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# Decomposing the relationship between mental speed and mental abilities

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ABSTRACT

It is unclear whether different elementary cognitive tasks (ECTs) are associated with intelligence because these tasks tap the same basic cognitive process (suggesting a single mental speed factor) or different ones (suggesting several mental speed factors), as it is not known which specific cognitive processes are measured in ECTs and because the factor structure of these processes is unknown. To address these questions, 40 participants (50% males) between 18 and 75 years drawn from a community sample completed the Hick paradigm, the Sternberg memory scanning paradigm, and the Posner letter matching paradigm while an EEG was recorded. We applied a diffusion model approach to the response-time data, which allows the mathematical decomposition of different cognitive parameters involved in speeded binary decisions. Behavioral and electrophysiological results indicated that ECT conditions varied in different neuro-cognitive components of information processing. Further analyses revealed that all speed and latency variables had substantial loadings on a second-order general factor marked by general intelligence, and that the association between ERP latencies and general intelligence was mediated by reaction times. These results suggest that there is a general neuro-cognitive speed factor across different tasks and different levels of measurement that is associated with general intelligence.


## 1. Introduction

After several decades of research, there is ample evidence of a moderate, but very consistent association between measures of intelligence and measures of mental speed. In a recent review of 172 studies, Sheppard and Vernon (2008) reported an average correlation of $r = -.24$ between different measures of intelligence and a variety of mental speed measures. This evidence indicates that more intelligent individuals have a higher speed of information processing. It is not yet known, however, if this association is driven by a general mental speed factor across different cognitive functions (e.g., information uptake, short-term memory, lexical access) or if there are several mental speed factors that are specific for cognitive functions and that are independently associated with general intelligence.

The aim of the present study was to address this question and to provide a rationale for a more refined analysis of the relationship between mental abilities and mental speed that may allow for a better understanding of the neuro-cognitive processes driving this association.

### 1.1. The study of mental speed

Almost all studies on the relationship between mental abilities and mental speed employ so-called elementary cognitive tasks (ECTs) when measuring reaction times (for a notable exception using pencil-and-paper tests see Neubauer & Knorr, 1998). These ECTs are tasks with very low cognitive demands that maximize the empirical control of task complexity and

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minimize unwanted sources of variance in individual differences. Because ECTs put only marginal cognitive requirements on participants, individual differences in strategy use and in previous experience with specific elements of the task are less likely to influence the association between RTs and intelligence than in more complex decision-making problems. Several of the often-used ECTs follow an idea in tradition of Donder's *subtraction method* (Donders, 1969): The *subtraction method* presumes that when two reaction time tasks differ only in the number of stimulus or response alternatives while every other detail of the task remains the same across conditions, the difference between RTs is an indicator of a purely mental processing speed. Following this logic, difference parameters are often the theoretically most interesting variables in ECT research. There are several paradigms in which this idea is pursued.

In the *simple and choice reaction time task* based on the Hick paradigm (Hick, 1952), participants are presented between one and ten response buttons arranged in a semi-circle around a single home button and have to react when the light next to one of the response buttons is switched on. Because Hick showed that there is a linear relationship between the amount of information that has to be processed and reaction times (Hick, 1952), individual intercept and slope parameters can be computed when regressing RTs on the logarithm of stimulus–response alternatives. This way, individual slope parameters can be used as estimates for the “rate of gain of information” (Roth, 1964), which are theoretically (though seldom statistically) independent of motoric movement time, and can be correlated with measures of mental abilities. Another application of the general idea of the subtraction method can be found in the *Sternberg memory scanning task* (Sternberg, 1969). In this task, participants see memory sets of different sizes and are then asked if a single probe item was part of the previously presented memory set. Because RTs again increase linearly with memory set size, the slope parameter of the regression of RTs on memory set size can be used as an indicator of individual speed of short-term memory search. A similar idea is applied in the *letter matching paradigm* (Posner & Mitchell, 1967) where participants have to decide whether two letters are the same in accordance with their physical identity or in accordance with their name. The difference of RTs between these conditions is an estimate for the speed of lexical access (Hunt, 1983), because of the additionally required access to long-term memory in the name identity condition.

### 1.2. Associations between mental speed and mental abilities

Correlations between RTs of ECTs and mental abilities are moderate, but consistent. Jensen (1987) reviewed 26 studies with a total $N$ of 2317 participants that investigated the relationship between different parameters of the Hick paradigm and mental abilities tests. He reported a multiple $R^2$ of .25 in a regression of IQ scores on different parameters derived from the Hick paradigm. In a review of ten studies using Sternberg's memory scanning task and psychometric intelligence tests, Neubauer (1997) reported a mean correlation of $r = -.27$ between mean RT and intelligence test scores. He also reviewed ten studies correlating RTs in the Posner letter matching task and mental abilities test scores and computed mean $N$-weighted correlations ranging between $r = -.23$ and $-.33$ for different parameters of the paradigm. In a recent review, Jensen (2006) reported canonical correlations ranging from $C = .55$ to .72 between different measures of mental abilities and of mental speed. It should be noted that correlations including the difference measures and slope parameters are usually substantially lower (Jensen, 1998; Neubauer, 1997). Taken together, these results suggest that there is a consistent negative association between mental speed and mental abilities in the way that more intelligent individuals have a higher speed of information processing.

### 1.3. Cognitive processes in elementary cognitive tasks

The general idea that ECTs measure specific cognitive processes like *speed of short-term memory access* or *information processing speed* is appealing, because correlations between difference and slope parameters in ECTs and general intelligence would then be informative about the association between specific cognitive processes and general intelligence. This general idea should, however, be treated with caution. Although ECTs already have rather low task complexities, each ECT still requires several cognitive processes such as attention, perception, encoding, representation in working memory, decision making, and response preparation. Moreover, it can be argued that ECT conditions might differ in the demands they put on several cognitive processes simultaneously, so that difference and slope parameters might not only be indicators of a specific cognitive process, but might also include variance of other cognitive processes that differ between conditions. This would violate one of the assumptions of the subtraction method proposed by Donders (1969) and question the validity of difference and slope parameters. Because this often-implicated premise has to our knowledge never been tested empirically, the first aim of the present study was to investigate whether conditions in three ECTs differ only in one or in several cognitive processes.

