polich, 1999). 17 participants did not complete the study, meaning that after participating in the first session, they did not show up for the second part of the experiment. 11 participants had to be excluded from the sample because of a technical problem during the EEG recording, which led to wrong or no recording of stimulus markers. Another participant had to abort the EEG recording due to an allergic skin reaction to the electrolyte gel used in the EEG set up. For the calculation of individual P300 averages a minimum of 15 acceptable trials was determined by the author. 14 participants had to be excluded from analyses because there were not enough acceptable trials left after the artefact rejection in the EEG data preparation. Finally, three participants were excluded from the final sample after the RT pre-analysis due to overly slow mean RTs across bit conditions. The final sample consisted of 113 participants ranging in age between 17 and 38 years. The average age of participants was 19.9 ± 2.7 years. 100 participants were right-handed and 13 left-handed. All participants had normal or corrected-to-normal vision and hearing. Prior to attendance, participants received information about the course of the study and gave informed written consent. Participants were asked not to consume caffeine or nicotine 2 hours prior to the EEG recording. They received either course credit and/or were paid $ 10 CAD per hour of participation. The study was approved by the local ethics committee.

Psychometric intelligence. Psychometric intelligence was assessed using a well-known measure of reasoning performance, the Culture Fair Test Scale 20-R (CFT 20-R; Weiss, 2006). This test was chosen because previous research suggested that the Hick RT-intelligence correlation is typically larger when using indicators of reasoning performance, fluid intelligence or g instead of indicators of crystallized intelligence (Sheppard & Vernon, 2008). Besides having a measure of reasoning performance, the applied test allowed for the extraction of a g-factor (Spearman, 1927) that is a strong predictor of general intelligence.

Reasoning performance. The short version of the Culture Fair Test Scale 20-R part one (CFT 20-R; Weiss, 2006) was administered as a measure of reasoning performance and fluid intelligence. CFT 20-R is a language free intelligence test to assess “general fluid ability”, a concept that was developed by R. B. Cattell (1971). The short version of CFT 20-R part one compromises four subtests: sequences, classifications, matrices, and topological conclusions. Weiß (2006) reported a test-retest reliability for CFT 20-R part one of r = .85 after two months and of r = .69 after five months, and a Spearman-Brown corrected internal consistency of r = .92.

Hick Paradigm. A modified version of the Hick reaction time task was used to assess speed of information processing (Rammsayer & Brandler, 2002). The task was modified following Neubauer (1991) and Neubauer, Riemann, Mayer, and Angleitner (1997) in the following ways: 1) stimuli were rectangles and plus-signs presented on a computer monitor; 2) participants responded on a “fingers-on-keys” response pad in order to keep the motoric component of speed of information processing as small as possible. As a further, new modification, in order to avoid the generation of P300 to the rectangle additional to the target stimulus, the rectangles (possible stimulus positions) were constantly presented during each condition and there was no fixation cross prior to the stimulus. For the same reason no motivational feedback was given.

Devices and stimuli. Stimuli consisted of white-framed rectangles (1.8 cm × 1.35 cm) and plus-signs (“+”, 0.6 cm) on a black background. Stimuli were presented and responses recorded using Eprime 2.0 on a Dell Trinitron 19” monitor with a screen resolution of 1024 × 768 pixel and a refresh rate of 75 Hz. Participants sat on a chair approximately 70 centimeters in front of the monitor. Responses were registered by an external Cedrus RB-830 response pad that was placed on the lap of the participants. Pretests showed that responses were registered with an accuracy of ± 1 milliseconds (ms). The arrangement of the presented rectangles corresponded to the arrangement of the buttons on the response pad (see Figure 3 for an illustration of the arrangement of stimulus presentation).

Procedure. The task consisted of four conditions with increasing complexity (0 bit, 1bit, 2 bit, 2.58 bit). The order of the conditions was counterbalanced across participants. Each condition consisted of 32 trials that were presented in constant order across participants. Prior to the 32 trials, ten practice trials were presented. The interstimulus interval (ISI) was randomly between 1000 and 2000 ms (1000 ms, 1333 ms, 1666 ms, 2000 ms). Each condition was introduced with written instructions (see Appendix A for detailed instructions). Instructions emphasized to respond as fast as possible while maintaining accuracy. Participants were instructed to use both of their hands except for the 0 bit condition, under which they had to use their right hand. If there were any questions, the examiner gave oral explanation until the task was fully understood by the participant.

In the 0 bit condition (simple RT condition), one rectangle was presented in the center of the screen. After a random ISI, the imperative stimulus ("+") was presented in the center of the rectangle (see Figure 3a). The imperative stimulus remained on the screen until the participant pressed a designated response button. After a random ISI, the next imperative stimulus was presented. In the 1 bit condition two rectangles were presented next to each other (see Figure 3b). The imperative stimulus was presented in one of the two rectangles with a probability of p = .5 for each position. Participants were instructed to press either the right or the left button on the response pad corresponding to the stimulus' position. In the 2 bit condition, four rectangles arranged in two rows were displayed in the center of the screen (see Figure 3c). After a variable ISI, the imperative stimulus was presented in one of the four rectangles with a probability of p = .25 for each position. Participants were instructed to press the corresponding response button after the stimulus was presented. In the 2.58 bit condition, six rectangles arranged in two rows were presented (see Figure 3d). After a variable ISI, the imperative stimulus was presented in one of the six rectangles with a probability of p = .167 for each position.

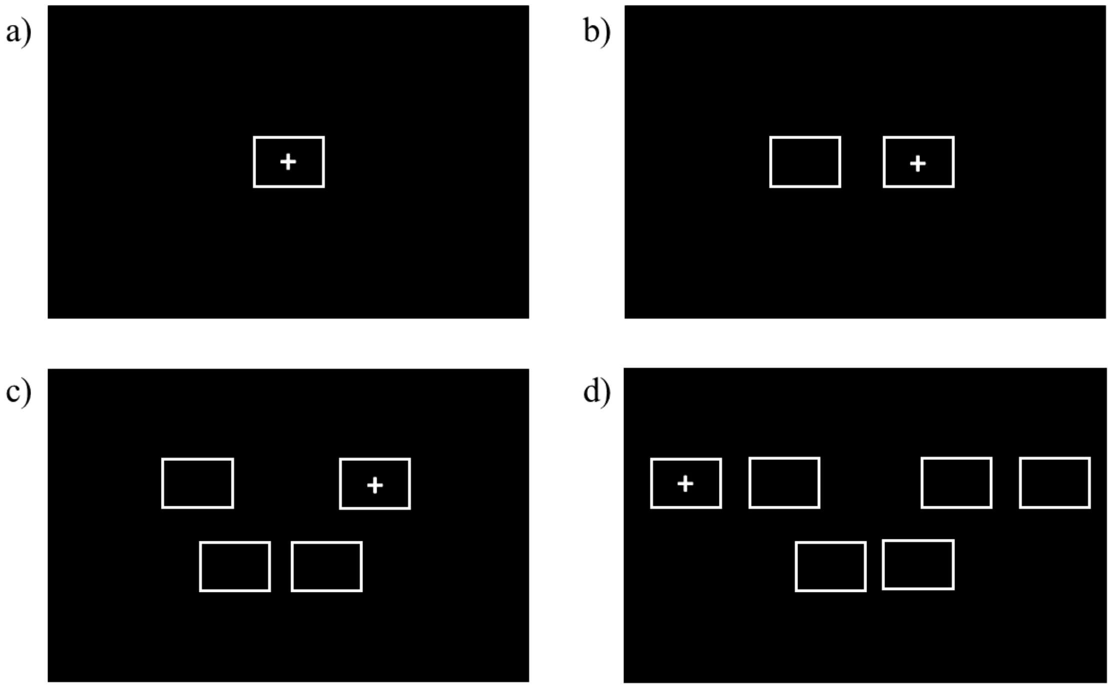

Figure 3. Illustration of the arrangement of the presented rectangles and exemplary stimulus presentation for each condition of the Hick task. a) 0 bit condition; b) 1 bit condition; c) 2 bit condition; d) 2.58 bit condition.

Electrophysiological Recordings. EEG was continuously recorded using a Neuroscan acquisition unit (Nuamps digital amplifier, Compumedics, Inc., El Paso, TX, USA) and 28 Ag/AgCl electrodes embedded in an EasyCap© International electrode cap with linked ears reference. EEG and electrooculogram (EOG) were digitized at a sampling rate of 1’000 Hz. The electrodes were located at standard left- and right-hemisphere positions over frontal, central, parietal, occipital, and temporal areas according to the 10-20 electrode placement system (FP1, FP2, Fz, F3, F4, F7, F8, FC1, FC2, FC5, FC6, Cz, C3, C4, T7, T8, CP1, CP2, CP5, CP6, Pz, P3, P4, P7, P8, O1, O2). EOG was measured using two electrodes placed on the supra- and infraorbital ridges of the right eye (vertical EOG) and another two electrodes (F7, F8) for the horizontal eye movements (HEOG). The ground electrode was affixed to the forehead, approximately 1 cm in front of Fz. Interelectrode impedances were held lower than 5 kΩ.

Artifact removal. EEG data was offline analyzed using Curry 6 software (Compumedics, Inc., El Paso, TX, USA). The continuous EEG data was first visually inspected for movement, sweat, or other artifacts. The manually marked sections were excluded from the data for further analysis. In a next step the manually cleaned data was digitally filtered by using a zero-phase shift 1 to 15 Hz bandpass filter (24 dB/Oct), followed by a ocular blink reduction (-100 and 300 µV) using a regression based procedure (Semlitsch, Anderer, Schuster, & Presslich, 1986).

Detection of P300 component. The cleaned and filtered data was segmented based on the stimulus onset marker of the target stimuli from the Hick task. Only trials that were correct and had an RT between 90 ms to 1500 ms were taken into further analysis. The size of the segments was 900 ms, beginning 100 ms prior to stimulus onset and ending 800 ms after stimulus onset. The segments were baseline corrected for the interval from -100 ms to stimulus onset. An automatic artifact rejection was applied and segments that jumped more than 50 µV/ms over an interval of 200 ms were excluded from further analysis. Data of participants that had less than fifteen segments per condition left after the artifact rejection were excluded from further analysis. In a next step, the segments of each condition were averaged for each participant. The averaged segments were summarized across participants in a grand average (GA) for each condition (see Figure 4 for the GAs of channel Pz).

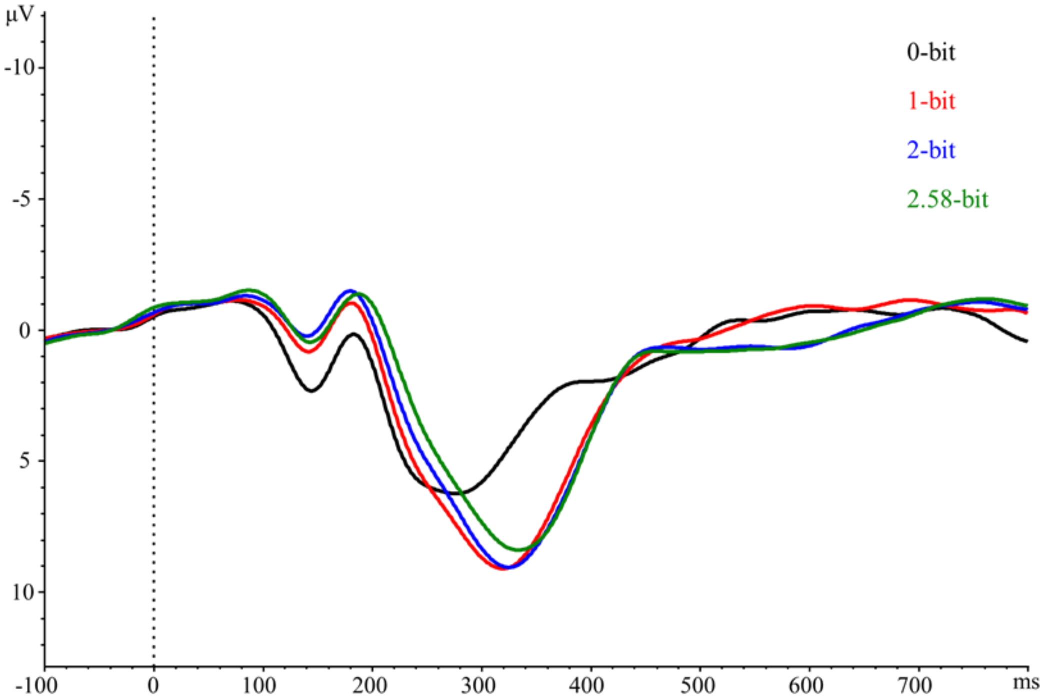

Figure 4. Illustration of the grand average waveforms for the target stimulus of each bit condition in channel Pz.

P300 latencies were only determined for channel Pz by using two different methods: 1) semi-automatic peak detection; 2) 50 percent area latency measurement. The peak detection method is the most frequent used method for determining ERP latencies. Within a defined time interval the maximum amplitude is determined, usually by using an automatic algorithm. The latency of this peak is used as measure of the particular ERP component, unless the following visual inspection leads to a manual shift of the peak. The peak latencies are usually shifted, if the maximum voltage is at the border of the time window, due to an included rising or falling edge of another, larger component, or if there is no distinct peak, e.g.

due to overlapping components or background noise (Luck, 2005). The 50 percent area latency is determined by first computing the area under the particular ERP waveform over a specified time interval (usually defined by means of GA). Afterwards, the time point that divides the computed area into half is used as the 50 percent area latency (Luck, 2005). According to Luck (2005), 50 percent area latency is less sensitive to noise and overlapping components than peak latency, and it is often a more eligible measure for a comparison with RT. However, interindividual variance is decreased in the 50 percent area latency by the constraint of the chosen time window determined by means of the GA. This constraint in variance is helpful for the detection of effects across different conditions but makes the investigation of individual differences difficult.

Semi-automatic peak detection. The time interval for the automatic peak detection was set from 200 ms to 650 ms after stimulus onset. Afterwards, the peaks were visually inspected, and if required, manually adjusted. GA and the activity of other channels were used as guidance for the potential manual adjustment of the peaks (Hoormann, Falkenstein, Schwarzenau, & Hohnsbein, 1998).

50 percent area latency. 50 percent area latency was only determined for channel Pz, too. For each condition, the area under the ERP waveform over a specified time window was computed for each participant. The time window was defined by using the peak latency of GA and adding ±50 ms. The time point at which half of the computed area was reached, was used as P300 latency.

Procedure. Participants completed the study in two sessions. The order of the sessions was constant across participants. In the first session psychometric intelligence was assessed by means of the Multidimensional Aptitude Battery (MAB; Jackson, 1984) and the CFT 20-R part one. The MAB is a well-established and especially in North America widely-used measure of individual levels of general intelligence with strong psychometric properties. It is a heterogeneous test battery and was designed after the Wechsler Adult Intelligence Scale – Revised (Wechsler, 1981). The MAB was assessed for another project and is therefore not further described. One to thirty days after completion of the first session, participants were administering the second part of the study, the assessment of speed of information processing. In the second session participants completed the modified Hick reaction time task, a continuous performance task and two auditory sensory discrimination tasks. The sensory discrimination tasks and the continuous performance task are not part of the present work and are therefore not explained in more detail. The intelligence testing lasted about two hours and the speed of information testing about one and a half hour.

Psychometric intelligence. Intelligence was assessed in individual or group testing sessions with maximally ten participants. Participants first read some general information about the study and gave written consent. Afterwards, the Edinburgh Handedness Questionnaire (Oldfield, 1971) as well as a general health questionnaire were completed. The order of the intelligence tests was always the same, first the MAB was conducted and afterwards the short version of CFT 20-R part one. After participants completed the MAB, there was a break of approximately ten minutes. The procedure of the short version of CFT 20-R part one was adopted from the original testing manual (Weiss, 2006). Participants completed as many items as possible in four minutes each for the first two subtests and in three minutes each for the latter two subtests. The instructions were translated from German to English by the author and edited by an native English speaking person (see Appendix B). It was intended to keep the instruction as close to the original as possible. Instructions for both tests, MAB and CFT 20-R, were given written and oral before each subtest. If there were any questions, the examiner gave explanation until the task was fully understood. Both tests, MAB and CFT 20-R, were performed as paper-and-pencil tests.

Speed of information processing. The assessment of speed of information processing took place in individual test sessions. After some general explanation about the course of the session and about EEG technique, participants got prepared for the EEG recordings. The electrode cap was put on and the electrodes were affixed by using electrolyte gel. Participants were then guided to a separated, sound-attenuated room where they performed the ECTs and sensory discrimination tasks. The order of ECTs and sensory discrimination tasks was constant for all participants, starting with the ECTs. Half of the participants began with the Hick task and half of the participants began with the continuous performance task. The order of the sensory discrimination tasks was constant across participants. During task performance, the examiner observed the participant from the set up room by using video recording. Examiner and participant were also able to communicate at any time by means of an intercommunication system. Participants were allowed to take breaks between tasks as long as needed. Written instructions were given before each task and the examiner gave additional oral explanation if required. After completion of all tasks, the EEG set-up was removed and the participant had the opportunity to wash their hair. At last, the examiner informed the participant about the goal of the study and thanked for their participation. Participants who did not receive course credit were getting paid at the end of the session.

Statistical analyses. Statistical analyses were mainly conducted by using the statistical software IBM SPSS statistics, version 22.0.0.0 (IBM Corporation, 2013). Mean RT and P300 peak latency of each Hick condition were used as measures of speed of information processing. The author decided for the peak latency method because the present investigation was focusing on individual differences rather than the detection of effects across different conditions. Nevertheless, all analyses were also performed using 50 percent area latencies, since this method is often recommended for comparisons with RT (Luck, 2005). However, the results with peak latencies and 50 percent area latencies did not differ (see Appendix C for a brief comparison). For the calculation of the individual means of both speed measures, only correct trials were included, and trials with RTs faster than 90 ms and slower than 1500 ms were excluded (Neubauer et al., 1997). The summarized raw scores of the four subscales of CFT 20-R part one were used as a measure of reasoning performance and fluid intelligence. The sample was median-split for any analyses that compared higher intelligence participants to lower intelligence participants. 51 participants were in the lower intelligence group. Their mean IQ score was M = 87.5 with a standard deviation of SD = 5.3. In the higher intelligence group were 62 participants with a mean IQ score of M = 107.2 and a standard deviation of SD = 8.1.