Because not much is empirically known about which specific cognitive processes contribute to the distribution of reaction times in ECTs, even less is known about the origins of inter-individual differences in these RTs. One important question is whether these different tasks are related to general intelligence because they tap the *same* basic property of the cognitive system, or whether these tasks tap *different* cognitive system parameters. Many researchers tend to conclude from these findings that there is indeed one basic property at work, which is mental speed. According to this view, greater mental speed facilitates a better cognitive performance. Despite the great theoretical relevance of this concept, only few studies provided data that may help to answer the question whether there is one general factor of mental speed. Most studies include only one or two elementary cognitive tasks and are not focused on a systematic study of the factor structure itself. There are a few studies that report correlation matrices or factor analyses of ECTs that favor the hypothesis of a large general mental speed factor explaining more than 40% of variance (Burns & Nettelbeck, 2003; Hale & Jansen, 1994; Neubauer & Bucik, 1996; Neubauer, Spinath, Riemann, Borkenau, & Angleitner, 2000), while other studies, which employ not only classical ECTs but a more diverse range of information-processing tasks, report multi-factorial models of mental speed (O'Connor & Burns, 2003; Roberts & Stankov, 1999). Clearly these inconsistent results require further systematic study of the factor structure of mental speed, although the preliminary findings may suggest that there is a general mental speed factor, probably in addition to more task-specific speed factors. The second aim of the present study was to address this question by decomposing the information-processing components in three ECTs and testing whether a single general mental speed factor emerges in a factor analysis of different speed measures across the three tasks.

As long as we do not have enough knowledge about the factor structure of ECTs, we cannot know which cognitive processes might be responsible for individual differences in RTs. Therefore, we do not know whether more intelligent individuals have a generally faster speed of information processing or whether they differ in very specific facets of mental speed from less intelligent individuals. The behavioral data do not inform us which of these processes differ between individuals of different cognitive ability. The third aim of the present study was to address this problem using methods that allow the decomposition of the stream of information processing during reaction time tasks and to analyze the association between individual differences in these distinct information processing components and mental abilities.

### 1.4. Decomposing the stream of information processing in ECTs

In the present study, we used two methods to decompose the stream of information processing in ECTs: The first method is the *diffusion model*, which decomposes the stream of information-processing and decision making in RT tasks into distinct components based on RT distributions (Ratcliff, 1978). Another method that decomposes the stream of neuro-cognitive information processing are electrophysiological measures, namely *event-related potentials* (*ERPs*), which allow to identify functionally distinct components in different time windows between the stimulus onset and the response execution. While diffusion models have only recently been applied in mental abilities research, ERPs are already used to a great extent.

Diffusion models are random walk-models used in the context of speeded binary decisions and provide a framework for analyzing the whole distribution of reaction time data (for recent reviews, see Ratcliff & McKoon, 2008; Wagenmakers, 2009; Voss, Nagler, & Lerche, 2013). They allow the identification of cognitive parameters by fitting predicted reaction time-distributions to empiric reaction time-distributions (Voss, Rothermund, & Voss, 2004). Diffusion models in their most basic form identify four distinct parameters: The first parameter, *drift rate* ($v$), describes the strength of the systematic influence on the diffusion process with larger drift rates causing shorter reaction times and smaller amounts of errors. This parameter is most akin to the idea of 'speed of information processing' mentioned earlier, as it indicates the amount of information gathered per time unit. The second parameter, *boundary separation* ($a$), is a measure for the distance between decision thresholds, i.e., an indicator for the conservatism of the decision criterion. The third parameter, *starting value* ($z$), indicates whether a person is biased towards one of two decision thresholds. If $z$ is closer to one threshold than the other, this threshold is reached more often due to random fluctuations, resulting in more and faster decisions associated with this threshold. The last parameter, *response-time constant* ($t_0$), encompasses processes unrelated to decision making, mainly stimulus encoding and response execution.

There are only a very small number of studies in which diffusion models were applied in intelligence research. In a study by Schmiedek, Oberauer, Wilhelm, Süß, and Wittmann (2007), university students had to complete several reasoning tasks and choice reaction tasks. They showed that a latent drift rate factor correlated positively with a latent reasoning ability factor ($r = .79$), whereas they reported a smaller negative association between a latent boundary separation factor ($r = -.48$) and reasoning ability. Ratcliff, Thapar, and McKoon (2010) asked participants in three different age groups (18–25, 60–74, 75–90 years) to complete different categorization tasks. They reported correlations ranging from r = .36 to .90 for the three age groups between a latent drift rate factor and intelligence, whereas they found no consistent association between other diffusion model parameters and intelligence. They found similar results in another study, where participants' drift rate in recognition tasks was the only diffusion model parameter consistently correlated with intelligence, $r = .47$ to .67 (Ratcliff, Thapar, & McKoon, 2011). Although these preliminary results are promising, it should be noted that none of these studies used ECTs that are normally used in intelligence research.

Another method suited to decompose cognitive components in the stream of information processing is the ERP. The ERP methodology allows identifying functionally distinct electrophysiological components (e.g., the N200 or P300) that might be affected differently by condition differences in ECTs. Moreover, according to the mental speed hypothesis, the latencies of ERP components should be negatively correlated with intelligence.

There are several electrophysiological studies that correlated ERP parameters with intelligence. In their review of 23 of these studies ($N > 2400$), Schulter and Neubauer (2005) concluded that there are no consistent associations between ERP latencies and intelligence. It should, however, be noted that most of these studies employed standard ERP paradigms such as the oddball paradigm and that behavioral data from these tasks is uncorrelated with intelligence. There are only a few studies in which classical ECTs were combined with ERP methodology. Houlihan, Stelmack, and Campbell (1998) and Pelosi et al. (1992) computed ERPs to probe stimuli in the Sternberg memory scanning tasks and found both weak and mostly insignificant associations between ERP latencies and intelligence test scores. McGarry-Roberts, Stelmack, and Campbell (1992) computed a factor analysis of P300 latencies recorded during six reaction time tasks including the Sternberg memory scanning task. They correlated this P300 factor with a general intelligence factor and reported a correlation of $r = -.36$ between these factors. All in all, these studies suggest that there may be a weak negative association between ERP latencies and mental abilities, but further studies are needed before any final conclusions can be drawn.