RT in the Hick paradigm. A repeated measures ANOVA with a within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed to investigate if RT was increasing across complexity. Post-hoc Tukey HSD tests were performed to elaborate the main effect. To examine the increase of RT in dependence of the bit conditions, within-subject contrasts were tested for a linear, quadratic, and cubical trend.

P300 latency in the Hick paradigm. To investigate if P300 latency was increasing across bit conditions, a repeated measures ANOVA with a within-subject factor of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed. Post-hoc Tukey HSD tests were conducted to determine the sources of the main effect. Within-subject contrasts were tested for a linear, quadratic, and cubical trend, to investigate the course of P300 latency in dependence of the complexity levels.

The relation of P300 latency and RT in the Hick paradigm. To investigate the relation of P300 latency with RT correlation coefficients between the two speed measures were computed for each condition. Furthermore, the sensitivity (s) of P300 latency to the experimental manipulation relative to RT was calculated according to Callaway's (1983) ratio as following:

$$s = \Delta P300\ latency / \Delta RT \qquad \textit{(Formula 1)}$$

With Δ being the delay in P300 latency or RT, respectively, between two experimental conditions. *S* was calculated for the delays from the 0 bit condition to the 1 bit condition, from the 1 bit condition to the 2 bit condition, and from the 2 bit condition to the 2.58 bit condition. The sensitivity measure was used to determine the size of the experimental effect in P300 latency compared to the experimental effect in RT.

The relation of RT with intelligence. In order to investigate if faster information processing was negatively related to intelligence, correlation coefficients between RT of each bit condition and intelligence were calculated. Furthermore, a two-way ANOVA with a within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and a between-subject factor intelligence (high vs. low) was computed. Post-hoc Tukey HSD tests were performed to determine the sources of main and interaction effects.

The relation of P300 latency with intelligence. To investigate if there is a relation between P300 latency and intelligence, correlation coefficients between P300 latency of each bit condition and intelligence were calculated. Furthermore, a two-way ANOVA with a within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and a between-subject factor intelligence (high vs. low) was performed. Post-hoc Tukey HSD tests were performed to determine the sources of main and interaction effects.

Contrasting P300 latency and RT as predictors of intelligence. To investigate whether P300 latency and RT are predicting unique or common variance in intelligence, multiple regression and commonality analyses with the factor scores of a P300 factor, a RT factor and a g-factor were performed. Commonality analysis examines the proportion of explained variance in the criterion variable that is unique to a predictor variable and the proportion that is common to two or more predictor variables (Rowell, 1996). Commonality analysis was chosen as a method of partitioning variance in g, because it is not necessary to have any a priori knowledge of the predictors' influence (Rowell, 1996). This allows for an explorative investigation of the contribution of each predictor. The unique part of a predictor is defined as a squared semipartial correlation between the criterion variable and the particular predictor after partialing out all other predictors (Rowell, 1996). The proportions of explained variance in a dependent variable *y* unique to predictor *1* and predictor *2*, respectively, are:

$$U(1) = R^2_{y.12} - R^2_{y.2} \qquad \textit{(Formula 2)}$$

$$U(2) = R^2_{y.12} - R^2_{y.1} \qquad \textit{(Formula 3)}$$

The proportion of variance in the dependent variable *y* explained commonly by predictor *1* and predictor *2* is:

$$C(1,2) = R^2_{y.12} - U(1) - U(2) \qquad \textit{(Formula 4)}$$

Results

Statistical Power. The anticipated statistical power considering the present sample size was computed using the free-source software G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007). A statistical power of $1-\beta = 1$ is anticipated performing a repeated measure ANOVA with an effect size of $f = 0.5$ and $\alpha < .05$ for the current sample size of 113 participants. For the correlational analyses, statistical power of $1-\beta = .56$ with an effect size of $r = .2$, and $1-\beta = .91$ with an effect size of $r = .3$ on a significance level of $\alpha < .05$ is expected.

Testing for Normality. Shapiro-Wilk tests for normality of mean RT, P300 peak latency of each complexity condition, as well as the intelligence measures were performed (see Table 1). The Shapiro-Wilk test is examining the probability of getting the distribution of the collected sample assuming the population is normally distributed. Significant values therefore indicate that the variable is not normally distributed in the sample. As summarized in Table 1, the CFT 20-R full score, P300 latencies under the 1 bit, 2 bit, and 2.58 bit conditions as well as RT under the 2.58 bit conditions were normally distributed. P300 latency under the 0 bit condition as well as RT under the 0 bit, 1 bit, and 2 bit conditions on the other hand were not normally distributed. Since both measures, P300 latency and RT, were not under all conditions normally distributed, the normality assumption for Pearson product-moment correlations was violated. Therefore, Spearman-Rho and Pearson product-moment coefficients were calculated and compared. However, Pearson product-moment coefficients and Spearman-Rho coefficients did not differ (see Appendix D). Hence, only Pearson product-moment coefficients are reported in the following sections.

Table 1
Summary of Shapiro-Wilk tests for normality in intelligence and speed of information processing measures.

		Shapiro-Wilk	
		Statistics	p-Value
CFT full score		.986	.305
P300 peak latency	0 bit	.933	***
	1 bit	.986	.284
	2 bit	.988	.438
	2.58 bit	.988	.418
Mean RT	0 bit	.958	**
	1 bit	.947	***
	2 bit	.952	***
	2.58 bit	.984	.201

Note. **p* < .05; ***p* < .01; ****p* < .001; *df* = 113

Control variables. In a next step, it was investigated if the control variable handedness had an influence on the electrophysiological data, since there are studies reporting differences in electrophysiological data between left- and right-handed individuals (Hoffman & Polich, 1999). A one-way ANOVA with the between-subject factor handedness (left vs. right) was performed for P300 latencies under each condition. Even though the size difference of the groups was large (n_{right} = 100, n_{left} = 13), Levene tests showed that homogeneity of variances was given for the P300 latencies of each bit condition. In none of the four bit conditions did P300 latency differ between handedness groups: 0 bit condition [$F(1, 111) = 0.4$, $p = .511$]; 1 bit condition [$F(1, 111) = 1.6$, $p = .214$]; 2 bit condition [$F(1, 111) = 0.1$, $p = .806$]; 2.58 bit condition [$F(1, 111) = 0.1$, $p = .773$]. Furthermore, the behavioral, as well as electrophysiological data, and the intelligence data were controlled for any influences of the order of tasks/tests, and incentives (course credit vs. money). There were no effects found. Therefore the control variables were excluded of any further analysis.

Performance and speed indicators. Mean error percentages for each Hick condition as well as *Minimum* and *Maximum* are reported in Table 2. Error rates were not included in any further analysis, since the variance in error rates was very low and did not differ between the intelligence groups: 1 bit condition [$F(1, 111) = 1.5$, $p = .217$]; 2 bit condition [$F(1, 111) = 0.4$, $p = .521$]; 2.58 bit condition [$F(1, 111) = 1.1$, $p = .296$].

Table 2
Mean (M), standard deviation (SD), minimum and maximum of the error percentages for each condition of the Hick task.

Error rates	*M*	*SD*	*Minimum*	*Maximum*
Hick 0 bit	0.0	0.0	0	0
Hick 1 bit	0.7	1.4	0	6
Hick 2 bit	2.6	3.3	0	16
Hick 2.58 bit	3.0	3.4	0	16

Note. Error rates are reported in percentages (%).

Table 3 summarizes the means (*M*), standard deviation (*SD*), *Minimum* and *Maximum* values of the intelligence measures and Hick RT as well as P300 latency.

Table 3.

Means (M), standard deviations (SD), minimum and maximum of the performance and speed indicators of intelligence and the Hick paradigm, respectively.

Performance indicators		*M*	*SD*	*Minimum*	*Maximum*
CFT 20-R	Summarized raw scores	38.3	5.1	27	50
	IQ scores	98.2	11.9	74	130
Hick mean RT	0 bit	285	41.2	205	433
	1 bit	342	49.2	242	559
	2 bit	424	67.1	298	686
	2.58 bit	476	65.4	340	644
Hick P300 latency	0 bit	285	46.0	216	450
	1 bit	316	33.4	229	404
	2 bit	324	36.0	223	412
	2.58 bit	333	37.5	225	443

Note. RT and P300 latency are reported in milliseconds.

RT in the Hick paradigm. Table 3 indicates that RT did increase across bit conditions. In order to statistically investigate the course of RT, a repeated measure ANOVA with the within-subject factor “conditions” of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed. Since Mauchly’s test of sphericity was significant [$\chi^2(5) = 43.8$, $p < .001$], the sphericity assumption was violated and the degrees of freedom for the within-subject effects were corrected after Greenhouse-Geisser (Bortz, 2006). Results showed a statistically significant increase of RT across bit conditions [$F(2.5, 281) = 663.1$, $p < .001$, $\eta^2 = .86$]. Post-hoc Tukey HSD tests revealed that RT was significantly increasing across all four bit conditions (all p values < .001) (see Figure 5). Furthermore, tests of within-subject contrasts showed a statistically significant linear and cubical trend in RT across bit conditions (see Table 4).

Table 4.
Tests of within-subject contrasts for linear, quadratical and cubical trends in RT and P300 latency across the bit conditions.

Within-subject contrasts		F	p	η^2
Hick RT	linear	1443.4	<.001	0.93
	quadratic	0.6	0.435	0.01
	cubical	17.6	<.001	0.14
P300 latency	linear	78.9	<.001	0.41
	quadratic	14.1	<.001	0.11
	cubical	4.4	<.05	0.04

Note. Df of within-factor = 1; df of error = 112.

P300 latency in the Hick paradigm. To investigate if P300 latency did increase across bit conditions, a repeated measure ANOVA with the within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed. Mauchly's test [$\chi^2(5) = 30.4$, $p < .001$] indicated that the sphericity assumption was violated. The degrees of freedom for the within-subject effects were therefore corrected after Greenhouse-Geisser (Bortz, 2006).The main effect condition was statistically significant [$F(2.5, 283) = 43.7$, $p < .001$, $\eta^2 = .28$]. However, post-hoc Tukey HSD tests revealed only a significant increase of P300 latency from the 0 bit conditions to all of the other conditions (all p values < .001), and from the 1 bit to 2.58 bit condition ($p < .001$), but not from 1 bit to 2 bit condition ($p = 0.272$), or from 2 bit to 2.58 bit condition ($p = .190$) (see Figure 5). Tests of within-subject contrasts were statistically significant for all tested trends, linear, quadratic, and cubical (see Table 4). This indicates that there was not distinct pattern of increase in P300 latency in dependence of bits of information that had to be processed.

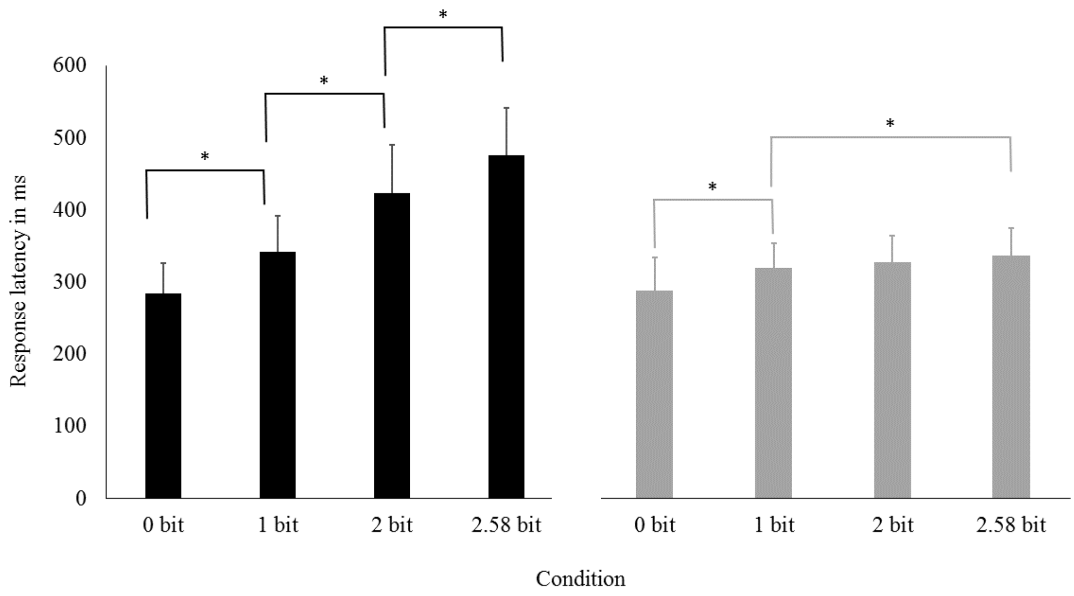

Figure 5. Illustration of the increase of RT (black) and P300 latency (grey) across bit conditions. Note. * $p < .001$

The relation of P300 latency and RT in the Hick paradigm. To investigate the relation between P300 latency and RT, correlation coefficients were calculated. Correlations between the two measures were calculated for each bit condition. The coefficients ranged between r = -.09 and r = .04 (see Table 5). None of the correlations reached statistical significance: r_{0bit} = -.09 (p = .364), r_{1bit} = .05 (p = .660), r_{2bit} = -.03 (p = .775), $r_{2.58bit}$ = -.08 (p = .423). In a next step, the size of the experimental effect across bit conditions in P300 latency relative to the effect in RT was investigated. For this purpose the sensitivity measure of Callaway (Callaway, 1983; Verleger, 1997) was used (see Formula 1). The sensitivity measure is the ratio between the delay in P300 latency and the delay in RT. The sensitivity (s) of P300 latency to the experimental manipulation relative to RT was medium from the 0 bit condition to the 1 bit condition (s_1 = 0.54), low from the 1 bit condition to the 2 bit condition (s_2 = 0.10), and low from the 2 bit condition to the 2.58 condition (s_3 = 0.17), respectively. This indicates that the addition of response alternatives had a larger effect on RT than on P300 latency.

Table 5
Summary of Pearson product-moment correlation coefficients between P300 latency, Hick RT, and intelligence.

Pearson product-moment correlation		P300 latency				Reaction time			
		0 bit	1 bit	2 bit	2.58 bit	0 bit	1 bit	2 bit	2.58 bit
P300 latency	0 bit	---							
	1 bit	0.2*	---						
	2 bit	0.23*	0.39**	---					
	2.58 bit	0.05	0.19*	0.45**	---				
Reaction time	0 bit	-0.09				---			
	1 bit		0.04			0.74**	---		
	2 bit			-0.03		0.55**	0.7**	---	
	2.58 bit				-0.08	0.58**	0.64**	0.69**	---
CFT full score		0.05	0.05	0.15	0.24**	-0.18	-0.19*	-0.06	-0.21*

Note. * p < .05; ** p < .01 (two-sided)

The relation of Hick RT with intelligence. Table 6 summarizes a comparison of Hick RT under each bit condition between intelligence groups. Only RT under the 2.58 bit conditions was larger for the less intelligence group than for the higher intelligence group: 0 bit condition [$F(1, 111) = 2.0$, $p = .160$]; 1 bit condition [$F(1, 111) = 2.3$, $p = .136$]; 2 bit condition [$F(1, 111) = 0.1$, $p = .906$]; 2.58 bit condition [$F(1, 111) = 4.2$, $p < .05$]. A two-way ANOVA with a within-subject factor conditions of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and a between-subject factor intelligence (high vs. low) was performed to investigate the interaction between complexity and intelligence. Mauchly's test showed that the assumption of sphericity was violated [$\chi^2(5) = 43.5$, $p < .001$], hence the degrees of freedom for the within-subjects effects were corrected after Greenhouse-Geisser (Bortz, 2006). The within-subject effect condition could be confirmed [$F(2.5, 277) = 666.1$, $p < .001$, $\eta^2 = .86$], whereas both, main effect intelligence [$F(1, 111) = 2.02$, $p = .158$, $\eta^2 = .02$] and the interaction condition * intelligence [$F(2.5, 277) = 2.2$, $p = .105$, $\eta^2 = .02$] did not reach statistical significance. This means that the increase of RT across conditions did not differ between intelligence groups. Furthermore, Pearson product-moment correlations were calculated between Hick RT of each bit condition and the summarized CFT 20-R full scores. The coefficients ranged between r = -.06 and r = -.21 (see Table 5). Only the correlation between Hick RT under the 1bit and 2.58 bit conditions and intelligence were statistically significant: r_{1bit} = -.19 (p < .05) and $r_{2.58bit}$ = -.2 (p < .05). The correlations between intelligence and Hick RT under the 0 bit and 2 bit condition were not statistically significant: r_{0bit} = -.18 (p = .06) and r_{2bit} = -.06 (p = .54).

Table 6
Summary of the means (M) and standard deviations (SD) of the speed measures RT and P300 latency across intelligence groups.

	low intelligence		high intelligence			
RT	*M*	*SD*	*M*	*SD*	*F*	*p*-Value
0 bit	290	47.7	279	34.7	2.0	.160
1 bit	349	56.7	335	41.5	2.3	.136
2 bit	424	74.9	422	60.6	< 0.1	.909
2.58 bit	489	71.5	464	58.1	4.2	*
P300 latency						
0 bit	283	45.3	287	46.9	0.1	.705
1 bit	310	34.2	321	32.2	3.1	.081
2 bit	316	35.5	331	35.2	5.2	*
2.58 bit	320	38.2	344	33.6	12.4	**

Note. Df1 = 1, *df2* = 111; * p < .05; ** p < .01

The relation of P300 latency with intelligence. As can be seen in Table 6, P300 latency was longer in the high intelligence group compared to the low intelligence group under the 2 and 2.58 bit conditions, but not under the two simplest conditions: 0 bit condition [F(1, 111) = 0.1, p = .705]; 1 bit condition [F(1, 111) = 3.1, p = .081]; 2 bit condition [F(1,

111) = 5.2, $p < .05$]; 2.58 bit condition [$F(1, 111) = 12.4$, $p < .01$]. By performing a two-way ANOVA with a within-subject factor conditions of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and the between-subject factor intelligence group (high vs. low), it was investigated if intelligence had a moderating role on the increase of P300 latency across complexity. Mauchly's test showed that the assumption of sphericity was violated [$\chi^2(5) = 28.7$, $p < .001$], hence the degrees of freedom for the within-subjects effects were corrected after Greenhouse-Geisser (Bortz, 2006). The main effect bit condition [$F(2.5, 282.7) = 42.$, $p < .001$, $\eta^2 = .27$], as well as the main effect intelligence [$F(1, 111) = 8.4$, $p < .01$, $\eta^2 = .07$] reached statistical significance. As already seen earlier, P300 latency did increase across bit conditions and was longer in more intelligent participants than less intelligent participants, especially under the more complex conditions. The interaction of condition and intelligence, however, did not reach statistical significance [$F(2.5, 282.7) = 1.8$, $p = .154$, $\eta^2 = .02$], which means that the increase in P300 latency across conditions was not moderated by the intelligence level. Furthermore, Pearson product-moment correlations were calculated between P300 latency of each bit condition and the CFT 20-R full scores. The coefficients ranged between $r = .05$ and $r = .24$ (see Table 5). The coefficients were all positive which means that participants with higher intelligence had longer P300 latencies. However, only the correlation between the P300 latency under the 2.58 bit condition and intelligence was statistically significant: $r_{0bit} = .05$ ($p = .583$), $r_{1bit} = .05$ ($p = .569$), $r_{2bit} = .15$ ($p = .120$) and $r_{2.58bit} = .24$ ($p < .01$).

Contrasting P300 latency and RT as predictors of intelligence. In a last step, P300 latency and RT were contrasted as predictors of intelligence. For this purpose not the manifest speed and performance measures were used, but the regression-based factor scores of each first unrotated factor of three principal component analyses (PCA). Two PCA were performed over P300 latency and RT of all four bit conditions, respectively. The Kaiser criterion was used for the extraction of factors (Kaiser, 1960). Based on this criterion, only one factor each had an eigenvalue larger than one (see Table 7). The factors extracted from both speed measures were representing speed of information processing captured by RT (RT SIP) and P300 latency (P300 SIP), respectively. Another PCA was performed over the four subtests of CFT 20-R part one. Again, based on the Kaiser criterion, only one factor was extracted with an eigenvalue larger than one. The factor scores of this first unrotated factor were used as an estimate of g. Pearson product-moment correlations were calculated between the factor scores of the three factors, RT SIP, P300 SIP and g. RT SIP and P300 SIP both correlated significantly with g ($r_{P300\ SIP\text{-}g} = .19$, $p < .05$; $r_{RT\ SIP\text{-}g} = -.23$, $p < .05$). There was no significant correlation between the two speed factors ($r_{P300\ SIP\text{-}RT\ SIP} = -.06$, $p = .524$).

Table 7
Summary of factor analytic results obtained from PCA: factor loadings of CFT 20-R subtests, as well as RT and P300 latency of each Hick conditions on each first unrotated factor (g, RT SIP, P300 SIP), eigenvalues, and explained variance

CFT 20-R	g	Hick task	RT SIP	Hick task	P300 SIP
Sequences	0.67	RT 0 bit	0.83	P300 latency 0 bit	0.45
Classifications	0.57	RT 1 bit	0.9	P300 latency 1 bit	0.68
Matrices	0.8	RT 2 bit	0.85	P300 latency 2 bit	0.84
Topological Conclusions	0.58	RT 2.58 bit	0.85	P300 latency 2.58 bit	0.66
Eigenvalue	1.75		2.95		1.8
Explained variance (%)	43.83		73.73		44.9

Three regression models $R^2_{g.P300RT}$, $R^2_{g.P300}$ and $R^2_{g.RT}$ were performed. Normality of all variables is an assumption of multiple regression analysis, unless the ratio of sample size and amount of variables is large enough ($n > 40$ while $k < 10$) (Bortz, 2006). With a sample size of $n = 113$ and $k = 3$ variables, multiple regression analysis was eligible for the current data. Table 8 summarizes the results of the three regression models. Model 1 and 2 showed that P300 SIP and RT SIP predicted each a significant portion of 3.7% and 5.2 %, respectively, of variance in g. Model 3 showed that the combined effect accounted for a portion of 8.4% of explained variance in g. However, in this combined model the contributed portion of P300 SIP was barely not statistically significant (β = .18, t = 1.96, p = .053). This indicates that there is a proportion of variance in g commonly explained by P300 SIP and RT SIP.

Table 8
Summary of regression analyses with the predictors P300 SIP and RT SIP, and the criterion variable g.

				g	
Model	Predictor(s)	F	df	R	R^2
1	P300 SIP	4.3*	1	.19	.037
2	RT SIP	6.1*	1	.23	.052
3	P300 SIP, RT SIP	5.1**	2	.29	.084

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

To elaborate the portions of variance explained in g uniquely by P300 SIP and RT SIP, respectively, as well as the commonly explained portion of variance in g, a commonality analysis according to Formulas 2, 3 and 4 was performed. Commonality analysis revealed that the part of variance in g uniquely explained by P300 latency was $U_{(P300\ latency)}$ = 3.2%, and the part uniquely explained by RT was $U_{(RT)}$ = 4.7%. There was only a small part of variance in g that was explained commonly by P300 latency and RT, $C_{(P300\ latency,\ RT)}$ = 0.5%. This suggests that P300 latency and RT are both predicting small, but distinct parts of variance in g.

Discussion

A linear increase in RT across bit conditions, known as Hick’s law, was reported in multiple studies (Hick, 1952; Jensen, 1982; Neubauer, 1995). It was therefore expected to find this pattern of RT in the present study, too. It can even be considered as a manipulation check for the modified Hick reaction time task used in the present study. Indeed, RT did increase in dependence of the amount of bits of information that had to be processed. A linear and cubical trend in RT across complexity was detected. The effect size of the linear trend was considerably larger than the effect size of the cubical trend, suggesting a linear increase of RT across bit conditions. This is an indication that the Hick reaction time task was properly conducted, and therefore a proper tool to systematically investigate P300 latency in the Hick paradigm for the first time.

A prominent P300 component was recognized in the grand average waveforms in channel Pz for each bit condition (see Figure 4). The P300 component is related to task-relevant stimuli and therefore considered to represent a context-updating of the mental representation in the working memory (Donchin, 1979; Polich, 2007). Accordingly, it is only generated if the current stimulus is allocating attentional resources in order to update the mental representation of the stimulus in the working memory. This view of P300 makes sense for the elicited P300 components under the 1 bit, 2 bit, and 2.58 bit conditions, since the position of the stimulus has to be updated from trial to trial. However, the generation of a P300 component under the 0 bit condition is not intuitive having the context-updating theory in mind. Under the 0 bit condition, each stimulus contains the exact same information, hence an update of the mental representation in the working memory is not necessary. There are two possible explanations in terms of the context-updating theory for why a P300 component was nevertheless elicited under the 0 bit condition. First, the generation of a P300 component under the 0 bit condition in the Hick task could indicate that even in this very simple task some attentional resources are activated and an update in the working memory is made as a confirmation of the current mental representation. Second, there is in fact no context updating under the 0 bit condition and the positive peak around 285 ms as it was found in the GA of the 0 bit condition is not an early P300 component, but instead a late P200 component. P200 is a component that is typically found in between of a N100 and N200 as the electrophysiological response of sensory processing (Luck, 2005; Polich, 2007). Theoretically this second explanation makes sense. As mentioned earlier, under the 0 bit condition each stimulus contains the exact same information and the participant is only required to react on a stimulus as soon as it appears. Therefore, it would be suggestive that the stimulus only activates sensory processing of the stimulus without engaging any further stages of information processing. However, looking at the grand average waveform of the 0 bit condition (see Figure 4), the typical sensory response of N100, P200, N200 is followed by a very salient positive peak around 285 ms, which highly suggests that this peak is a P300 component. Hence, it can be said that there was a generation of a P300 component under all four conditions of the Hick task. This indicates that there is an attention-driven process involved in the Hick task in addition to the sensory processing and response execution, which is reflected by the P300 component. The course of P300 latency across bit conditions was investigated explorative, since it has not been investigated in the Hick paradigm before. Results showed that there was an overall increase of P300 latency across bit conditions. However, the increase mainly happened from the 0 bit condition to the 1 bit condition. In the higher bit conditions P300 latency did not increase much more and no salient trend of increase could be recognized across conditions in the electrophysiological data. Instead, P300 latency seemed to reflect the qualitative change of the task from the 0 bit condition, a simple reaction time task, to the higher bit conditions that are choice reaction time tasks. The functional significance of the P300 latency can be determined based on the process that is associated with the experimental manipulation and that is affecting the P300 latency (Meyer et al., 1988). The main change from the 0 bit to the 1 bit condition is the transition from a simple reaction time task to a choice reaction time tasks. The expected information processing stage associated with this change is response selection. However, the complexity of response selection did also increase from the 1 bit to the 2 bit condition and from the 2 bit to the 2.58 bit condition, while P300 latency did not. Therefore, based on the present data, the functional significance of the P300 latency in the Hick paradigm seems not to be response selection per se, it rather seems to reflect the change from a simple to a choice reaction time task. The process that determines the P300 component must be related to this transition. This transition could be characterized by a decision process or the decision confidence. Decision confidence has been related to the P300 component in previous studies (Mars et al., 2008). While the latency of the P300 component did increase across conditions, the latencies of the early endogenous components (N100, P200, and N200) were constant across complexity (see Figure 4). According to Meyer et al. (1988), this pattern suggests that very early stages of information processing, like stimulus apprehension, are not affected by the addition of response alternatives, while some later information processing stages, like encoding or response selection, must be affected by this manipulation.

To gain some further information about the functionality of P300 latency in the Hick task, the ratio of delay in P300 latency and in RT across conditions was investigated (Callaway, 1983; Verleger, 1997). This ratio revealed a smaller experimental effect in P300 latency relative to RT. While the delay in P300 latency from the 0 bit condition to the 1 bit condition was in a medium range relative to RT, the sensitivity of P300 latency was only low from 1 bit to 2 bit condition and from 2 bit to 2.58 bit conditions. This confirms that P300 latency had the highest sensitivity as the task changed from a simple reaction time task to a choice reaction time task. Meyer et al. (1988) described further how to make conclusions about the location of an experimental effect by comparing the change in RT and P300 latency across conditions. Only requirement is to know the functional significance of the involved ERP component, in this case the P300 component. As elaborated in the previous section, the functional significance of the P300 latency in the Hick paradigm is, based on the present data the change form a simple to a choice reaction time task which is most likely a process related to response selection. According to Meyer et al. (1988) only response selection or a preceding process would be involved, if the change across conditions in both, RT and P300 latency, is about the same. If the manipulation, however, has a larger impact on RT than on P300 latency, a following process would be involved, that influences the open response to a stimulus, but not the generation of P300 latency. Lastly, if the manipulation has an impact on the peak latency of the P300 component but not on its onset time, only response selection would be involved but no previous one. Applied to the present data, Callaway's sensitivity measure of P300 latency revealed that the experimental manipulation had a smaller impact on P300 latency than on RT, which suggests that the main impact of the experimental manipulation in the Hick paradigm is happening at a processing stage after the response selection. In the case of the Hick paradigm this is response execution. Considering that the increase in P300 latency mainly happened from the 0 bit to the 1 bit condition, it is very plausible that the locus of experimental effect is mainly happening at the response execution stage. The increase of P300 latency across bit conditions can in that case be attributed to the addition of the time of an information processing step, namely response selection, under the 1-2.58 bit conditions compared to the 0 bit condition, in which no response selection had to be made. This addition of response alternatives can lower the confidence in the decision, which has an influence on the P300 component (Mars et al., 2008). The relation of P300 latency and RT was additionally investigated by looking at their correlations. The correlations can expose if there is a systematic relation between P300 latency and RT across complexity. Such a systematic relation would indicate that both measures are capturing at least a subset of common underlying processes. Under none of the conditions were RT and P300 latency correlated with each other. This indicates that RT and P300 latency are not measuring the same aspects of speed of information processing in the Hick paradigm. It suggests that the underlying subsets of processes that influence RT and P300 latency are largely different. Even though both speed measures were increasing across complexity conditions, P300 latency and RT seem to be independent measures of speed of information processing. Summed up, it can be said that the present results on the relation between P300 latency and RT in the Hick paradigm show that the addition of response alternatives has a smaller impact on P300 latency than on RT and that there is no relation between the two measures of speed of information processing. This suggests that P300 latency and RT are reflecting different aspects of speed of information processing in the Hick paradigm. Furthermore, the independency of P300 latency and RT, as well as the different sensitivity of the two measures to the experimental manipulation, indicate that the experimental effect in the Hick paradigm might be happening to a large part at late information processing stages, like response execution.

After evaluating the course of P300 latency and RT in the Hick paradigm, as well as the relation of the two speed of information processing measures, the next few sections are aiming to assess the role of speed of information processing for individual differences in intelligence. For this purpose, both, P300 latency and RT, were first separately investigated in relation with intelligence, before they were contrasted as predictors of intelligence. As expected, RT was negatively correlated with intelligence, even though only the correlation between RT under the 1 bit and 2.58 bit condition with intelligence were statistically significant. Hick RT is typically negatively correlated with intelligence in a range of about r = -.10 and r = -.30 (Neubauer, 1995), increasing across bit conditions. As in previous sections elaborated, the correlation is usually rather weak between intelligence and RT under the 0 bit condition, but is increasing across complexity levels (Neubauer, 1995). The non-significant relation between RT under the 0 bit condition and intelligence in the present data is therefore nothing to be concerned about. However, the correlation between RT under the 2 bit condition and intelligence is surprisingly low and needs to be evaluated in more detail. This weak correlation between RT and intelligence could be affiliated to a poorly designed Hick task.

However, the course of RT, as elaborated earlier, was according to Hick's law and thus, the conduction of the Hick task can be considered as properly done. It is also possible that the weak correlations between RT and intelligence are due to a limitation in the intelligence testing. The negative correlation between RT and intelligence is especially strong if the intelligence test is a high g-loading test (Jensen, 1998). CFT 20-R, which was used as intelligence measure in the present study, is described as a measure of reasoning performance and should therefore be a good predictor of fluid intelligence and g. However, there was no difference found in RT between participants with higher compared to lower CFT 20-R scores. It is possible that there was a problem with the translation of the CFT 20-R. Even though CFT 20-R is considered a culture-free and language free intelligence test, CFT 20-R has some instructions that were translated by the non-native English speaking author from German to English. The translated instructions were carefully reviewed and edited by a native English speaking person and the examiner took effort in explaining the tasks by going through some example tasks and answering questions during the intelligence testing sessions. Furthermore, another intelligence test, the Multidimensional Aptitude Battery (MAB; Jackson, 1984) was assessed, however not used for the present study. The MAB is a well-established and especially in North America widely-used measure of individual levels of cognitive ability with strong psychometric properties. It is a heterogeneous test battery and was designed after the Wechsler Adult Intelligence Scale – Revised (WAIS-R; Wechsler, 1981). The MAB comprises five verbal and five performance subtests, which can be summarized as a verbal and a performance score. Furthermore, a full scale score accounting for general intelligence can be computed. The correlation between CFT 20-R raw scores and the MAB full scale raw scores was r = .51. The correlation was statistically significant and it indicates that both intelligence tests measured some common variance. Weiß (2006) reported similar correlation coefficients between CFT 20-R and two extension tests of the CFT 20-R, “Wortschatz” (r = .51) and “Zahlenfolgen” (r = .59). Weiß (2006) also reports a correlation of r = .55 between

CFT 20-R and the “Prüfsystem für Schul-und Bildungsberatung von Horn für 4. bis 6. Klassen” (PSB-R 4-6; Horn, Lukesch, Kormann, & Mayrhofer, 2002) that is a heterogeneous intelligence measure similar to the MAB. Furthermore, the unrotated factor structure of the PCA over the four subtests of the first part of CFT 20-R was very similar to the factor structure of the same analysis reported in the manual of the test (Weiß, 2006). Thus, all in all there is no obvious evidence that the translation of the CFT 20-R had an impact on the validity of the test. Nevertheless, there remains a possibility that the translated CFT 20-R was not a valid measure of intelligence for the current sample. However, the direction of the found correlation between RT and CFT 20-R scores was in the expected way and correlations between MAB full scale scores and Hick RT are about the same size as between CFT 20-R and Hick RT (see Appendix E). All in all, the hypothesis about the relation of Hick RT and intelligence was confirmed in the current study. The negative correlation between RT and intelligence was found. It was, however, weaker than expected. The weakness of this relation was also seen in RT that did not differ between the higher and lower intelligence groups. Although this unexpected weak Hick RT-intelligence relation could indicate a limitation of the present study, the relation between P300 latency and intelligence was still investigated, since there was no clear evidence of invalid data.