### 1.5. The present study

The goal of the present study was to decompose the information-processing components in three different ECTs (Hick paradigm, Sternberg memory scanning task, Posner letter matching task) by applying diffusion models to reaction time distributions and by monitoring the neuro-cognitive correlates of information processing with EEG methodology. We pursued three aims: First, we wanted to investigate whether differences between ECT conditions represent one or multiple cognitive processes, as the general idea of ECT implies that these differences represent a single process within each task. Contrary to this idea, we expected ECT conditions to represent a range of different processes such as attention, perception, encoding, representation in working memory, decision making, and response preparation, i.e., we anticipated that these tasks differ in several behavioral and electrophysiological parameters simultaneously. Our second aim was to investigate the factor structure of mental speed. We expected to identify a single general mental speed factor across all behavioral and electrophysiological measures and all tasks in addition to more specific factors. Our third aim was to investigate the association between mental speed and mental abilities across the different measures and tasks. We expected a) that a general mental speed factor is significantly associated with general intelligence, and b) that the association between ERP latencies and mental abilities is mediated by reaction times. This mediation model is based on the methodological framework of Baron and Kenny (1986), who suggested that mediation models are causal models. A proposed mediator variable Z mediates the relationship between an independent variable X and an outcome variable Y only if the independent variable has a causal effect on the mediator variable that in turn has a causal effect on the outcome variable (Baron & Kenny, 1986, p. 1176). While the mediation model allows for some part of the causal influence to take the direct path from the independent variable to the outcome variable ($X \geq Y$), it presumes that a substantial part of the causal influence is exerted through the indirect effect via the proposed mediator ($X \geq Y \geq Z$). In all ECTs of the present study, a stimulus has first to be processed visually and then relayed to frontal areas associated with executive functions and decision making before a motor response reflecting this decision can be initiated. Thus, there is a stream of processing that has some temporal order, with neurocognitive events taking place before behavioral events occur. Therefore, we expected that ERP latencies exert the majority of their influence on general intelligence indirectly through the proposed mediator reaction times.

## 2. Method

### 2.1. Participants

We recruited a sample of $N = 40$ participants (20 females, 20 males) between 18 and 75 years old ($M = 47.4$, $SD = 15.6$) from different educational and occupational backgrounds via local newspaper advertisement. All participants had normal or corrected to normal vision and no history of mental illness. They received 10€ as payment for their participation and could indicate whether they wanted to be informed about their personal results.

### 2.2. Measures

#### 2.2.1. Elementary cognitive tasks

*2.2.1.1. Hick paradigm.* In order to control for visual attention effects, response bias effects, and top-down strategies associated with the classical Jensen apparatus and the use of a home button (Longstreth, 1984) and in order to ensure compatibility of this paradigm with EEG measurements, we adopted the modified Hick paradigm developed by Neubauer, Bauer, and Höller (1992). This modified paradigm is presented on a computer screen and does not employ a home button. Participants' middle and index fingers rested on four keys of a modified keyboard, on which all other keys irrelevant to the task were removed. Those keys were positioned directly underneath the squares relevant for the task, thus increasing stimulus–response compatibility as much as possible. Participants were instructed to always keep their fingers on the keys during the whole task. In the 2 bit condition, four squares arranged in a row with a fixation cross in their middle were shown on the screen for a time period varying between 1000 and 1500 ms. After this period, a cross appeared in one of the four squares and participants had to press the corresponding response-key. The screen remained unchanged for 1000 ms following the response, as we wanted to record post-decisional neuronal processes. After this time period, an ITI varying between 1000 and 1500 ms was presented, followed by the next trial.

We implemented two 1 bit conditions: One condition (comparability low: 1 $bit_{CL}$) adopted from Neubauer et al. (1992) and a second one (comparability high: 1 $bit_{CH}$) designed to maximize stimulus comparability with the 2 bit condition. At the beginning of each trial in the 1 $bit_{CL}$ condition, only two squares appeared on the screen with a fixation cross in the middle of the screen. These two squares appeared pseudorandomly in two of the four locations used in the 2 bit condition. As in the 2 bit condition, a cross appeared in one of the two squares after 1000 to 1500 ms and participants had to press the corresponding key. In the 1 $bit_{CH}$ condition, however, all four squares were presented on the screen, but participants were instructed to only pay attention to two of them, because the cross could only appear in one of these two squares. There were four blocks with 20 items each instructing participants to pay attention to the left/right/middle/outer two squares. We implemented this additional 1 bit condition because it shared all stimulus features with the 2 bit condition and only differed from this condition in the instruction participants were given. This is a necessary prerequisite for ruling out confounds in the interpretation of ERP effects, because small changes in physical stimulus features can result in sizeable changes in ERP amplitudes. For an overview over the different conditions, see Fig. 1.

Participants were instructed to respond as quickly and accurately as possible. The order of conditions was the same for all participants. First they completed the 2 bit condition, then the 1 $bit_{CL}$ condition followed by 1 $bit_{CH}$ condition. Each condition consisted of a learning phase with ten sample items and direct feedback, followed by 80 test items. Participants made short breaks between blocks. There were two fixed sequences of the location of squares and crosses that were balanced across participants.

*2.2.1.2. Sternberg memory scanning task.* Participants were shown digits between 0 and 9 on a computer screen. There were three blocks of ten sample items each with feedback and 80 test items with a memory set size of 1, 3, and 5 digits. Each trial began with a fixation cross varying between 1000 and