The correlation between P300 latency in the Hick paradigm and intelligence was investigated in an explorative manner. If P300 latency actually is a measure of stimulus evaluation time, as often suggested, a negative correlation between P300 latency and intelligence would be in accordance with the mental speed approach of intelligence. But, in the present study, P300 latency was larger in the high intelligence group compared to the low intelligence group. Hence, P300 latency under all conditions was positively correlated with intelligence, although only the latency of the 2.58 bit condition reached statistical significance. However, previous results on the relation of P300 latency in other tasks with intelligence were not conclusive (Schulter & Neubauer, 2005). Typically, a negative correlation with intelligences is found when P300 latency is investigated in the classical oddball task (De Pascalis et al., 2008; Jaušovec & Jaušovec, 2000; Stelmack & Houlihan, 1995). But, there were also studies that used different tasks than the oddball task reporting none or even a positive correlation between intelligence and P300 latency (Barrett & Eysenck, 1992; Egan et al., 1994; Houlihan et al., 1998; Widaman et al., 1993). The study of Houlihan et al. (1998) is the only previous one that reported a positive correlation between P300 latency and intelligence. In this study, P300 latency was measured to the memory set in a Sternberg memory task. The authors explained this correlation with a longer encoding stage in higher ability individuals, which was captured with P300 latency. Studies that found a negative correlation on the other hand, used mostly the oddball task, which is a stimulus discrimination task. The Hick task used in the present study requires participants to react on the target stimulus as fast as possible and the manipulation of the task consists in the uncertainty of the stimulus' position. Participants need to encode and evaluate the position of the target stimulus before they select and execute the response. As elaborated earlier P300 latency in the Hick paradigm is based on the present data most likely somehow related to the time of the response selection. The positive yet for most conditions weak correlation between P300 latency and intelligence as well as the difference in P300 latency between higher and lower intelligence groups suggest that higher intelligence participants were slower in their response choice than lower intelligence participants. Furthermore, this effect seemed to get amplified the more bits of information had to be processed (e.g. under 2 bit and 2.58 bit conditions). Houlihan et al. (1998) suggested that the longer encoding time but still overall shorter RT in individuals with higher intelligence compared to lower intelligent individuals could indicate that the RT-intelligence correlation is partly mediated by response-related components. The current results confirm this suggestion. As elaborated earlier, the addition of response alternatives in the Hick paradigm is mainly affecting the response-related processing stages that influence RT, but only to a small degree P300 latency.

To have more reliable measures of the underlying processes of RT, P300 latency and intelligence, analyses with the factor scores of a g factor and two speed of information processing factors, RT SIP and P300 SIP, were conducted. The pattern of the manifest data could be confirmed with the factor scores. RT SIP correlated negatively with g, P300 SIP correlated positively with g, while the factor scores of the two speed of information processing factors were independent. Furthermore, RT SIP and P300 SIP both predicted unique parts of variance in g and only an insignificant part was common variance. This suggests indeed, what was already indicated by the results of the manifest data. RT and P300 latency are not representing the same aspects of speed of information processing in the Hick paradigm. While RT seems to be a stronger index of the time of response selection and response execution, P300 latency seems to reflect the change from a simple to a choice reaction time task, but is not representing the same underlying processes as RT. These results also indicate that P300 latency cannot be a measure of stimulus evaluation time. The change from a simple to a choice reaction time task is not related to the stimulus evaluation process. Furthermore, if P300 latency would be proportional to the stimulus evaluation time, a positive correlation to RT and a negative correlation to intelligence would be expected.

However, these conclusions are very speculative. P300 latency was investigated for the first time in the Hick paradigm and results need to be replicated before any clear statements about the role of P300 latency in the Hick paradigm can be made. There are also some limitations of the current study that need to be addressed and possibly overcome in future research. Even though the design of the study was carefully planned and realized, not all of the results were as expected. Hick RT was linearly increasing across bit conditions as predicted by Hick's law, however, the inverse relation of RT and intelligence was weaker than expected, especially in the 2 bit condition. The Hick task used in the current study was programmed and conducted taking into account previous criticisms. Longstreth (1984), for example, criticized Jensen's (1982) practice of the Hick paradigm in his extensive investigation of the role of mental speed in intelligence. He stated that the increasing order of presented bit conditions, which Jensen always kept constant, leads to learning effects. This learning effect could cause an underestimation of the slope in RT since it would make the higher bit condition easier for the participants. Following studies that investigated order effects of the bit conditions were not conclusive. However, most studies that investigated the critique of Longstreth (1984) reported no learning effect (Kranzler, Whang, & Jensen, 1988; Larson & Saccuzzo, 1986). Nevertheless, to prevent potential learning effects, the order of presented bit conditions was counter-balanced in the present study. Another criticism of Longstreth (1984) was that the amount of information that has to be processed is confounded by the different sizes of the visual field across the conditions, which has also an impact on the estimation of the RT slope. It is known that peripheral representations on the retina are slower processed than foveal representations (Carrasco, McElree, Denisova, & Giordano, 2003). However, this confounding in the Hick paradigm could not be empirically confirmed (Widaman & Carlson, 1989). Since eye movements have a big impact on electrophysiological recordings and oftentimes overwrite the actual component that is investigated, the visual field of the task was kept as small as possible, as it was also suggested by Neubauer (1991). Furthermore, participants were instructed to keep their eyes in the middle of the screen during the whole task. In this way potential confounding of visual attention effects should be reduced. Even though there was no evidence for a confounding of the RT slope by visual attention effects, Neubauer (1995) mentions that these effects could still have a negative impact on the estimation of the correlation between RT and intelligence. This could be an explanation for the rather weak correlation between RT and intelligence found in the present study. Nevertheless, it would be difficult to completely prevent any visual attention effects, since the addition of response alternatives and therefore an extension of the visual field, is the core of the Hick task. To prevent a confounding of RT by movement time and individual response strategies, which was also a critique of Longstreth (1984), the distinction between

RT and MT was completely renounced in the present study. Participants kept their fingers placed on the response keys during the whole task and there was no home button. This approach was recommended in different studies (Neubauer, 1991, 1995; Smith, 1989). Therefore, it can be said that the Hick task in the current study was meeting today’s standards. However, the task had some new modifications in the stimulus presentation in order to be able to derive clean P300 components to the imperative stimulus. Typically one trial of the Hick task starts with a fixation cross that is followed by the rectangles (possible stimulus locations), and after a random time interval the target stimulus appears in one of the rectangles. After the participant’s response, the monitor turns black before the next trial starts with the fixation cross. Because the appearance of both, the fixation cross and the rectangles, would elicit a P300 component that could have possibly interfered with the P300 component to the target stimulus, the rectangles in the present study were constantly presented during the whole task and no fixation cross was applied. These modifications had apparently no impact on the course of RT in the Hick task, but, it is possible that it could have caused the relatively weak correlation between RT and intelligence. However, since there are no apparent reasons for an impact of the presentation mode to the RT-intelligence relation, it is rather unlikely. Furthermore, the EEG set-up itself, like the wearing of the electrode cap, the potential inconvenience of the electrolyte gel, the new situation, could all have had some influence on the attention of the participants and therefore caused the weaker correlation between RT and intelligence. It is possible, however unlikely, that these modifications of the presentation mode of the stimuli could have had an influence on the RT-intelligence relation. This would be a bad supposition for a valid investigation of the P300 latency in the Hick paradigm. However, the modifications were necessary to be able to derive a reliable P300 latency in the first place. Therefore, to investigate if the present findings were the result of some systematic error in the task design or just a fluke, a replication of the study with the same task, but in a different laboratory was conducted in Study 2.

Study 2

Method

Study 2 was conducted with the intention of determining whether the results from Study 1 could be replicated. Some of the results from Study 1 were surprising, like the complete independence of P300 latency and RT in the same task, as well as the positive correlation between P300 latency and intelligence, and some of the results of Study 1 were expected, like the increase of P300 latency and RT across complexity. The linear increase of RT in dependence of bit conditions indicated that there were no mistakes in the experimental design and the modified Hick task. To my knowledge, P300 latency has never been investigated in a Hick task before and thus the results were somewhat surprising but nonetheless valid. In this second study it was intended to replicate those results to have the opportunity of making more generalizable conclusions. Hence, the goal was to conduct the study as equal as possible to the first study. Therefore, only changes to the original method are reported in the following sections.

Participants. Recruitment was ensued by the University's online psychology experiment management system. Participants were not eligible if they were taking any centrally acting medication or if they had an underlying neurological disorder. 148 undergraduate students from University of Bern, Bern, Switzerland participated in the study. Six participants did not complete the study, meaning that after completion of the first session, they did not participate in the second session. Five participants had to be excluded from the sample because of a technical problem during the EEG recording due to a relocation of the EEG laboratory. 17 participants had to be excluded from analysis because of the poor quality of EEG data that led to an insufficient amount of useful trials. Finally, one participants was excluded after pre-analysis of RT. The final sample consisted of 119 participants (26 male) ranging in age between 18 and 36 years. The average age of participants was 22 ± 3 years. All participants had normal or corrected-to-normal vision and hearing. Prior to attendance, participants received information about the course of the study and gave informed written consent. Participants were asked not to consume caffeine or nicotine 2 hours prior to the EEG recording. They received course credit for the participation. The study was approved by the local ethics committee.

Psychometric intelligence. Psychometric intelligence was assessed using the CFT 20-R (Weiß, 2006) that is a measure for reasoning performance and fluid intelligence, and is explained in more detail in Study 1.

Hick Paradigm. The modified version of the Hick reaction time task of Study 1 was used in the present study to assess speed of information processing. Since the study took place in a different laboratory, the changes to Study 1 are reported in the next section.

Devices and stimuli. Stimuli consisted of white-framed rectangles (2 × 1.7 cm) and plus-signs ("+", 0.5 cm) on a black background. Stimuli were presented and responses recorded using Eprime 2.0 Software on a Dell 17" monitor. Participants sat approximately 60 centimeters in front of the monitor having their head on a head rest in order to have a standardized visual field across participants. Pretests showed that responses were registered with an accuracy of ± 1 ms by an external Cedrus RB-830 response pad that was placed on a table in front of the participant.

Procedure. Each condition was introduced with written instructions (see Appendix F for detailed instructions). Instructions emphasized to respond as fast as possible while maintaining accuracy.

Electrophysiological Recordings. EEG was continuously recorded using a BrainVision© recorder 1.03 (BrainAmp amplifier; Brain Products GmbH, Gilching, Germany) and eight Ag/AgCl electrodes embedded in an EasyCap© International electrode cap with linked ears reference. EEG and electrooculogram (EOG) were digitized at a sampling rate of 1,000 Hz. The electrodes were located at standard left- and right-hemisphere positions over frontal, central, parietal, occipital, and temporal areas according to the international 10-20 electrode placement system (Fz, F3, F4, Cz, Pz, P3, P4, Oz). EOG was measured using two electrodes placed on the supra- and infraorbital ridges of the right eye (vertical EOG) and another two electrodes for the horizontal eye movements (HEOG). The ground electrode was affixed to the forehead, approximately 1 cm in front of Fz. Interelectrode impedances were held lower than 5 kΩ.

Artifact removal. EEG data was analyzed offline using BrainVision© Analyzer version 2.0.4.368 (Brain Products GmbH, Gilching, Germany). Due to a relocation of the EEG laboratory, 23 participants were not tested in the EEG cabin. The raw data of those participants was filtered before the data inspection using a highpass filter of 0.1 Hz, a lowpass filter of 35 Hz and a notch filter of 50 Hz (24dB/Oct) with a time constant of 1.592 seconds. The rest of the data preparation was the same for all participants. First, the continuous EEG data was visually inspected for movement, sweat, or other artifacts. These sections were excluded from the data for further analysis. In a next step the manually cleaned data was digitally filtered by using a highpass filter of 0.5 Hz and a lowpass filter of 35 Hz (24 dB/Oct) with a time constant of 0.318 seconds, followed by an ocular correction after Gratton and Coles (Gratton, Coles, & Donchin, 1983).

Detection of P300 component. The cleaned and filtered data was segmented based on the particular stimuli marker of the target stimuli from the Hick task for each condition. The size of the segments was 1700 ms, beginning 200 ms prior to stimulus onset and ending 1500 ms after stimulus onset. Only correct trials that had an RT within the range of 90 ms to 1500 ms after stimulus onset were taken into further analysis. The segments were baseline corrected for the interval of -200 ms to stimulus onset as baseline. A semi-automatic artifact rejection was applied and segments that jumped 50 µV/ms or more over an interval of 200 ms were marked for exclusion from further analysis. Segments that exceeded ± 100 µV or fell below 0.5 µV within a 100 ms interval were also excluded. Afterwards, every single segment was visually inspected and conspicuous segments were manually excluded. Data of participants that had less than fifteen segments per condition left after the cleaning were excluded from further analysis. In a next step, the segments of each condition were averaged for each participant. The averaged segments were once more filtered by using a highpass filter of 0.5 Hz, a lowpass filter of 15 Hz, and a notch filter of 50 Hz (24dB/Oct) with a time constant of 0.318 seconds. Another baseline correction with the baseline interval of -200 ms to 0 ms was applied and the averaged segments were summarized across participants in a GA for each condition (see Figure 6 for an illustration of the GAs of channel Pz).

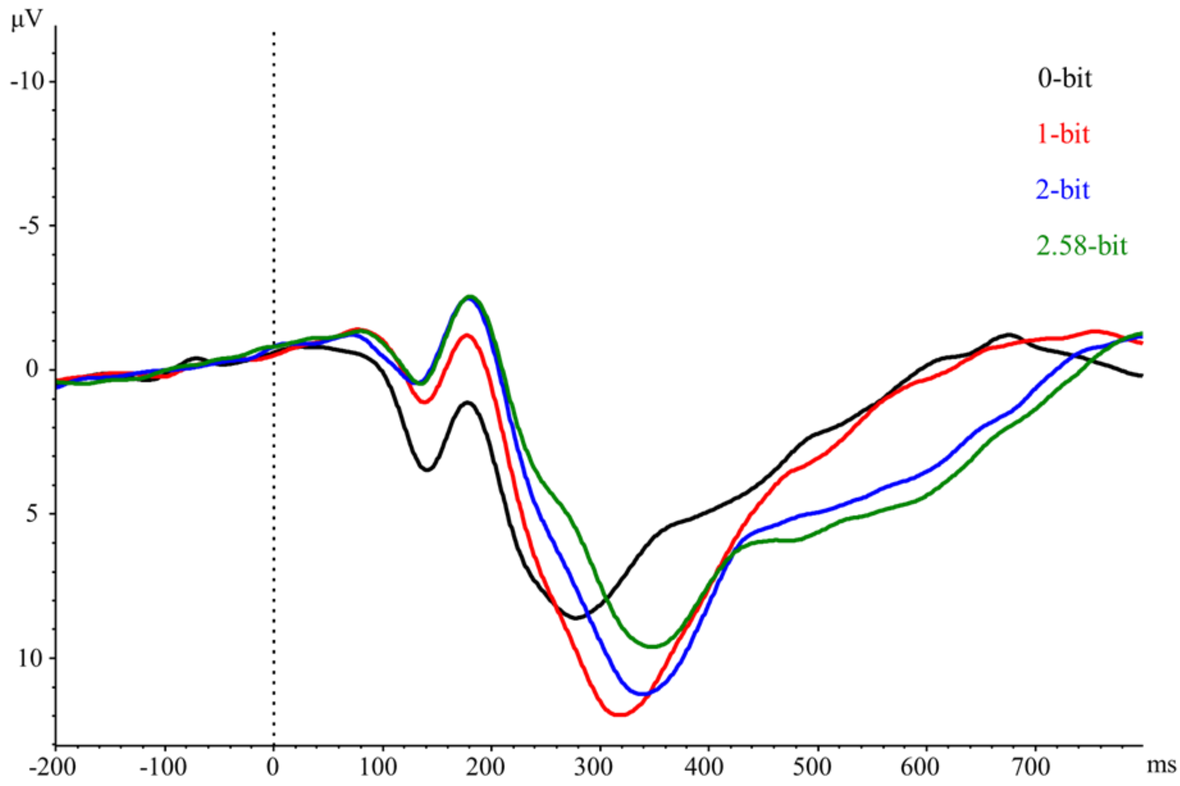

Figure 6. Illustration of the grand averages waveforms for the target stimulus of each bit condition in channel Pz.

P300 latencies were only determined for channel Pz by using the same two methods that were used in Study 1, namely the peak latency method and the 50 percent area method.

Procedure. Participants completed the study in two sessions. The order of the sessions was constant across participants. In the first session, participants filled out questionnaires about demographic data, about general health, about their handedness as well as an impulsivity measure. Afterwards, participants administered the CFT 20-R. One to thirty days later, participants were completing the second part of the study. The second session included the modified Hick reaction time task, a continuous performance task and the Wiener Matrizen-Test 2 (Formann, Waldherr, & Piswanger, 2011). The Wiener Matrizen-Test 2 as well as the continuous performance task were not part of the present thesis and are therefore not explained in more detail. The first session lasted about one hour and the second session about two hours.

Session one. Session one was assessed in individual or group testing sessions with maximally 5 participants per session. Participants first read some general information about the study and gave written consent. The Edinburgh Handedness Questionnaire (Oldfield, 1971), a general health questionnaire as well as the short version of Dickman’s Impulsivity Inventory (Kuhmann & Ising, 1996) were then completed. Afterwards, participants performed part one and two of CFT 20-R (Weiß, 2006). Instructions for all questionnaires and the CFT 20-R, were given written and oral. If there were any questions, the examiner gave explanation until everything was fully understood. All questionnaires and the CFT 20-R were administerd in paper-and-pencil form.

Session two. The second part of the study took place in individual testing sessions. After some general explanation about the course of the session and about EEG technique, participants got prepared for the EEG recordings. The electrode cap was put on and the electrodes were affixed by using isopropyl alcohol and electrolyte gel. Participants were then guided to a separated, sound-attenuated EEG cabin where they performed the Hick task and the continuous performance task. Half of the participants began with the Hick task and half of the participants began with the continuous performance task. During task performance, the examiner observed the participant through a window. The participant was able to press an emergency button at any time in order to cancel the session or inform the examiner about potential problems. Participants could take breaks between tasks as long as needed. Written instructions were given before each task and the examiner gave additional oral explanation if required. After completion of all tasks, the EEG set up was removed and participants had the opportunity to wash their hair. Afterwards, participants completed the paper-pencil version of the Wiener Matrizen-Test 2. At last, the examiner informed the participants about the goal of the study and thanked them for participation.

Statistical analyses. Statistical analyses were mainly conducted by using the statistical software IBM SPSS statistics, version 22.0.0.0 (IBM Corporation, 2013). Mean RT and P300 peak latency of each Hick condition were used as measures of speed of information processing. The author decided again to report only the peak latency method. Nevertheless, all analyses were also performed using 50 percent area latencies, since this method is often recommended for comparisons with RT. A brief summary of the results with the 50 percent area method are reported in Appendix C. For both speed measures, P300 latency and RT, only correct trials were included for the calculation of individual means. Furthermore, trials with RTs faster than 90 ms and slower than 1500 ms were excluded (Neubauer et al., 1997). The summarized raw scores of the CFT 20-R part one were used as a measure of reasoning performance and fluid intelligence. The sample was median-split for any analyses that compared higher intelligence participants to lower intelligence participants. 58 participants were in the lower intelligence group with a mean IQ score of M = 100.8 and a standard deviation of SD = 6.5. In the higher intelligence group were 61 participants with a mean IQ score of M = 121.9 and a standard deviation of SD = 7.8.

The same statistical analyses were performed as in Study 1. There were two more control variables, namely gender and impulsiveness.

Results

Statistical Power. The free-source software G*Power 3.1.9.2 (Faul et al., 2007) was used to estimate the statistical power considering the present sample size of n = 119. A statistical power of 1-β = 1 is anticipated performing a repeated measure ANOVA with an effect size of f = 0.5 and α < .05 for the current sample size of 119 participants. For the correlational analyses, statistical power of 1-β = .60 with an effect size of r = .2, and 1-β = .93 with an effect size of r = .3 on a significance level of α <.05 is expected.

Testing for Normality. Because normality of the variables is a precondition to calculate parametric correlations like the Pearson product-moment correlation coefficients, Shapiro-Wilk tests for normality of mean RT, P300 peak latency for each complexity condition, as well as the intelligence measures were performed. As summarized in Table 9, only the CFT 20-R full score and P300 latency under the 1 bit condition was normally distributed. P300 latency under the 0 bit, 2 bit and 2.58 bit conditions as well as RT under all bit conditions on the other hand were not normally distributed. Since both measures, P300 latency and RT, were not under all conditions normally distributed, the normality assumption for Pearson product-moment correlations was violated. Therefore, Spearman-Rho and Pearson product-moment coefficients were calculated. However, Appendix D shows that the coefficients did not differ. Hence, only Pearson product-moment coefficients are reported in the following sectios.

Table 9
Summary of Shapiro Wilk tests of normality in intelligence and speed of information processing measures

		Shapiro-Wilk	
		Statistics	p-Value
CFT full score		.983	0.139
P300 peak latency	0 bit	.95	***
	1 bit	.985	0.208
	2 bit	.956	***
	2.58 bit	.899	***
Mean RT	0 bit	.946	***
	1 bit	.934	***
	2 bit	.942	***
	2.58 bit	.927	***

Note. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$; $df = 119$

Control variables. In a next step, it was investigated if the control variables gender, impulsiveness and handedness had an influence on the speed of information processing measures. Since there are studies reporting larger P300 components in females than in males (Hoffman & Polich, 1999), a one-way ANOVA with the between factor gender (male vs. female) was performed for P300 latencies under each condition. Even though the size difference of the groups was large (n_{male} = 26, n_{female} = 93), Levene tests showed that homogeneity of variances was given in the 1 bit, 2 bit and 2.58 bit conditions. In the 0 bit condition the variances of the groups was heterogenous, which is a violation of the assumptions for a one-way ANOVA. However, Bortz (2006) suggests that the violation of the homogeneity assumption is negligible if the size of the samples are acceptable ($n_i > 10$). In none of the four bit conditions did P300 latency differ between gender: 0 bit condition [$F(1, 117) = 0.1$, $p = .768$]; 1 bit condition [$F(1, 117) = 1.3$, $p = .264$]; 2 bit condition [$F(1, 117) = 0.2$, $p = .691$]; 2.58 bit condition [$F(1, 117) = 0.1$, $p = .738$]. Furthermore, the behavioral, as well as electrophysiological data, and the intelligence data were controlled for any influences of the order of tasks (starting with the Hick task vs. starting with continuous performance task), handedness and impulsiveness. There were no effects found. Therefore the control variables were not included in any further analysis.

Performance and speed indicators. *Mean* error percentages for each condition as well as *minimum* and *maximum* are reported in Table 10. Since the variance in error rates was very low, only speed measures were included in the analyses for the investigation of individual differences.

Table 10
Mean (M), standard deviation (SD), Minimum and Maximum of the error rates for each condition of the Hick task

Error rates	*M*	*SD*	*Minimum*	*Maximum*
Hick 0 bit	0.0	0.0	0	0
Hick 1 bit	0.9	1.9	0	13
Hick 2 bit	2.6	3.2	0	16
Hick 2.58 bit	3.5	3.4	0	19

Note. Error rates are reported in percentages (%).

Table 11 shows the means (*M*), standard deviation (*SD*), *minimum* and *maximum* values of Hick RT, P300 latency and the intelligence measures.

Table 11

Means (M), standard deviations (SD), minimum and maximum of the performance indicators of intelligence and the Hick paradigm.

Performance indicators		*M*	*SD*	*Minimum*	*Maximum*
CFT 20-R	Summarized raw scores	43.5	4.6	31	54
	IQ scores	111.6	12.8	84	145
Hick mean RT	0 bit	266	31.8	211	376
	1 bit	318	38.0	244	500
	2 bit	404	58.9	280	611
	2.58 bit	462	70.7	315	753
Hick P300 latency	0 bit	292	42.8	208	441
	1 bit	323	37.1	226	452
	2 bit	343	43.6	228	478
	2.58 bit	371	64.0	217	592

Note. RT and P300 latency are reported in milliseconds.

RT in the Hick paradigm. As indicated in Table 11, RT did increase across bit conditions. A repeated measure ANOVA with the within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed to examine this increase. Mauchly's test revealed that the sphericity assumption was violated [$\chi^2(5) = 87.4$, $p < .001$]. Therefore, the degrees of freedom for the within-subjects effect were corrected after Greenhouse-Geisser (Bortz, 2006). A statistically significant main effect [$F(2.1, 246.8) = 734.4$, $p < .001$, $\eta^2 = .86$] was observed. As illustrated in Figure 7, post-hoc Tukey HSD tests revealed that RT increased significantly across each bit condition (all p values < .001). Furthermore, a statistically significant linear and cubical trend in RT across bit conditions was found by performing tests of within-subject contrasts (see Table 12). However, the effect size of the linear trend was substantially larger. This suggests that RT increased linearly across conditions.

Table 12
Tests of within-subject contrasts for linear, quadratical and cubical trends in RT and P300 latency across the bit conditions.

Within-subject contrasts		*F*	*p*	η^2
Hick RT	linear	1177.6	<.001	0.91
	quadratic	1.3	0.266	0.01
	cubical	41.1	<.001	0.26
P300 latency	linear	147.2	<.001	0.56
	quadratic	0.1	0.726	0.00
	cubical	2.9	0.093	0.02

Note. *Df* of within-factor = 1; *df* of error = 118.

P300 latency in the Hick paradigm. Table 11 summarizes the *means* of P300 latency across bit conditions. A repeated measure ANOVA with the within-subject factor conditions of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) was performed in order to investigate if P300 latency did increase across bit conditions. The degrees of freedom for the within-subject effect had to be corrected after Greenhouse-Geisser, because Mauchly's test showed that the sphericity assumption was violated [$\chi^2(5) = 58.9$, $p < .001$]. The main effect was statistically significant [$F(2.5, 283) = 43.7$, $p < .001$, $\eta^2 = .28$]. Post-hoc Tukey HSD tests revealed a statistically significant increase of P300 latency across all conditions (p values all <.001, except for the increase from 1 bit to 2 bit p < .01) (see Figure 7). Tests of within-subject contrasts were only statistically significant for a linear trend, not for a quadratic or cubical trend (see Table 12). This suggests that P300 latency increased linearly in dependence of bits of information that had to be processed.

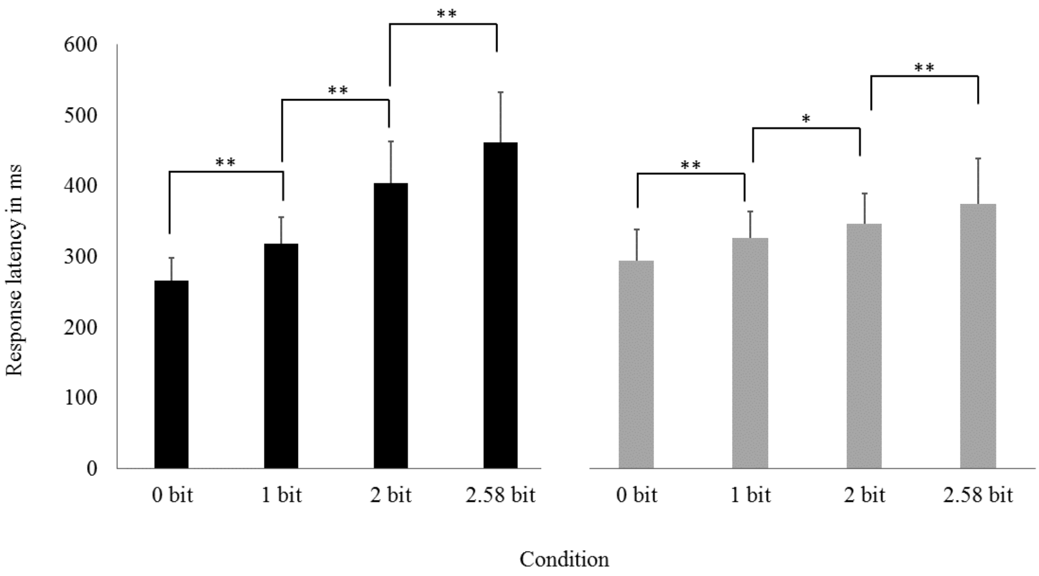

Figure 7. Illustration of the increase of RT (black) and P300 latency (grey) across bit conditions. Note. * $p < .01$; ** $p < .001$.

The relation of P300 latency and RT in the Hick paradigm. Pearson product-moment correlations between P300 latency and RT were calculated for each bit condition to examine the relation between the two measures of speed of information in the Hick paradigm. The coefficients ranged between $r = -.25$ and $r = .03$ (see Table 13). Only the correlation between P300 latency and RT under the 2 bit condition reached statistical significance ($r_{2bit} = -.25$, $p < .01$). The correlations under all other bit conditions were not significant: $r_{0bit} = -.04$ ($p = .671$), $r_{1bit} = .03$ ($p = .730$), $r_{2.58bit} = .01$ ($p = .947$). The size of the experimental effect across bit conditions in P300 latency relative to the effect in RT was investigated by using the sensitivity measure of Callaway (1983) (see Formula 1). The sensitivity (s) of P300 latency was medium for the delay from the 0 bit condition to the 1 bit condition ($s_1 = 0.60$), low for the delay from the 1 bit condition to the 2 bit condition ($s_2 = 0.23$), and medium for the delay from the 2 bit condition to the 2.58 condition ($s_3 = 0.49$), respectively. This suggests that the addition of response alternatives across bit conditions had a larger impact on RT than on P300 latency.

Table 13

Summary of Pearson product-moment correlation coefficients between P300 latency, Hick RT, and intelligence.

Pearson product-moment correlation		P300 latency				Reaction time			
		0 bit	1 bit	2 bit	2.58 bit	0 bit	1 bit	2 bit	2.58 bit
P300 latency	0 bit	---							
	1 bit	0.41**	---						
	2 bit	0.35**	0.45**	---					
	2.58 bit	0.13	0.12	0.35**	---				
Reaction time	0 bit	-0.04				---			
	1 bit		0.03			0.61**	---		
	2 bit			-0.25**		0.46**	0.72**	---	
	2.58 bit				0.01	0.44**	0.62**	0.75**	---
CFT full score		-0.03	0.13	0.07	-0.10	-0.07	-0.21*	-0.2*	-0.33**

Note. * p < .05; ** p < .01 (two-sided)

The relation of Hick RT with intelligence. As summarized in Table 14, only RT under the 2.58 bit condition was significantly larger in the lower intelligence group than the higher intelligence group [$F_{2.58bit}(1, 117) = 9.9$, $p < .01$], although there was a trend under the 1 bit and 2 bit conditions [$F_{1bit}(1, 117) = 3.8$, $p = .054$; $F_{2bit}(1, 117) = 3.6$, $p = .062$]. Under the 0 bit condition, RT did not differ between intelligence groups [$F_{0bit}(1, 117) = 0.8$, $p = .369$]. The relation of Hick RT and intelligence across complexity was investigated by performing a two-way ANOVA with a within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and the between-subject factor intelligence group (high vs. low). Mauchly's test indicated that the sphericity assumption for the within-subject effect was violated [$\chi^2(5) = 80.6$, $p < .001$]. Degrees of freedom were therefore corrected after Greenhouse-Geisser (Bortz, 2006). Both main effects, condition and intelligence, as well as the interaction between condition and intelligence were statistically significant [$F_{condition}(2.1, 250.7) = 763.6$, $p < .001$, $\eta^2 = .86$; $F_{intelligence}(1, 117) = 6.6$, $p < .05$, $\eta^2 = .05$; $F_{interaction}(2.1, 250.7) = 5.3$, $p < .01$, $\eta^2 = .04$]. Post-hoc Tukey HSD tests were calculated for the interaction effects. In both intelligence groups

RT of all conditions were significantly different from each other (all p values < .001). This means that there was an increase of RT across all bit conditions in both intelligence groups. However the increase was steeper for the less intelligent group. Furthermore, Pearson product-moment correlations were calculated between Hick RT of each bit condition and the CFT full scores. The coefficients ranged between r = -.07 and r = -.33 (see Table 13). Only the correlation between the 0 bit RT and intelligence did not reach statistical significance r_{0bit} = -.07 (p = .44), all other correlations were statistically significant: r_{1bit} = -.21 (p < .05), r_{1bit} = -.20 (p < .05), $r_{2.58bit}$ = -.33 (p < .01).

Table 14
Summary of the means (M) and standard deviations (SD) of the speed of information measures RT and P300 latency across intelligence groups.

	low intelligence		high intelligence			
RT	*M*	*SD*	*M*	*SD*	*F*	*p*-Value
0 bit	269	36.0	264	27.3	0.8	.369
1 bit	325	45.3	312	28.4	3.8	.054
2 bit	414	63.6	394	52.8	3.6	.062
2.58 bit	482	82.3	443	51.3	9.9	**
P300 latency						
0 bit	289	48.2	296	37.2	0.7	.394
1 bit	316	39.4	330	33.5	4.7	*
2 bit	337	47.3	348	39.5	2.0	.161
2.58 bit	372	76.0	371	50.8	< 0.1	.938

Note. Df1 = 1, *df2* = 117; * p < .05; ** p < .01

The relation of P300 latency with intelligence. Table 14 shows that P300 latency under the 1 bit condition was larger in the higher intelligence group than in the lower intelligence group [$F_{1bit}(1, 117) = 4.7$, p < .05]. Under all other conditions P300 latency did not differ between intelligence groups: [$F_{0bit}(1, 117) = 0.7$, $p = .394$; $F_{2bit}(1, 117) = 2.0$, $p = .161$; $F_{2.58bit}(1, 117) < 0.1$, $p = .938$]. The relation of P300 latency and intelligence across complexity was tested by means of a two-way ANOVA with a within-subject factor condition of four levels (0 bit, 1 bit, 2 bit, 2.58 bit) and the between-subject factor intelligence group (high vs. low). Mauchly's test showed that the sphericity assumption for the within-subject effect was violated [$\chi^2(5) = 58.1$, $p < .001$]. Degrees of freedom were therefore corrected after Greenhouse-Geisser (Bortz, 2006). The main effect condition reached statistical significance [$F(2.2, 259.5) = 77.3$, $p < .001$, $\eta^2 = .4$]. The main effect intelligence [$F(2.2, 259.5) = 0.8$, $p = .468$, $\eta^2 = .01$] as well as the interaction of bit condition and intelligence [$F(1, 117) = 1.8$, $p = .108$, $\eta^2 = .02$] did not reach statistical significance. This suggests that P300 latency did not differ between intelligence groups and neither did the increase of P300 latency across complexity. Furthermore, Pearson product-moment correlations were calculated between P300 latency of each bit condition and the CFT full scores. The coefficients ranged between $r = -.10$ and $r = .13$ (see Table 13). None of the correlations was statistically significant: $r_{0bit} = -.03$ ($p = .732$), $r_{1bit} = .13$ ($p = .156$), $r_{1bit} = .07$ ($p = .469$), $r_{2.58bit} = -.10$ ($p = .291$).

Contrasting P300 latency and RT as predictors of intelligence. In a last step, P300 latency and RT were contrasted as predictors of intelligence. For this purpose the regression-based factor scores of the first unrotated factors yielded from three principal component analyses (PCA) were used as measures of speed of information processing and g. Two PCA were performed over P300 latency and RT of all four bit conditions, respectively. The Kaiser criterion was used for the extraction of factors (Kaiser, 1960). Based on this criterion, only one factor each had an eigenvalue larger than one (see Table 15). The factors extracted from both speed measures were representing speed of information processing captured by RT (RT SIP) and P300 latency (P300 SIP), respectively. Another PCA was performed over the four subtests of the CFT 20-R. Again, based on the Kaiser criterion, only one factor was extracted with an eigenvalue larger than one. The regression-based factor scores of this first unrotated factor were used as an estimate of g. Pearson product-moment correlations were calculated between the factor scores of the three factors, P300 SIP, RT SIP and g. RT SIP correlated significantly with both, P300 SIP and g ($r_{P300\text{-}RT} = -.23$, $p < .05$; $r_{RT\text{-}g} = -.25$, $p < .01$). However, the correlation between P300 SIP and g was not statistically significant ($r_{P300\text{-}g} = .05$, $p = .624$).