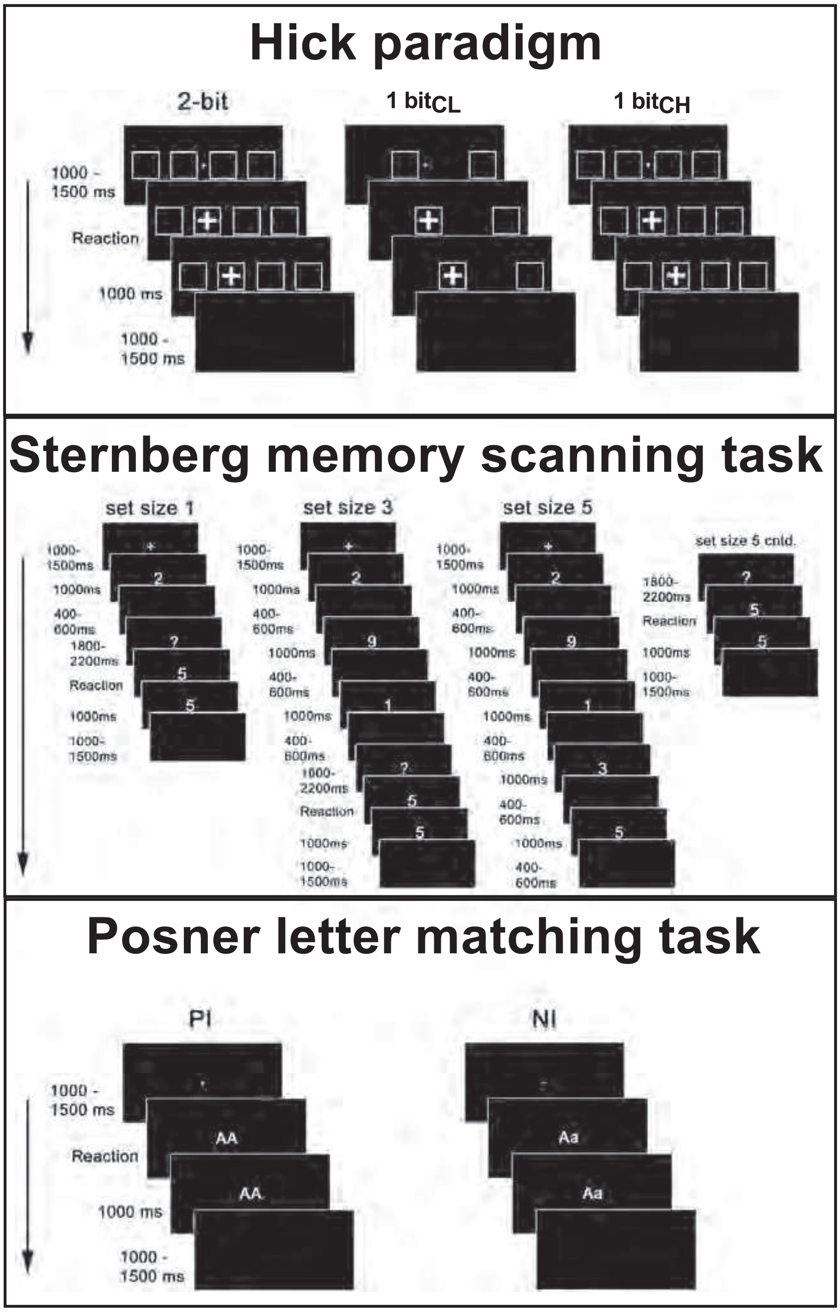


**Fig. 1.** Stimulus material for the three ECTs. Upper part: The three conditions of the modified Hick paradigm. 2-bit = 2-bit condition, 1-bit$_{CL}$ = 1-bit condition with low stimulus comparability to the 2-bit condition, 1-bit$_{CH}$ = 1-bit condition with high stimulus comparability to the 2-bit condition. Middle part: Different memory set sizes in the Sternberg memory scanning task. Lower part: Physical identity (PI) and name identity (NI) condition in the Posner letter matching task.

1500 ms. Digits were presented sequentially for 1000 ms with a blank screen of 400 to 600 ms between single digits. After the last digit of the memory set was presented, a black screen with a question mark was shown for 1800 to 2200 ms, followed by a probe item showing a single digit. Participants had to press one of two keys with their index fingers indicating whether the digit was part of the memory set seen immediately before. The probe item remained on screen for 1000 ms after the reaction was made and the intertrial interval was 1000 to 1500 ms. See Fig. 1 for illustration.

All participants began with set size one and then progressed to set sizes three and five. They were given the option to make short breaks between blocks. There were two versions of stimulus material counterbalanced across participants. The probe item was previously presented in the memory set in 50% of the trials. The position of keys indicating whether the probe item was part of the memory set was counterbalanced across participants.

*2.2.1.3. Posner letter matching task.* After a fixation cross lasting between 1000 and 1500 ms, two letters were presented in the middle of the screen and participants had to decide whether this pair was identical or not by pressing the corresponding key. In the physical identity condition, participants were instructed to judge letters as identical only if they were identical in physical characteristics (thus, "AA" would be identical, while "Aa" or "AB" would be judged as different). In the name identity condition, participants were instructed to judge the name identity of stimuli (thus, "AA" and "Aa" would be judged as identical, while "AB" would not be). Afterwards, the pair of letters remained on the screen for 1000 ms and was followed by an ITI varying between 1000 and 1500 ms. See Fig. 1 for illustration.

The two conditions were separated into blocks of 10 sample items with feedback and 200 test items each. All participants began with the physical identity condition and made a short break between blocks. There were two versions of stimulus material assorted to participants depending on their number. We used the upper- and lowercase letters A, B, F, H, and Q as stimulus material. The pair of letters was identical in 50% of the trials. The position of keys indicating whether the pair was identical was counterbalanced across participants.

### 2.2.2. Intelligence tests

*2.2.2.1. Fluid intelligence.* We used a self-programmed computerized version of Raven's Advanced Progressive Matrices (APM; Raven, Court, & Raven, 1994) to measure fluid intelligence. In this computer adapted version of the APM, one item was presented at a time with its eight possible alternatives and participants had to indicate their solution with a mouse click. They were able to go back and forth between the different items at any time with the exception that they could not go back to Item set I once they had started working on Item Set II. According to the test manual, the APM raw test score was computed as the number of correctly solved items and used in all further analyses. Cronbach's alpha was $\alpha = .82$.

*2.2.2.2. Crystallized intelligence.* We constructed a short version of the knowledge test from the German Intelligenz-Struktur-Test 2000-R (IST 2000-R; Liepmann, Beauducel, Brocke, & Amthauer, 2007) as an indicator of crystallized intelligence. The knowledge test of the IST 2000-R consists of several knowledge questions tapping different fields of knowledge like "What does π (pi) mean?", "In which street is the New Yorker stock exchange?", or "What does the octane index indicate?". To create a short version, we chose the 20 items with the highest loadings on crystallized intelligence, although we lost some diversity in the content of test items. The knowledge test was administered according to the manual and the number of correctly solved items was used as the test score for all further analyses. We did not compute IQ scores because we had no normative data of our abbreviated version. Cronbach's alpha was $\alpha = .65$.