Table 15

Summary of factor analytic results obtained from PCA: factor loadings of CFT 20-R subtests, as well as RT and P300 latency of each Hick condition on each first unrotated factor (g, RT SIP, P300 SIP), eigenvalues, and explained variance

CFT 20-R	g	Hick task	RT SIP	Hick task	P300 SIP
Sequences	0.73	RT 0 bit	0.73	P300 latency 0 bit	0.69
Classifications	0.66	RT 1 bit	0.89	P300 latency 1 bit	0.76
Matrices	0.72	RT 2 bit	0.89	P300 latency 2 bit	0.80
Topological Conclusions	0.62	RT 2.58 bit	0.85	P300 latency 2.58 bit	0.49
Eigenvalue	1.88		2.81		1.94
Explained variance (%)	47.0		70.2		48.5

Since there was no correlation between P300 latency and intelligence, whether it was calculated with manifest nor latent data, the investigation of P300 latency as a predictor of intelligence did not make sense. Regression and commonality analyses were therefore not performed.

Discussion

Study 2 was conducted with the intention of replicating the results of Study 1. In Study 1, RT did not fully match the expected pattern of Hick RT based on previous research. While RT of Study 1 did linearly increase according to Hick's law, and there was a negative correlation between RT and intelligence, the correlations between RT and intelligence did not increase across bit conditions and not all correlations were statistically significant. Based on results of previous studies, however, this would have been the expected pattern of results (Jensen, 2006; Neubauer, 1995; Sheppard & Vernon, 2008). The validity of the Hick task that had to be modified in order to elicit a reliable P300 component was therefore questionable and the interpretation of the results had to be handled with caution. Furthermore, P300 latency has never been investigated in the Hick paradigm before, thus even if the applied, modified Hick task was a proper instrument to measure speed of information processing, a replication of the study is a good way to confirm the electrophysiological results found in Study 1. Since the modifications of the Hick task were necessary to reliably investigate the P300 latency in the Hick paradigm, the same task was used in Study 2. However, there were some changes in the procedure of the experiment. In order to have a better control of the visual field of the stimuli across participants, they were instructed to put their head on a headrest that was placed 60 cm in front of the monitor while working on the Hick task. In Study 1, there was no headrest, participants just sat on a chair approximately 70 cm in front of the monitor. Furthermore, even though the sample consisted again of only university students, Study 2 also accepted male participants, however, results did not differ between genders. Lastly, Study 2 was conducted in a different laboratory than Study 1 and the EEG recording and analyze equipment was from a different manufacturer.

In Study 2, the pattern of Hick RT was in accordance with results from previous studies. RT of each bit condition increased significantly in dependence of the amount of bits of information that had to be processed. A linear and cubical trend across complexity was recognized in the RT data. However, the effect size of the linear trend was distinctly larger than the effect size of the cubical trend. Thus, RT data was in accordance with Hick’s law (Hick, 1952). Furthermore, in contrast to Study 1, the negative relation of RT with intelligence was found in the expected size (Neubauer, 1995; Sheppard & Vernon, 2008), and was increasing across complexity. Participants with higher intelligence reacted faster to the stimuli than participants with lower intelligence. The increase of RT across complexity was furthermore larger in the lower intelligence group than in the higher intelligence group. The correlation coefficients between intelligence and Hick RT under the 1 bit, 2 bit, and 2.58 bit conditions were statistically significant. Only the correlation between intelligence and Hick RT und the 0 bit condition was very weak and did not reach statistical significance. This pattern of RT is consistent with previous findings (Jensen, 2006; Neubauer, 1995) that showed that the correlation between Hick RT and intelligence is increasing across complexity. Jensen (1982) also showed that the correlation between intelligence and Hick RT varies significantly between samples, and that especially the correlation between intelligence and RT under the 0 bit condition is often low. This indicates that the modified Hick reaction time task used in Study 1 and Study 2 was properly designed and conducted in order to investigate speed of information processing. The task was therefore an appropriate measuring tool for the investigation of P300 latency as a complementary measure of speed of information processing besides RT in the Hick paradigm.

Looking at the grand average waveforms for the target stimuli for each complexity level, a salient P300 component that was following the sensory series of N100, P200, and N200 could be identified under each bit condition (see Figure 6). This means that under each condition the target stimulus did not only activate sensory processing, but also some additional attention-driven resources in order to update the current mental representation in the working memory (Polich, 2007). P300 latency did linearly increase across bit conditions, in a very similar course as RT. This suggests that the addition of response alternatives, and therefore the increase of uncertainty about the stimulus' position did have an impact on P300 latency. The functional significance of an ERP component can be determined based on the process that is associated with the experimental manipulation that is affecting the component (Meyer et al., 1988). The information processing stage mainly associated with the increase in response alternative is response selection. This would suggest that in the present study, the functional significance of the P300 latency was the time of response selection. Surprisingly though, P300 latencies under the 0 bit and 1 bit condition were longer than the corresponding RTs of those two conditions. This indicates that P300 latency cannot reflect an information processing stage itself, since the response was given before P300 reached its peak. At least not, if information processing is considered a series of contingent processing stages, as it is also the case in Carroll's (1981) model (see Figure 1). However, there has been suggestions of parallel instead of serial information processing. Pfefferbaum et al. (1986), for example, suggested that information processing is only serial in very difficult tasks, while in simple tasks information is processed in parallel. Parallel information processing leads to simultaneous activation of information processing stages. This means that response selection could be engaged before stimulus evaluation is completed. Pfefferbaum et al. (1986) suggest that from the standpoint of the stimulus evaluation time view of P300 latency, in those parallel information processing cases, P300 latency is influenced by response-related processing stages. Verleger (1997) on the other hand, claimed that parallel information processing per se does not change the sensitivity of P300 latency to response-related processing, since a delay in response selection would still not affect stimulus evaluation, even if they were engaged simultaneously. Verleger (1997) therefore rather suggests that the sensitivity of P300 latency to response-related processing is not due to a parallel occurrence of stimulus evaluation and response selection, but instead due to a parallel occurrence of the P300 component and response selection. The idea is that whatever process determines the P300 component cannot form back if response selection happens at the same time. Therefore, based on the present data, the functional significance of the P300 latency in the Hick paradigm is not expected to be the time or the speed of response selection, but the time of a process that is related to response selection. This also implies that P300 latency does not reflect stimulus evaluation time as suggested by previous research (Duncan-Johnson, 1981; Duncan-Johnson & Donchin, 1982; Kutas et al., 1977; McCarthy & Donchin, 1981).

Although the course of P300 latency and RT were very similar across conditions, the addition of response alternatives had a larger impact on RT resulting in a steeper slope in RT than in P300 latency as it was indicated by the medium sized P300 latency/RT ratio (Callaway, 1983). According to Meyer et al. (1988), a larger experimental effect in RT than P300 latency suggests that the affected underlying processes that influenced mainly the overt response to the target stimulus, resulting in RT, were following the processes generating the P300 component. The experimental effect, based on current data, was therefore occurring at the response selection and stages after it, thus response execution. Summarizing the present electrophysiological results in the Hick paradigm, it can be concluded that P300 latency did linearly increase across complexity, but in a slower pace than RT. This means that the experimental effect in the Hick paradigm is mainly happening after response selection.

On the other hand, no systematic correlation between RT and P300 latency was found. Even though RT and P300 latency correlated negatively under the 2 bit condition, this inverse relation of the two speed measures is most likely a fluke, considering that under all other conditions RT and P300 latency were independent of each other. Independency of RT and P300 latency in the same task alludes that both measures are each capturing a subset of processes that is largely different. Kutas et al. (1977), for example, suggest that RT is an index for the time of response selection and execution, whereas P300 latency is an index for the time of stimulus evaluation processes and that the overlap of variance in P300 latency and RT indicates how much response selection processes are contingent on stimulus evaluation processes. Typically, if the participant is focusing on accuracy, response selection is contingent on stimulus evaluation. But, if the participant is focussing on speed, stimulus evaluation is not depending on response selection, and responses can be given without complete stimulus evaluation. Accordingly, it is known that correlations between RT and P300 latency are usually weak under speed instructions (Pfefferbaum et al., 1983), which was also the case in the present Hick task. The present data on the relation between P300 latency and RT in the Hick paradigm suggests that the experimental effect is mainly happening at an information processing stage after the response selection. The independency of P300 latency and RT suggests that the linear increase across bit conditions found in both measures is not because they are both measuring the same aspects of speed of information processing. It rather indicates that the subset of processes that are generating the P300 component happen at the same time as the processes affected by the experimental manipulation that are represented by RT, namely response selection.

In a next step the relation of P300 latency with intelligence was investigated. In previous research there were no conclusive results on the relation between P300 latency and intelligence (Schulter & Neubauer, 2005). Negative, positive, as well as no correlations were reported and it was concluded that the relation highly depends on what the functional significance of the P300 component in the particular task is, or in other words on what particular processes were represented by the P300. In the present study, there was no difference found in P300 latency between participants with higher compared to lower intelligence. Furthermore, only weak correlations between intelligence and P300 latency under all conditions were found that didn’t reach statistical significance. At first sight, this might not be very intuitive results, since P300 latency did, just like RT, linearly increase across complexity levels, and RT was negatively correlated with intelligence. However, P300 latency did increase in a slower pace than RT and was also completely independent of RT. As elaborated earlier, it is possible that P300 latency did not increase in dependence of the addition of response alternatives per se, but rather because P300 and response selection occurred at the same time, which resulted in a division of cognitive resources and consequently in a reduction of speed of the P300 generating processes. So even though both, P300 latency and RT, might be valid indices of speed of information processing, the independency between both measures suggests that they don’t measure the same aspects of speed of information processing. Therefore, it is possible that the aspects of speed of information processing represented by RT and those reflected by P300 latency do have a different relation to intelligence. In the present data, P300 latency seems to be related to response selection, as examined in an earlier section. If P300 latency actually represents the time of response selection, the current data would suggest that there is no relation between the level of intelligence and the time of response selection. However, participants higher in intelligence did respond faster than participants lower in intelligence. This would suggest that even though individuals with higher intelligence are not faster in making the response selection in the Hick paradigm than individuals with lower intelligence, they are faster in executing the response.

To have more reliable measures of the underlying processes indexed by RT, by P300 latency and by intelligence, analyses with the factor scores of a RT factor, a P300 latency factor and a g factor were conducted. Analyses with factor scores showed the same pattern as the manifest data: a negative correlation between RT and g; no relation between P300 latency and g; and, an inverse relation between RT and P300 latency, which can be explained by the negative correlation of RT and P300 latency under the 2 bit condition, which is most likely a fluke.

General Discussion

Results of both studies were interpreted and discussed separately in previous sections. In the following part, the findings of both studies will be integrated in one discussion in order to find some answers to the research questions. Results from Study 1 and Study 2 were not completely consistent. However, there were some clear results. These conclusive results will be elaborated first, before the more ambiguous findings will be discussed.

RT in the Hick paradigm

In both studies, Study 1 and Study 2, RT increased linearly across conditions in dependence of the amount of bits of information that had to be processed. This increase of RT in the Hick reaction time task is known as Hick's law (Hick, 1952; Jensen, 2006) and was an expected result that can be considered as a manipulation check of the used Hick reaction time task. Since the Hick task that was used in both studies had to be modified slightly in order to derive a reliable P300 component, it was important to confirm the expected pattern of RT. This indicates that the task was a proper instrument to investigate speed of information processing in the Hick paradigm despite the applied modifications. Furthermore, in accordance with the mental speed approach of intelligence, RT did negatively correlate with intelligence in both studies. Even though the correlations were a little weak in Study 1, they were nevertheless consistently negative across conditions. Weak correlations between Hick RT under certain conditions and intelligence is not necessarily something to be concerned about. Although the inverse relation between Hick RT and intelligence is well-established in multiple studies, the size of the correlation varies largely across different samples (Jensen, 1982). Especially the correlation of intelligence with RT under the simplest condition is often rather low (Jensen, 1982). In Study 2, the correlation between RT and intelligence was ranging in the from previous research expected average size of r = -.24 (Sheppard & Vernon, 2008). Overall, results from both samples confirmed the hypothesis that RT increases across complexity in dependence of the amount of bits of information that has to be processed. In addition, in accordance with the mental speed approach of intelligence, more intelligent participants were reacting faster in the Hick task than less intelligent participants, which indicates that more intelligent participants were processing information faster than less intelligent participants. This negative intelligence-RT correlation was furthermore larger across bit conditions, which suggests that complexity affects speed of information processing in less intelligent individuals to a larger degree than in more intelligent individuals.

P300 latency in the Hick paradigm

RT and P300 latency have both been used as measures of speed of information processing in various studies. While RT is a measure of the overall time an individual needs to respond to a stimulus, P300 latency is often considered as an index of only stimulus evaluation time (Duncan-Johnson, 1981; Kutas et al., 1977; McCarthy & Donchin, 1981). The stimulus evaluation time view of P300 latency has been challenged by findings showing a sensitivity of P300 latency to manipulations focusing on response selection (Christensen et al., 1996; Doucet & Stelmack, 1999; Falkenstein et al., 1994a; Pfefferbaum et al., 1986). However, the manipulations used in those studies were often confounded by stimulus evaluation requirements. Furthermore, the sensitivity of P300 latency to response selection is not always found (Magliero et al., 1984; McCarthy & Donchin, 1981). The functional significance of P300 latency is not fully resolved. The Hick reaction time task is a simple and choice reaction time task that systematically varies complexity of response selection by adding response alternatives while keeping stimulus evaluation constant and minimal. It is therefore a qualified tool to investigate the sensitivity of the P300 latency to response selection without a confounding of stimulus evaluation demands. P300 latency and RT were investigated as measures of speed of information processing time in the Hick paradigm in order to get some clarity about its functional significance. While results from RT and intelligence data was consistent in both samples, the findings from P300 latency were ambiguous. Table 16 gives a short overview of the electrophysiological results in both present studies.

Table 16
Summary of electrophysiological data in study 1 and study 2

Study 1	Study 2
A prominent P300 component was found under all bit conditions	A prominent P300 component was found under all bit conditions
P300 latency increased only from 0 bit to 1 bit condition	P300 latency increased linearly across bit conditions
P300 latency and RT were not correlated	P300 latency and RT were not correlated
P300 latency and intelligence were positively correlated	P300 latency and intelligence did not correlate
Factor scores of P300 latency predicted a unique part of variance in the g-factor	Factor scores of P300 latency did not correlate with g scores

As can be seen in Table 16, there were not only, but some consistent results found in the electrophysiological data across the samples. First, as a very basic, but important finding, a prominent P300 component was elicited under each of the four bit conditions of the used Hick paradigm. Since the P300 component was, to my knowledge, never explicitly investigated in the Hick paradigm, this finding is not self-evident. Especially under the 0 bit condition, which is a simple reaction time task, it was not sure, if a P300 component would be generated in the first place. The 0 bit condition should only activate very basic information processing (Jensen, 1982). Under the 0 bit condition, only one response alternative is given, so there is no uncertainty about the stimulus' position. There is no stimulus encoding or converting needed to successfully solve the task since the stimulus is always the same.

Therefore, the finding of a clear P300 component under the 0 bit condition is not really compatible with the context-updating theory of the P300 component. The context-updating theory suggests that a P300 component is elicited if the mental representation of a stimulus in the working memory needs to be updated. If there is no change in the stimulus characteristics, on the other hand, the current mental representation in the working memory is maintained, and only potentials that are elicited by sensory processing (N100, P200, N200) are detected (Polich, 2007). Since each stimulus is exactly the same under the 0 bit condition and there is only one possible stimulus position, an update of the mental representation in the working memory is not needed. The P300 component could at most represent an allocation of attention in order to confirm the mental representation of a stimulus. However, as illustrated in the grand average waveforms for the target stimuli of Study 1 and Study 2 (see Figure 4 and 6, respectively), there was a prominent P300 component following the sensory sequence of ERP components N100, P200, N200 under each bit condition. This is a first hint that the P300 component might not be a reflection of context-updating and P300 latency therefore not a measure of stimulus evaluation time. Verleger, Jaśkowski, and Wascher (2005) suggest an alternative role of the P300 component after showing that in a discrimination task with an incompatibility instruction P300 amplitudes were the same size for slow and fast responses, while P300 latencies varied across response time quartiles. This was true for both, stimulus- and response-locked averages. Verleger et al. (2005) proposed therefore that the P300 component reflects a process that is linking perceptual and response processing. They furthermore suggest that this process might be a monitoring process that checks if the first decision to evaluate a stimulus and the according acting has led to the expedient processing. But again, the 0 bit condition of the Hick task does not actually require a perceptual analysis of a stimulus nor a response selection. A monitoring process to validate the consequential processing steps of the stimulus evaluation seems to be unnecessary for a simple reaction time task. Roche and O’Mara (2003) on the other hand suggest that P300 might be partially determined by the dorsal “action” stream. The dorsal stream influences the guidance of actions towards visually perceived objects (Goodale, 1993), for example the response selection to a visually perceived stimulus. The P300 component might therefore reflect the development of a stimulus-response association. This suggestion would be compatible with the observed P300 component in the Hick paradigm. It would also explain the evoked P300 component under the 0 bit condition, even though the response there seems more or less like an anticipated reflex without much cognitive processing involved.

Another partly consistent result found in both present studies was the increase of P300 latency across bit conditions. In Study 1 and 2, it was shown that both measures of speed of information processing, RT and P300 latency, did increase across bit conditions. Hence, the addition of response alternatives seems to have an impact on both speed measures. Hick’s law describes the linear increase in RT in dependence of the amount of information that has to be processed. Therefore, this result was a confirmation of an already known relation. P300 latency, on the other hand, was the first time used as a speed of information processing measure in the Hick paradigm. While P300 latency mainly increased from the 0 bit to the 1 bit condition in Study 1, P300 latency increased linearly across all bit conditions in Study 2. This means that in Study 1, P300 latency seems mostly to reflect the change from a simple to a choice reaction time task, while in Study 2, P300 latency seems to represent a process related to response selection that increases continuously across bit conditions. There are two reasons that could explain the different results across the samples. First, it is possible that P300 latency was not measuring the same underlying construct in both samples. As elaborated in the introduction, the determining processes of P300 are not fully discovered yet. There are several hypotheses though that associate the generation of P300 with different processes like decision confidence (Mars et al., 2008), uncertainty (Duncan-Johnson & Donchin, 1977), context-updating (Donchin & Coles, 1988; Polich, 2007), monitoring of processing steps (Verleger et al., 2005), stimulus-response association (Roche & O’Mara, 2003) or stimulus classification (Kok, 2001). Furthermore, the P300 component is an endogenous component, because it is rather evoked by an individual's performance elicited by a stimulus than by the stimulus itself (Luck, 2005). P300 might therefore also be influenced by an individual's overall task strategy. So even though the same task was used in both samples of the present investigation, P300 may have captured a different subset of processes across samples. Furthermore, the samples were tested in two different laboratories with different EEG equipment. Although there is no obvious reason for why the different equipment should have measured different underlying constructs since the procedure was kept standardized, there is a chance that in one of the laboratories P300 was not reliably derived. P300 latencies were therefore tested for invariance across the samples. This means that it was determined whether the used speed of information processing measure actually measured the same underlying construct in both samples (He & van de Vijver, 2012; Helfrich, 2013). Multiple group confirmatory factor analyses (CFA) with different cross-group constraints were performed, followed by a comparison of the different model fits (Cheung & Rensvold, 2002). For the present work, speed of information processing measured by P300 latency was tested with three models in a hierarchical order to investigate measurement invariance across samples. Results confirmed that metric invariance was achieved across the samples of Study 1 and Study 2 (see Appendix G for detailed explanations and results). This suggests that P300 latency did measure the same underlying construct in both samples. The different pattern of increase in both studies cannot be explained by a measurement bias.

An alternative explanation for the different patterns of increase in P300 latency across the samples is that even though the P300 component captured the same underlying construct, the sensitivity of P300 latency to the experimental manipulation was not the same in both samples. Assuming that P300 component does not capture information processing per se, it is possible that P300 latency was only minimally influenced by the increasing complexity of response selection in Study 1 while in Study 2, P300 latency was more affected by response selection. There are studies that showed that P300 latency is sometimes not only affected by stimulus-related but also by response-related parts of a task (Verleger et al., 2005). Verleger (1997) even concluded that P300 latency is especially sensitive to response-related processing when responses are made early. As elaborated in the discussion of Study 2, there is some evidence that indicates that the P300 component might have occurred at the same time as response selection and was therefore affected by it. Especially the data from Study 2 indicates that P300 latency might have been delayed by a parallel occurrence of response selection rather than by response selection itself. In the two simpler conditions, RT was shorter than the corresponding P300 latency. A shorter P300 latency than RT does not agree with the concept of P300 being related to context-updating in the working memory and P300 latency as stimulus evaluation time. Under those assumptions, the longer P300 latency compared to RT would suggest that in the two least complex conditions, participants responded before the target stimulus has been fully evaluated, and before the stimulus evaluation was completed. This would imply, however, that error rates rise because stimulus evaluation was not completely ensued, which was not the case in the present data. Pfefferbaum et al. (1986) claim that in very simple tasks information is processed not in an additive way and response selection and execution can therefore be engaged before the stimulus is completely evaluated. This implies that the particular processing stages are not contingent on each other, but are affecting each other since cognitive resources have to be divided over different processes at the same time. In very simple tasks, it is therefore possible that response selection and the P300 component occur at the same time. This simultaneous occurrence could lead to a delay in P300 latency because the component cannot form back. Verleger (1997) found some evidence speaking for this proposal in a large review about the P300 latency. By computing correlations between the base-level RT (RT in the simplest condition, e.g. simple reaction time task) and the corresponding P300 latency in tasks that require response selection, Verleger (1997) confirmed that P300 latency was typically more sensitive to response selection manipulations in tasks with shorter RTs. This suggests, that in very simple tasks that have short response latencies, the P300 component and response selection happen at the same time. It also implies that in those cases, response-related processing stages can have an impact on P300 latency. Verleger (1997) assumes that if the P300 component occurs at the same time as response selection, a forming back of the component is not possible, and therefore P300 latency gets delayed.

Summed up, it is possible that the different patterns of increase in P300 latency across complexity between the studies is reflecting a difference in sensitivity, nameley a sensitivity to only stimulus-related processing versus a sensitivity to stimulus- and response-related processing. The present data also agrees with Verleger's (1997) suggestion that P300 latency is more sensitive to response selection if responses are shorter. Responses in Study 2 were overall shorter than in Study 1. Accordingly P300 latency was affected throughout all bit conditions in Study 2. In Study 1, however, P300 latency was only minimally affected by the experimental manipulation, mostly from the 0 bit to the 1 bit condition, possibly reflecting a change from a simple to a choice reaction time task.

Different aspects of speed of information processing

A further consistent result from the electrophysiological data found in both samples is the independency of P300 latency and RT. Even though there are studies that report a positive correlation between RT and P300 latency in tasks that focus on stimulus evaluation (Duncan-Johnson & Donchin, 1982; Kutas et al., 1977; Magliero et al., 1984), a dissociation between the two measures of speed of information processing under specific conditions has been reported as well. As previous research shows, small or no correlations between RT and P300 latency are often observed in tasks that are mainly focusing on response selection or execution (Duncan-Johnson & Donchin, 1982; McCarthy & Donchin, 1981). Additionally, Pfefferbaum et al. (1983) elaborated that the correlation between RT and P300 latency is often small or not existent in tasks with speed instructions. Since response selection is the important part of the Hick reaction time task and it also typically has a speed instruction, the independency between RT and P300 latency is in accordance with these previous reported findings. Nevertheless, this does not necessarily mean that P300 latency is not a proper measure of information processing time in speeded tasks. Duncan-Johnson and Donchin (1982) attributed the occasional dissociation of RT and P300 latency to the participant's strategy in a task, but also to the nature of the task. Assuming that the P300 amplitude is reflecting contextual updating that implies information for not just the current response to a certain stimulus, but rather for the participant's future strategy in the overall task, it is possible that RT is determined by a subset of processes that are generating the current response in contrast to processes dealing with the overall strategy that determine the P300 component. Verleger et al. (2005) suggested that the process that determines P300 is a monitoring process that evaluates if the classification of a stimulus and the consequent acting, in other terms the stimulus encoding and converting, have ended in suitable processing steps like response selection and execution (see Figure 8).

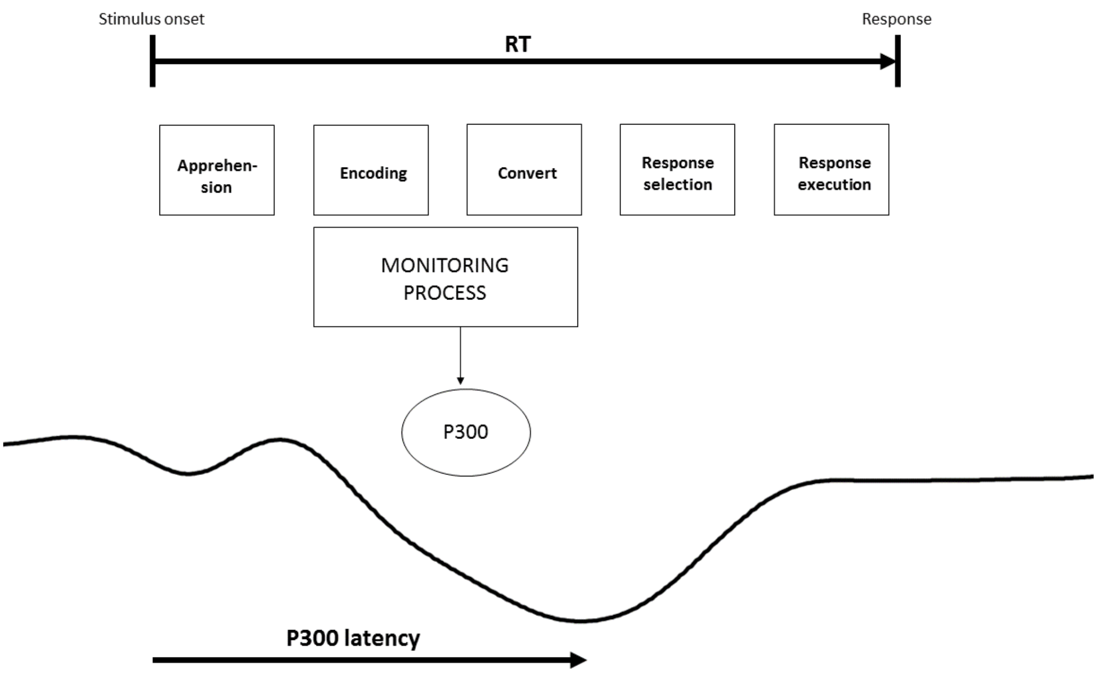

Figure 8. Illustration of Verleger et. al's (2005) idea of the role of P300 as a connection of perceptional analysis and the response.

This monitoring process is thought to begin parallel to stimulus encoding and to end at the response onset. Under this assumption, the peak of the P300 component is the starting point of the response. According to Verleger et al. (2005), P300 has the role of linking perception processes and response-related processes. This is also in accordance with Roche and O'Mara (2003) who suggested that P300 reflects the formation of a stimulus-response association. In this sense, P300 latency is a valuable measure of speed of information processing, but not because P300 is generated by stimulus evaluation processes but because it is generated by a monitoring process that is proportional to the cognitive processing time. Verleger et al. (2005) found some empirical evidence speaking for the role of the P300 component as a connection of perceptual analysis and response initiation as they showed that stimulus- and response-locked P300 amplitudes did not vary, not even in dependence of response speed. However, stimulus- and response-locked P300 latencies did vary across response speed. Under the assumption of P300 as the linking role between perception and response, determined by monitoring processes, it is possible that RT and P300 latency run at different paces and are therefore not correlated. According to Duncan-Johnson and Donchin (1982), the dissociation between RT and P300 latency is especially likely if the stimulus event is highly expected, which leads to an anticipated stimulus encoding and a response selection starting prior to the completion of stimulus evaluation. In the Hick paradigm, the stimulus event is highly expected, especially under the 0 bit condition. The correlation between RT and P300 latency could therefore be displaying the amount of contingency between the processes that determine the two measures. Kutas et al. (1977) even state that the correlation of RT and P300 latency is reflecting how much response selection depends on stimulus evaluation. However, as previously elaborated, the current data is not compatible with the evaluation time view of P300 latency. The conclusion of Kutas et al. (1977) that the independency of P300 latency and RT represents independency of stimulus evaluation and response selection is not applicable for the present data. The lack of a correlation between the two speed measures in the present data rather suggests that they are determined by different underlying processes and are therefore representing different aspects of speed of information processing. According to the understanding of P300 as a linkage between reaction and perception (Verleger et al., 2005), the lack of a correlation between RT and P300 latency would rather reflect the independency of response selection and the monitoring process that determines P300.

P300 latency and intelligence

The relation between P300 latency and intelligence was investigated in several previous studies with no conclusive results. This issue was not solved in the present investigation either. In Study 1, P300 latency was positively correlated with intelligence, and factor scores of the P300 latency factor even explained a unique part of variance in g. However, in Study 2, there was no correlation found between P300 latency and intelligence, nor did the factor scores of P300 SIP explain some variance in g. Nevertheless, results from both studies are not compatible with the stimulus evaluation time view of P300 latency. If

P300 latency would represent the stimulus evaluation time, a negative relation to intelligence would be the expected result within the framework of the mental speed approach. In a recently published study, in which three ECTs, namely the Hick paradigm, the Sternberg memory task, and the Posner letter matching task, were investigated with behavioral and electrophysiological measures, it was suggested that the relation of ERP latencies and intelligence is mediated by RT (Schubert, Hagemann, Voss, Schankin, & Bergmann, 2015). This means that ERP latencies and intelligence are only correlated because ERP latencies are predicting RT, while RT is predicting intelligence. However, in both of the present studies RT and P300 latency were not related. A mediating role of RT that explains the relation between P300 latency and intelligence is therefore impossible. Houlihan et al. (1998) on the other hand found a positive correlation between intelligence and P300 latency to the probe stimulus of a Sternberg memory task. They interpreted this as a longer stimulus encoding in more intelligent individuals. However, more intelligent participants did still react faster than less intelligent participants. Houlihan et al. (1998) suggested that the negative relation of RT and intelligence, but the positive relation of P300 latency and intelligence might indicate that the mental speed-intelligence correlation is partly mediated by response-related processes, thus response selection and execution. However, this conclusion is only valid if P300 latency is considered as stimulus evaluation time. Therefore, this hypothesis could not be confirmed in the present work. As elaborated earlier, present data is not compatible with the stimulus evaluation time explanation of P300 latency. The longer P300 latency than RT under the two least complex conditions suggest that especially in Study 2 response selection was happening at the same time as P300, which would not be possible if P300 latency would reflect stimulus evaluation time. Plus, there was no significant correlation found between P300 latency and intelligence in Study 2. In Study 1, on the other hand, the simultaneous occurring of response selection and P300 component is less evident, since P300 latency was consistently shorter than RT under all bit conditions. Furthermore, P300 latency in Study 1 was less sensitive by the complexity of response selection, mainly only from the 0 bit to the 1 bit condition. However, P300 latency was positively correlated to intelligence in Study 1. The relation between P300 latency and intelligence needs to be investigated further in order to really get a detailed understanding of it.

Conclusions

The aim of the present work was to get a more detailed understanding of the functional significance of the P300 latency. P300 latency is often used as measure of stimulus evaluation time. However, the interpretation of P300 latency as stimulus evaluation time was challenged by findings of a P300 latency sensitivity to response-related manipulations. In two studies with samples from two different countries, not only RT, but also P300 latency were used as measures of speed of information processing examining the Hick paradigm. P300 latency has been used as speed of information processing measure before, but to my knowledge never in the Hick task. The advantage of using the Hick paradigm is that the influence of response selection on P300 latency can be systematically investigated while keeping stimulus evaluation constant and minimal. Furthermore, a comparison of P300 latency and RT revealed some more information about the functionality of P300 latency. By contrasting both speed of information processing measures as predictors of intelligence, it was also investigated if RT and P300 latency explain common and/or unique parts of variance in intelligence. The present investigation replicated once more the increase of RT in dependence of the amount of bit of information that needs to be processed. Furthermore, in accordance with the mental speed approach of intelligence, participants with higher intelligence were performing faster in the Hick task than participants with lower intelligence levels. Moreover, this inverse relation between RT and intelligence was enhanced across complexity. In addition, the present work also revealed some new insights about the functional significance of P300 latency. These insights are the following:

1. A clear P300 component was elicited under all four bit conditions, including the 0 bit condition. This indicates that even in simple reaction time tasks some cognitive processing is activated. P300 is often associated with a context updating of the current mental representation in the working memory. Since each stimulus under the 0 bit condition is exactly the same as the previous one, present data suggests that

P300 might have other or additional functions than context updating. One alternative function could be a monitoring role, which is determining the stimulus-response association.

2. P300 latency did increase across bit conditions. This indicates that P300 latency is not only sensitive to manipulations that focus on stimulus evaluation, but also to manipulations focusing on response selection. This finding is not compatible with the idea of P300 latency as an index of stimulus evaluation time.

3. RT and P300 latency are often expected to capture the time of similar underlying processes. Indeed, P300 latency is, similar as RT, increasing across bit conditions. However, P300 latency and RT were not related. This suggests that P300 latency and RT are not reflecting the same aspects of speed of information processing. P300 latency might be proportional to stimulus evaluation time in task that focus on stimulus evaluation. But, as the current results show, it is probably determined by completely different processes than RT. Further research is needed to get a more complex pictures of the determinants of the P300 component.

4. The relation between P300 latency and intelligence is still not clear. Present data does not confirm the suggestion of Houlihan et al. (1998) that the relation of RT and intelligence might be partly mediated by response-related processes. However, there might be other factors like subjective task difficulty and complexity, or the subject's strategy that play a significant role in individual differences in both, P300 latency and intelligence. Further research is needed to get a more complex pictures of these factors.

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Appendix

Appendix A. Instructions of the modified Hick reaction time task used in Study 1.

Welcome to this section. You will now work on four tasks one after another. The tasks are similar, but not identical. Please read all instructions very carefully. Respond as quickly as possible, but try also to avoid errors. Use buttons "1"-"6" on the response pad for completing the tasks. To start with the tasks, please press one of the buttons.

> In the following task a rectangle will be presented in the middle of the screen. At different time intervals there will repeatedly appear a plus sign in this rectangle. Every time a plus sign appears, press button "4". Please respond as quick and correct as possible. There will be a practice section at the beginning. If there are any questions, please ask them now or after the practice section. Press button "4" for starting the practice section.
> If you have any questions, please ask now the experimenter. If everything is clear, please press button "4" to start the task.
>
> In the following task two rectangles will be presented in the middle of the screen. At different time intervals there will appear a plus sign in one of those rectangles. Each time a plus sign appears in the left rectangle press button "3". Press button "4" each time the plus sign appears in the right rectangle. Please respond as quick and correct as possible. There will be a practice section at the beginning. If there are any questions, please ask them now or after the practice section. Press button "4" for starting the practice section.
> If you have any questions, please ask now the experimenter. If everything is clear, please press button "4" to start the task.
>
> In this task four rectangles will be presented in the middle of the screen. At different time intervals there will appear a plus sign in one of those rectangles. Each time a plus sign will appear please press the corresponding button on the response pad. Place your fingers on the response pad, so that the two index fingers are on buttons "3" and "4" and the two middle fingers are on buttons "2" and "5". Please respond as quick and correct as possible. There will be a practice section at the beginning. If there are any questions, please ask them now or after the practice section. Press button "4" for starting the practice section.
> If you have any questions, please ask now the experimenter. If everything is clear, please press button "4" to start the task.
>
> In the following task six rectangles will be presented in the middle of the screen. At different time intervals there will appear a plus sign in one of those rectangles. Each time a plus sign appears please press the corresponding button on the response pad. Place your fingers on the response pad, so that the two index fingers are on buttons "3" and "4", the two middle fingers are on buttons "2" and "5" and the ring fingers are on buttons "1" and "6". Respond as quick and correct as possible. There will be a practice section at the beginning. If there are any questions, please ask them now or after the practice section. Press button "4" for starting the practice section.
> If you have any questions, please ask now the experimenter. If everything is clear, please press button "4" to start the task.