### 2.3. Procedure

Participants read and signed an informed consent. They were seated on a comfortable chair in a dimly lit EEG cabin in front of a computer screen. All participants completed the three ECTs in the same order with small breaks between the tasks: Hick paradigm, Sternberg memory scanning task, and Posner letter matching task. ECTs were followed by a short break, after which participants completed the APM and the knowledge test based on the IST 2000-R. Information about demographic variables was gathered at the end of the session.

### 2.4. EEG recording

The EEG was recorded with nine Ag–AgCl electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) that were positioned according to the international 10–20 system. We used the aFz electrode as the ground electrode. Electrodes were initially referenced to Cz and later re-referenced to linked mastoids (TP9, TP10). To correct for ocular artifacts, we recorded the electrooculogram (EOG) bipolarly with two electrodes positioned above and below the right eye and two electrodes positioned at the outer canthi of the eyes. All electrode impedances were kept below 5 kΩ. The EEG was recorded continuously with a sampling rate of 2500 Hz (band-pass 0.1–100 Hz). We applied an offline low-pass filter of 16 Hz for the determination of average activity within time windows and low-pass filters of 12 Hz (early ERPs) and 8 Hz (late ERPs) for latency detection.

### 2.5. Data analysis

*2.5.1. Response times*

Trials with extremely fast RTs (<200 ms for the Hick paradigm and <300 ms for the Sternberg memory scanning and the Posner letter matching task) or extremely slow RTs (>3000 ms) were removed. We used the *fast-dm* program developed by Voss and Voss (2007) to fit diffusion models to RT distributions, which is free software that utilizes the Kolmogorov–Smirnov test statistic to estimate model parameters. The parameter $z$ for mean starting point was set equal to $a/2$, presuming that participants had no response bias towards the correct or incorrect alternative. We computed separate diffusion models for each condition of the three ECTs in which the parameters $a$, $v$, $t_0$, and $s_{t0}$ were allowed to vary freely. For correlational analyses, we averaged the respective parameters across all conditions for each ECT. Thus, we computed an average drift and an average response-time constant for each of the three ECTs in order to reduce the number of variables entered into the subsequent factor analysis while increasing their reliability. Inter-trial variability parameters of the diffusion model ($s_v$, $s_z$) were fixed to 0 to keep the model parsimonious with the exception of $s_{t0}$, because it led to a notable improvement of model fit.

To assess how well diffusion models fit the individual-level data, we conducted Monte-Carlo simulations and simulated 1000 data sets from the diffusion model that matched the characteristics of the empirical data (i.e., simulated parameter values were based on empirical parameters values, and the number of trials and conditions was equivalent to the tasks used in the present study). We then re-analyzed the simulated data sets with the diffusion model and used the 5% quantile of the distribution of fit-values in each ECT condition as the critical value to assess individual model fit in the empirical models.

*2.5.2. EEG parameters*

We calculated ERPs time-locked to the onset of probe items in all tasks, using the preceding 200 ms as baseline and including an interval from 200 ms before stimulus onset until 1000 ms afterward. Ocular artifacts were corrected using the regression procedure of Gratton, Coles, and Donchin (1983). Epochs with amplitudes exceeding $\pm 70$ μV, with amplitude changes exceeding 100 μV within 100 ms, or with lower activity than 0.5 μV were discarded as artifacts. We identified ERP components by visual inspection of the grand average waveforms (Fig. 3–5) for the three ECTs and computed mean EEG activity in the following time windows: In the Hick paradigm, we computed the P200 (175–215 ms), the N200 (210–240 ms), and the P300 (360–420 ms). In the Sternberg memory scanning paradigm, we computed the N150 (115–160 ms), the P200 (200–245 ms), the N300 (300–360 ms), and the P300 (400–600 ms). In the Posner letter matching paradigm, we computed the N140 (115–155 ms), the P210 (190–235 ms), the N300 (240–365 ms), and the P300 (465–580 ms). For ERP latencies, we inspected participants' individual averaged waveforms at all nine electrode positions for peaks during the time windows described above and used these peak latencies as individual latency measures. For correlational analyses, we inspected grand average waveforms and determined at which electrode position each ERP component was greatest and used the corresponding electrode position for all further analyses. We used the same electrode position for each ERP component for all participants.

*2.5.3. Statistical analyses*

In order to characterize ECTs in terms of information processing components, we ran repeated measures ANOVAs with the factor condition separately for median RTs, drift rates, and response-time constants for each ECT. In the following analyses on average EEG activity, we ran an omnibus repeated-measures ANOVA for each ECT with four within-subject factors: ERP component (with three levels for the Hick paradigm: P200, N200, P300; four levels for the Sternberg memory scanning task: N150, P200, N300, P300; with four levels for the Posner letter matching task: N140, P210, N300, P300), condition (with two levels for the Hick paradigm: 1 bit vs. 2 bit; three levels for the Sternberg memory scanning task: set size 1, set size 3, set size 5; two levels for the Posner letter matching task: PI vs. NI), caudality (with three levels for all tasks: frontal, central, parietal), and laterality (with three levels for all tasks: left, central, right) in order to test if condition effects differed between time windows. We then ran follow-up repeated measures ANOVAs for each ECT with the three within-subject factors condition, caudality, and laterality to test for condition differences in specific ERP components in each ECT. For these analyses, we dropped the fourth factor ERP component that was included in the omnibus ANOVAs, because we wanted to test for condition differences in specific time frames.

For factor analyses, we first computed principal component analyses (PCA) a) for intelligence test scores and b) for each of six time-domain variables across the three ECTs (Table 8 shows a list of variables). We included only time-domain variables that were available and comparable in at least two different ECTs, which led to the exclusion of slower ERP components because their time windows were not comparable across ECTs. Next, we computed individual factor scores of the first principal component of these seven PCAs that yielded individual factor scores for RT, $v$, $t_0$, and three ERP latencies. A hierarchical PCA was then run on the correlation matrix of these factor scores and the number of factors was determined by the scree plot (Cattell, 1966) and the parallel analysis criterion (Horn, 1965). Because of their intercorrelations, factors were rotated obliquely.

Finally, we ran mediation analyses to test whether the relationship between ERP latencies on intelligence test scores was mediated by reaction times and used the bootstrap procedure to test for an indirect effect (Preacher & Hayes, 2004).

We repeated all correlational analyses controlling for age because of the heterogeneous sample. Since age had no influence on the pattern of results, we did not include these analyses in this report.

## 3. Results

*3.1. Descriptive data*

The median RT in the Hick paradigm was $M = 447.22$ ($SD = 91.62$) and the mean accuracy was $M = 0.98$ ($SD = .01$). In the Sternberg memory scanning paradigm, the median RT was $M = 736.78$ ($SD = 133.17$) and the mean accuracy was $M = 0.96$ ($SD = .02$). The median RT in the Posner letter matching task was $M = 663.41$ ($SD = 104.89$) and the mean accuracy was $M = 0.98$ ($SD = .01$). Please consult Table 1 for the descriptive data of the different ECT conditions. The mean score of correctly solved APM items was $M = 24.55$ ($SD = 5.09$), which corresponds to a mean IQ of $M = 91.68$ ($SD = 14.6$). IQ scores were normally distributed (skew $= 0.16$, kurtosis $= -0.24$) and ranged from 78 to 123 IQ points. The mean score of correctly solved knowledge test items was $M = 15.49$ ($SD = 2.72$). No corresponding IQ score could be computed, because we only used an abbreviated version of the full IST 2000-R knowledge test. Knowledge test scores were also normally distributed (skew $= -0.17$, kurtosis $= -0.49$).

Descriptive statistics for the diffusion model parameters are shown in Table 1. Model fits were satisfactory for all three ECTs. In the Hick paradigm, 5% of the models in the 1 bit condition and 2.5% of the models in the 2 bit condition had $p$-values smaller than the critical $p$-values of $p_{crit} = .794$ and .843, respectively. In the set size 1 condition of the Sternberg memory scanning paradigm, there were no models with $p$-values below the critical value of $p_{crit} = .834$, while 2.5% and 7.5% of the models in the set size 3 and in the set size 5 condition had $p$-values smaller than $p_{crit} = .839$ and $p_{crit} = .836$. Model fits were slightly worse in the Posner letter matching paradigm with 10% of the models falling short of the critical $p$-value $p_{crit} = .833$ in the physical identity condition and 5% of the models falling short of the critical $p$-value $p_{crit} = .824$ in the name identity condition. We kept the models with bad model fits in our analyses, because excluding these models did not change the pattern of results.

*3.2. Characterization of ECTs in terms of neuro-cognitive processing*

One aim of this study was to identify neuro-cognitive parameters differing between conditions of the three ECTs. The

**Table 1**
Median RTs, mean accuracies, mean drift rates and mean response-time constants for the different conditions in the three ECTs (SD in parentheses).

| ECT | Condition | Median RT | Accuracy | $v$ | $t_0$ | $a$ | $s_{t0}$ |
|---|---|---|---|---|---|---|---|
| Hick paradigm | 1 $bit_{CL}$ | 483 (172.41) | .97 (.03) | 3.53 (1.57) | 0.31 (0.10) | 1.47 (0.56) | 0.13 (0.11) |
| | 1 $bit_{CH}$ | 380 (73.59) | 1.00 (.01) | 5.26 (1.34) | 0.30 (0.04) | 1.18 (0.33) | 0.11 (0.06) |
| | 2 bit | 461 (98.73) | .99 (.02) | 4.89 (1.44) | 0.37 (0.06) | 1.17 (0.26) | 0.15 (0.08) |
| Sternberg memory scanning task | Set size 1 | 599.25 (105.60) | .96 (.03) | 3.15 (0.81) | 0.40 (0.08) | 1.35 (0.35) | 0.18 (0.13) |
| | Set size 3 | 732.75 (146.69) | .97 (.03) | 2.86 (0.79) | 0.51 (0.10) | 1.54 (0.36) | 0.21 (0.16) |
| | Set size 5 | 851.25 (187.74) | .96 (.03) | 2.36 (0.72) | 0.56 (0.13) | 1.68 (0.41) | 0.20 (0.14) |
| Posner letter matching task | PI | 618 (96.44) | .98 (.01) | 3.98 (0.94) | 0.46 (0.07) | 1.37 (0.35) | 0.13 (0.07) |
| | NI | 683.50 (120.78) | .98 (.02) | 3.03 (0.84) | 0.47 (0.08) | 1.64 (0.31) | 0.15 (0.14) |

*Note.* 1 $bit_{CL}$ = 1 bit condition with low comparability; 1 $bit_{CH}$ = 1 bit condition with high comparability; PI = Physical Identity; NI = Name Identity; $v$ = drift rate; $t_0$ = response-time constant; $a$ = boundary separation; $s_{t0}$ = intertrial-variability of the response-time constant.

main purpose of the analyses reported in this section was to test whether there are specific RT and ERP parameters that differ between conditions or whether we have to assume that ECT conditions differ in several steps in the course of neuro-cognitive information processing.

### 3.2.1. RT characterization and diffusion model results of ECTs

As expected, median RTs increased with increasing task difficulty in all ECTs (Fig. 2). *In the Hick paradigm*, median RTs were significantly larger in the 2 bit than in the 1 $bit_{CH}$ condition, $F(1,38) = 92.73$, $p < .001$, $\omega^2 = .71$. In the 1 $bit_{CL}$ condition, however, median RTs were significantly larger than in the 2 bit condition, $F(1,38) = 4.62$, $p = .038$, $\omega^2 = .09$, which was unexpected as less information (only two alternatives) had to be processed in the 1 $bit_{CL}$ than in the 2 bit condition (four alternatives). As we did not know which cognitive processes were responsible for this unexpected increase in RTs, we dropped the 1 $bit_{CL}$ condition from all further analyses and renamed the "1 $bit_{CH}$" condition to "1 bit" condition for the remainder of this report. When we analyzed the effects of condition on drift rates and response-time constants separately, we observed no change in drift rates with increasing number of stimulus alternatives, $F(1,38) = 2.02$, $p = .163$, $\omega^2 = .03$, but an increase in response-time constants, $F(1,38) = 58.62$, $p < .001$, $\omega^2 = .60$.

*In the Sternberg memory scanning paradigm*, RTs increased with set size, $F(2,78) = 113.17$, $p < .001$, $\omega^2 = .74$, $\varepsilon = .68$, in a strictly linear way, $F(1,39) = 133.53$, $p < .001$, $\omega^2 = .77$. As expected, drift rates decreased with memory set size, $F(2,76) = 18.47$, $p < .001$, $\omega^2 = .31$, $\varepsilon = .91$, also following a linear pattern, $F(1,38) = 31.16$, $p < .001$, $\omega^2 = .44$. $t_0$ also differed between conditions, $F(2,76) = 35.57$, $p < .001$, $\omega^2 = .48$, $\varepsilon = .82$, and increased linearly with memory set size, $F(1,38) = 46.76$, $p < .001$, $\omega^2 = .55$.