Thank you for participating. Please inform the experimenter that the task is completed.

Appendix B. Translated instructions of CFT 20-R used in Study 1.

Oral: You will now work on four different subtests. The subtests will all contain figural, abstract problems. Each subtest will start with the easier problems and end with some more difficult ones. It is very likely that no one will solve each problem correctly. But, you should try to solve as many problems as possible in the given time. If you will get stuck at one problem, skip it and try to solve it at the end if there is some time left. If you are not sure about one problem, try to choose the answer that seems to be correct the most. Each problem has only one correct solution. You will be given a limited time to complete each subtest. If you are finished before time is over, do not disturb the others, instead check your own answers again. All answers must be marked on the answer sheets. Do not write anything in the test books. Do not turn the page before you are told to do so. Are there any questions so far?

Subtest 1
Oral: In the first test, each problem consists of a series of figures on the left. The last figure is missing. Your task is to figure out the pattern of the series on the left and choose the one figure on the right that completes the series of figures on the left. In the first example the lines are getting longer and longer. As you can see, there is only one figure, figure a, on the right that is longer than the third line of the series on the left. Therefore, figure a is the right answer. Are there any questions? Let us solve example two and three. In example 2, figure c is the correct answer because the little bent line switches direction from left to right. In example 3, figure a is the correct answer because the black triangle is moving clock-wise starting at the top. Are there any questions?
Written: In each row, please select the one of the five figures on the right side that best completes the series on the left.
The letter corresponding to the figure has to be marked on the answer sheet.
On the next two pages, you will find 15 questions that are to be complete in a similar fashion.

Subtest 2
Oral: In the second test, each problem consists again of a series of figures. This time, you need to figure out which one doesn't fit to the others. So you need to choose the odd-one out. In the first example, figure d is the correct answer because this block is upright, while all other blocks are not. In the second example, figure a is the correct answer because it is the only circle that is black, all the other circles are white. Are there any questions?
Written: In each row, chose one of the five figures in the boxes that differs most from the other 4 figures, hence which of the figures does not fit with the others.
There are 15 questions like these examples.
Notice that the tasks are spread over 2 pages. Once you have finished the first page, continue to work on the next page.

Subtest 3
Oral: In the third test, each problem consists of a big rectangle on the left. One box within this rectangle is missing. Your task is to find out which figure on the right side completes the rectangle on the left. Figure c is the correct answer of the first example because it completes the rectangle on the left the best. In the second example, figure a is the correct answer. Figure d is the correct answer for the third example. Are there any questions?
Written: In each question, select the box on the right side that best completes the series in the large block on the left side.
There are 15 questions presented on the next three pages.

Subtest 4
Oral: In the fourth subtest, your task is to first figure out in which relation the spot is drawn to the other figures. Then you need to choose a figure on the right in which it would be possible to draw a spot in the same relation. Let us look at example one. The spot is drawn in the circle, but outside of the rectangle. Now choose one figure on the right in which it would be possible to draw a dot in the circle but outside of the rectangle. Only in figure c is it possible to draw a spot inside of the circle but outside of the rectangle. Therefore, figure c is the correct answer. Are there any questions? Let us solve example two. In example two the spot is inside of the oval and under the line. Figure b is the correct answer because it is the only figure in which we could draw a spot inside of the oval and under the line. In example three, the spot is drawn inside of both rectangles, but outside of the circle. Only in figure b it is possible to draw a spot inside of both rectangles, but outside of the circle. Therefore, figure c is the correct answer. Are there any questions?
Written: In each task, notice where the spot is drawn in the figure on the left side. Then decide in which of the figures on the right side it would be possible to draw the spot in the same relation as in the left figure. In some questions there will be 2 or 3 spots. This time there will be only 11 questions on the next two pages.
Please remember that you are not allowed to draw the spot on the paper. Just mark the corresponding letter on the answer sheet.

Appendix C. Comparison of P300 latency detection methods: Peak latency vs. 50% area latency

Table 17

Summary of means (M), standard deviations (SD), t- and p-values of the comparison of P300 latency deteremined either with the peak latency method or the 50 percent area method, for Study 1 and Study 2, respectively.

	Study 1				Study 2			
	M (*SD*)				*M* (*SD*)			
	Peak	50% area	*t*-value	*p*-value	Peak	50% area	*t*-value	*p*-value
0 bit	285 (46)	274 (13)	2.7	**	292 (43)	281 (10)	3.1	**
1 bit	316 (33)	319 (9)	-1.0	.319	323 (37)	320 (7)	1.1	.256
2 bit	324 (36)	325 (9)	-0.3	.767	342 (44)	342 (10)	0.3	.760
2.58 bit	333 (37)	334 (10)	-0.1	.893	371 (64)	347 (12)	4.2	***

Note. Df_{Study1} = 112, df_{Study2} = 117; ** $p < .01$, *** $p < .001$

Table 18

Summary of correlation coefficients, z- and p-values of the comparison of the correlation coeffictients between RT as well as intelligence and P300 latency deteremined either with the peak latency method or the 50 percent area method, for Study 1.

		Correlation coefficients			
		Peak	50% area	z-Value	p-Value
RT	0 bit	-.09	-.01	-.60	.276
	1 bit	.04	.15	-.82	.205
	2 bit	-.03	-.04	.07	.470
	2.58 bit	-.08	-.002	-.21	.418
CFT 20-R	0 bit	.05	.08	-.22	.412
	1 bit	.05	.09	-.30	.383
	2 bit	.15	.26	-.62	.269
	2.58 bit	.24	.18	.47	.321

Table 19

Summary of correlation coefficients, z- and p-values of the comparison of the correlation coeffictients between RT as well as intelligence and P300 latency deteremined either with the peak latency method or the 50 percent area method, for Study 2.

		Correlation coefficients			
		Peak	50% area	z-Value	p-Value
RT	0 bit	-.04	-.07	.23	.109
	1 bit	.03	.07	-.31	.380
	2 bit	-.25	.002	-1.96	*
	2.58 bit	.01	.02	-.08	.470
CFT 20-R	0 bit	-.03	.07	-.76	.223
	1 bit	.13	.07	.46	.322
	2 bit	.07	-.07	-1.07	.143
	2.58 bit	-.10	-.02	-.61	.270

Note. * $p < .05$

Appendix D. Comparison of Spearman-Rho and Pearson product-moment correlation coefficients.

Table 20

Summary of correlation coefficients, z- and p-values of the comparison of the correlations between RT, intelligence and P300 latency calculated either with Pearson product-moment coefficients or with Spearman-Rho coefficients, for Study 1.

Correlations with intelligence

		Pearson	Spearman-Rho	Z	p-Value
P300 peak latency	0 bit	.05	.08	-.22	.412
	1 bit	.05	.06	-.07	.470
	2 bit	.15	.19	-.31	.380
	2.58 bit	.24	.25	-.08	.469
Mean RT	0 bit	-.18	-.16	-.15	.439
	1 bit	-.19	-.13	-.46	.324
	2 bit	-.06	-.02	-.3	.383
	2.58 bit	-.21	-.16	-.38	.350

Correlations with Mean RT

		Pearson	Spearman-Rho	Z	p-Value
P300 peak latency	0 bit	-.09	-.06	-.22	.411
	1 bit	.04	.15	-.82	.205
	2 bit	-.03	-.004	-.19	.424
	2.58 bit	-.08	-.04	-.3	.383

Table 21

Summary of correlation coefficients, z- and p-values of the comparison of the correlations between RT, intelligence and P300 latency calculated either with Pearson product-moment coefficients or with Spearman-Rho coefficients, for Study 2.

Correlations with intelligence

		Pearson	Spearman-Rho	Z	p-Value
P300 peak latency	0 bit	-.03	.04	-.53	.297
	1 bit	.13	.12	.08	.469
	2 bit	.07	.03	.31	.380
	2.58 bit	-.10	-.04	-.46	.323
Mean RT	0 bit	-.07	-.01	-.46	.324
	1 bit	-.21	-.13	-.63	.265
	2 bit	-.2	-.17	-.24	.406
	2.58 bit	-.33	-.29	-.34	.368

Correlations with Mean RT

		Pearson	Spearman-Rho	Z	p-Value
P300 peak latency	0 bit	-.04	.01	-.38	.352
	1 bit	.03	.13	-.77	.221
	2 bit	-.25	-.15	-.80	.214
	2.58 bit	.01	-.01	.15	.439

Appendix E. Comparison of the correlations between RT and CFT 20-R scores and between RT and MAB scores in Study 1

Table 22

Summary of correlation coefficients, z- and p-values of the comparison of the correlations between RT and intelligence measured either with the CFT 20-R or with the MAB, for Study 1.

Correlations with intelligence					
		CFT 20-R	MAB	*Z*	p-Value
P300 peak latency	0 bit	.05	.08	-.22	.412
	1 bit	.05	-.08	.97	.167
	2 bit	.15	.17	.15	.440
	2.58 bit	.24	.21	.23	.407
Mean RT	0 bit	-.18	-.08	-76	.225
	1 bit	-.19	-.09	-.76	.224
	2 bit	-.06	-.11	.38	.354
	2.58 bit	-.21	-.11	-.76	.223

Appendix F. Instructions of the modified Hick reaction time task in study 2.

Herzlich Willkommen. Es werden Ihnen nacheinander vier Aufgaben präsentiert. Die Aufgaben sind zwar ähnlich, aber nicht identisch. Lesen Sie bitte alle Erklärungen ganz genau durch. Antworten Sie so schnell wie möglich, versuchen Sie aber auch Fehler zu vermeiden. Zum Antworten verwenden Sie die Tasten „1“-„6“ auf der Antwortbox. Um mit den Aufgaben zu beginnen, drücken Sie eine der Tasten.

> In dieser Aufgabe wird Ihnen in der Mitte des Bildschirms ein Rechteck präsentiert. In diesem Rechteck erscheint in unterschiedlichen Zeitabständen ein Kreuz. Ihre Aufgabe besteht darin, sobald das Kreuz erscheint, die Taste „4“ zu drücken. Antworten Sie bitte so schnell und korrekt wie möglich. Zuerst gibt es einen Übungsdurchgang. Falls es noch Fragen gibt, können Sie diese jetzt oder nach dem Übungsdurchgang stellen. Drücken Sie die Taste „4“ um den Übungsdurchgang zu starten.
> Falls Sie noch Fragen zu der Aufgabe haben, können Sie die jetzt stellen. Wenn alles klar ist, können Sie mit der Taste „4“ die Aufgabe starten.
>
> In der nächsten Aufgabe werden Ihnen zwei Rechtecke in der Mitte des Bildschirms präsentiert. In unterschiedlichen Zeitabständen erscheint jeweils ein Kreuz in einem der beiden Rechtecke. Ihre Aufgabe ist es, wenn das Kreuz links erscheint die Taste „3“ und wenn es rechts erscheint die Taste „4“ zu drücken. Antworten Sie bitte so schnell und korrekt wie möglich. Zuerst gibt es einen Übungsdurchgang. Falls es noch Fragen gibt, können Sie diese jetzt oder nach dem Übungsdurchgang stellen. Drücken Sie eine der Tasten um den Übungsdurchgang zu starten.
> Falls Sie noch Fragen zu der Aufgabe haben, können Sie die jetzt stellen. Wenn alles klar ist, können Sie mit der Taste „4“ die Aufgabe starten.
>
> In der nächsten Aufgabe werden Ihnen jeweils vier nebeneinanderstehende Rechtecke präsentiert. In unterschiedlichen Zeitabständen erscheint jeweils ein Kreuz in einem der vier Rechtecke. Ihre Aufgabe ist es, wenn das Kreuz erscheint, die entsprechende Taste „2“-„5“ zu drücken. Platzieren Sie bitte Ihre Finger so, dass die beiden Zeigefinger auf den Tasten „3“ und „4“ und die beiden Mittelfinger auf den Tasten „2“ und „5“ sind. Zuerst gibt es einen Übungsdurchgang. Falls es noch Fragen gibt, können Sie diese jetzt oder nach dem Übungsdurchgang stellen. Drücken Sie eine der Tasten um den Übungsdurchgang zu starten.
> Falls Sie noch Fragen zu der Aufgabe haben, können Sie die jetzt stellen. Wenn alles klar ist, können Sie mit der Taste „4“ die Aufgabe starten.
>
> In der nächsten Aufgabe werden Ihnen jeweils sechs nebeneinanderstehende Rechtecke präsentiert. In unterschiedlichen Zeitabständen erscheint jeweils ein Kreuz in einem der sechs Rechtecke. Ihre Aufgabe ist es, wenn das Kreuz erscheint, die entsprechende Taste „1“-„6“ zu drücken. Platzieren Sie bitte Ihre Finger so, dass die beiden Zeigefinger auf den Tasten „3“ und „4“ und die beiden Mittelfinger auf den Tasten „2“ und „5“, die beiden Ringfinger auf den Tasten „1“ und „6“ sind. Zuerst gibt es einen Übungsdurchgang. Drücken Sie eine der Tasten um den Übungsdurchgang zu starten.
> Falls Sie noch Fragen zu der Aufgabe haben, können Sie die jetzt stellen. Wenn alles klar ist, können Sie mit der Taste „4“ die Aufgabe starten.

Vielen Dank für die Teilnahme. Bitte die Untersuchungsleiterin oder den Untersuchungsleiter informieren, dass die Aufgabe beendet ist.

Appendix G. Invariance analysis of P300 latency across the samples of Study 1 and Study 2

Measurement invariance was investigated for speed of information processing measured by P300 latency using the free-source statistical software R with the structure equation modeling package lavaan (Rosseel, 2012). Multiple group confirmatory factor analyses (CFA) with different cross-group constraints were performed, followed by a comparison of the different model fits (Cheung & Rensvold, 2002). Using this sequential procedure two issues can be tested (Byrne, Shavelson, & Muthén, 1989): 1) measurement invariance refers to invariance of regression intercepts and factor loadings across two samples in order to determine what analyses are eligible to perform; 2) structural invariance refers to invariance of factor means across samples in order to determine the manifestation of the latent factors in the samples. In the present thesis, speed of information processing measured by P300 latency was tested with three models in a hierarchical order to investigate measurement invariance across samples. The first model was performed to test for construct invariance and consisted of a multiple group CFA without any constraints in order to compare the factor structure of the measured underlying constructs in both samples. In accordance with the PCA described in the earlier result sections, a P300 SIP factor was extracted from P300 latencies of the four conditions of the Hick task. Construct invariance means that the same theoretical construct is captured by the used instrument across the tested samples (He & van de Vijver, 2012). The second model was examining metric invariance. The first model was extended by constraining the factor loadings to be equal across the samples. Metric invariance determines if the measurements have the same measurement unit across samples. However, it cannot determine if they have the same origin (He & van de Vijver, 2012). Thus the second model examined if the performance under a particular condition was to an equal amount determined by the underlying construct across the samples. This means, a difference in P300 SIP would result in an equal performance difference under the particular condition across samples. However, it cannot test if the scales of the performance under the particular condition have the same origin, which means, it is possible that a participant from one sample has the same P300 SIP score as a participant of the other sample, but they have a different P300 latency mean in the particular conditon. If metric invariance is given, factor scores can be compared within a sample, but not directly between the samples (He & van de Vijver, 2012). However, mean patterns and correlations are comparable across samples. In the third model not only factor loadings were constrained to be equal across samples, but also the intercepts. This model was performed in order to test for scalar invariance. Scalar invariance examines if not only the measurement unit is the same across the samples, but also the origin (He & van de Vijver, 2012). This model therefore determined if the P300 latencies under a particular condition reflect the same P300 SIP score across samples. Scalar invariance is needed if factor scores are directly compared across samples, e.g. in t-tests or ANOVAs. The fourth and last model, lastly, constrained besides factor loadings and intercepts also the mean of the latent variable to be equal across groups. This last model determined if there is a difference in the mean of the underlying construct across samples. After the models were computed, each model fit was compared to the next stricter one starting with the most liberal one. This comparison of models was performed to determine the level of invariance for P300 SIP. A summary of the results is given in Table 16. The first model testing for construct invariance had an acceptable fit [$\chi 2_{Construct}(4) = 9.47$, $p = .050$]. The model testing for metric invariance also resulted in a good fit [$\chi 2_{Metric}(7) = 11.63$, $p = .113$]. The increase in chi-square from the construct to the metric model was not significant [$\Delta\chi 2$ (3) = 2.16, $p = .054$]. Scalar invariance was tested with the third model that did not have a good fit [$\chi 2_{Scalar}(10) = 27.07$, $p < .01$]. The increase of chi-square from the metric to the scalar model was nevertheless tested. Results showed that scalar invariance across the samples of Study 1 and Study 2 was not given [$\Delta\chi 2$ (3) = 15.44, $p < .01$]. This confirms that metric invariance was reached and that P300 latency did measure the same underlying construct in both samples.

Table 23

Summary of the multigroup confirmatory factor analyses and the comparison of the model fits: Chi square values ($\chi 2$) for each model, degrees of freedom (df),p-values for each model and for the comparison (Δ) of the stricter to the more liberal model.

Invariance	χ2	df	p-value	Reference model	χ2	df	p-value
Construct	9.47	4	.050				
Metric	11.63	7	.113	1	2.16	3	.054
Scalar	27.07	10	**	2	15.44	3	**
Structural	43.03	11	***	3	15.96	1	***

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