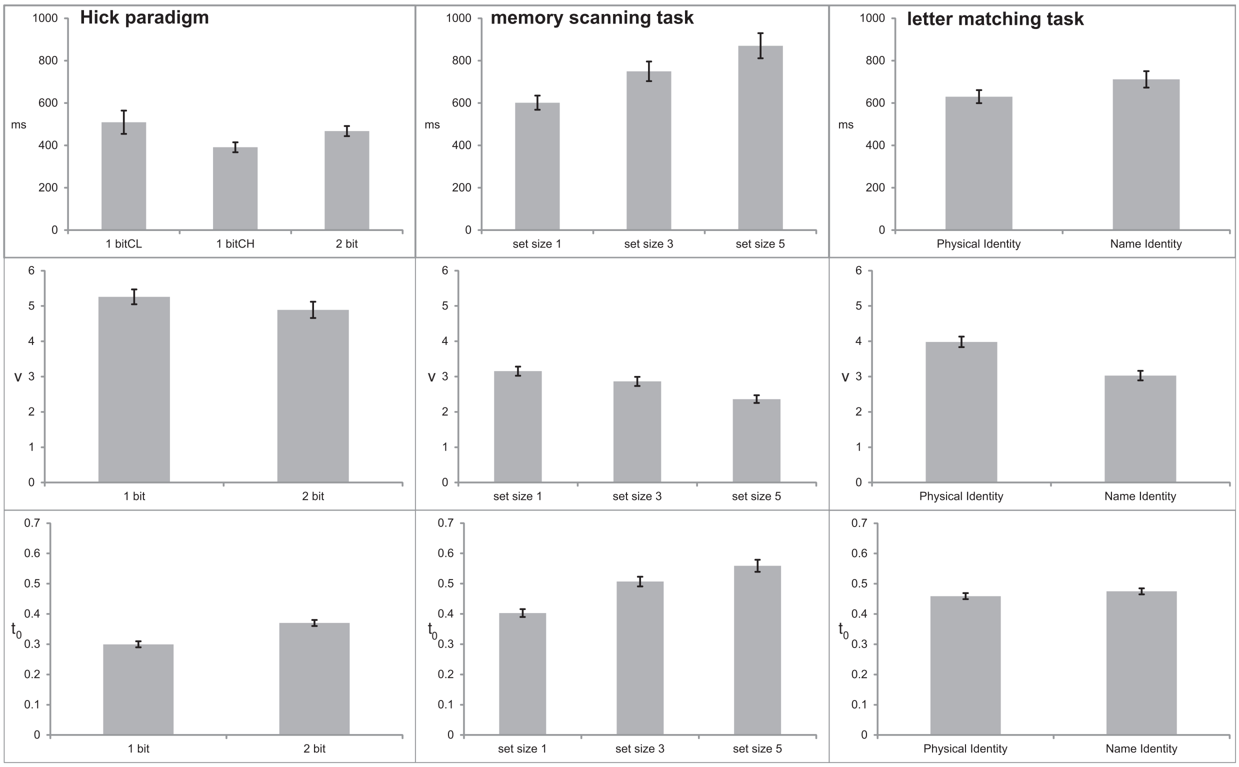


**Fig. 2.** Median RTs, mean drift rates, and mean response time-constants for the different conditions of the three ECTs. Error bars represent doubled standard errors.

*In the Posner letter matching paradigm*, median RTs were higher in the name identity than in the physical identity condition, $F(1,38) = 70.36$, $p < .001$, $\omega^2 = .64$. When $v$ and $t_0$ were compared between conditions, we found that drift rates decreased in the NI condition, $F(1,38) = 35.76$, $p < .001$, $\omega^2 = .48$, and that there was no significant difference in response-time constants between conditions, $F(1,38) = 2.64$, $p = .112$, $\omega^2 = .04$. Overall, these results indicated that there was substantial variation between tasks in which diffusion model parameters varied significantly between ECT conditions. Only in the Sternberg memory scanning paradigm did different conditions differ not only in their information processing demands, but also in their sensomotoric difficulties.

### 3.2.2. ERP characterization of ECTs

In order to investigate whether electrophysiological activity differed between conditions within each of the three ECTs, we compared average activity and peak latencies across different time windows in the course of information processing. Our main aim was not to identify specific processes differing between conditions, but to test if ECT conditions differed in only one or several electrophysiological components. We only reported main effect and interactions including the factor ECT condition, as we were only interested in condition effects on ERPs; additional topographical information on the ERP components can be found in the tables detailing the complete ANOVA results in the supplementary material.

*In the Hick paradigm*, we compared mean activity and peak latencies between conditions in three different time windows. First, we computed an omnibus ANOVA with the four within-subject factors ERP component (P200: 175–215 ms, N200: 210–240 ms, P300: 360–420 ms), condition (1 bit vs. 2 bit), caudality (frontal, central, parietal), and laterality (left, central, right) to test whether condition effects differed between time windows. For mean activity, we observed a significant interaction between component and condition, $F(2,70) = 20.26$, $\varepsilon = .71$, $p < .001$, $\omega^2 = .55$, as well as significant three-way interactions between ERP component, condition and caudality, $F(4,140) = 5.12$, $\varepsilon = .39$, $p = .014$, $\omega^2 = .11$, and between ERP component, condition and laterality, $F(4,140) = 3.16$, $\varepsilon = .53$, $p = .045$, $\omega^2 = .06$. For ERP latencies we observed a significant interaction between ERP component and caudality, $F(4,140) = 3.96$, $\varepsilon = .64$, $p = .032$, $\omega^2 = .08$, and a significant three-way interaction between ERP component, condition and caudality, $F(4,140) = 8.96$, $\varepsilon = .56$, $p < .001$, $\omega^2 = .18$. See Fig. 3 for the ERPs elicited by stimuli in the Hick paradigm.

In a next step, we compared mean activity and ERP latencies between conditions in each of the three different time windows. Please see Table 2 for detailed results of the main effects and interactions including the factor condition on ERP amplitudes and Table 3 for detailed results on ERP peak latencies. We found a significant difference in mean P200 and N200 activity with amplitudes being greater in the 1 bit than in the 2 bit condition for the P200, $\omega^2 = .41$, and with amplitudes being greater in the 2 bit than in the 1 bit condition for the N200, $\omega^2 = .42$. The significant interactions between condition and caudality, $\omega^2 = .25$, and between condition and laterality, $\omega^2 = .22$ and .30, indicated a specific topography of this effect. In particular, condition differences were largest at central and central parietal electrode sites for both ERP components. Moreover, P200 latencies were shorter in the 2 bit than in the

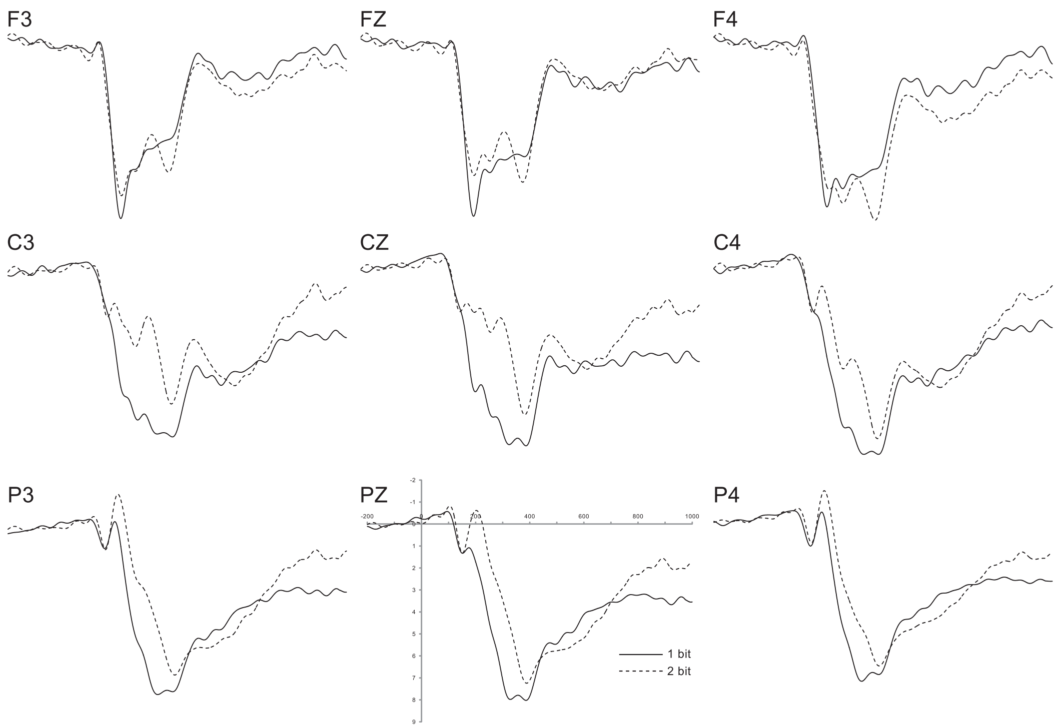


**Fig. 3.** Event-related potentials elicited by the onset of the cross in the 1 bit condition (solid lines) and 2 bit condition (broken lines) in the Hick paradigm. Electrodes are arrayed from most anterior (top) to most posterior (bottom) and from left to right.

**Table 2**
Results of the ANOVA with the three within-subject factors condition (1 bit vs. 2 bit), caudality (frontal, central, parietal), and laterality (left, central, right) on a) P200 (175–215 ms) amplitude, b) N200 (210–240 ms) amplitude, and c) P300 (360–420 ms) amplitude in the Hick paradigm. (n = 36).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) P200 | Condition | 1,35 | 25.18 | <.001 | – | .41 |
| | Condition × Caudality | 2,70 | 12.40 | <.001 | .67 | .25 |
| | Condition × Laterality | 2,70 | 11.08 | <.001 | .90 | .22 |
| | Condition × Caudality × Laterality | 4,140 | <1 | .765 | .66 | .00 |
| b) N200 | Condition | 1,35 | 25.89 | <.001 | – | .42 |
| | Condition × Caudality | 2,70 | 27.79 | <.001 | .43 | .25 |
| | Condition × Laterality | 2,70 | 16.17 | <.001 | .82 | .30 |
| | Condition × Caudality × Laterality | 4,140 | <1 | .654 | .72 | .00 |
| c) P300 | Condition | 1,35 | <1 | .497 | – | .00 |
| | Condition × Caudality | 2,70 | 12.90 | <.001 | .69 | .25 |
| | Condition × Laterality | 2,70 | 8.21 | <.001 | .71 | .13 |
| | Condition × Caudality × Laterality | 4,140 | <1 | .526 | .59 | .00 |

1 bit condition, $\omega^2 = .27$, but the significant interaction between condition and caudality, $\omega^2 = .17$, suggested that this was mostly the case for frontal electrode sites, as P200 latencies were slightly shorter in the 1 bit than in the 2 bit condition at parietal electrode sites, $F(1,35) = 4.26$, $p = .046$, $\omega^2 = .09$. Furthermore, we found significant interactions between condition and caudality, $\omega^2 = .11$, between condition and laterality, $\omega^2 = .08$, and between condition, caudality and laterality, $\omega^2 = .11$, for the N200 peak latencies. These interactions indicated that N200 latencies were shorter in the 2 bit condition than in the 1 bit condition at Fz and F4, $F(1,35) = 6.78$, $p = .013$, $\omega^2 = .14$, and marginally larger in the 2 bit than in the 1 bit condition at Cz and Pz, $F(1,35) = 3.14$, $p = .085$, $\omega^2 = .06$.

We observed no main effect of condition on average activity in the P300 component, $\omega^2 = .00$. The significant interactions (see Table 2c)) between condition and caudality, $\omega^2 = .25$, and between condition and laterality, $\omega^2 = .13$, indicated that amplitudes in the 1 bit were greater than in the 2 bit condition at central electrode sites, $F(1,35) = 4.36$, $p = .044$, $\omega^2 = .09$, and tended to be smaller at frontal electrode sites in comparison to the 2 bit condition, $F(1,35) = 3.58$, $p = .067$, $\omega^2 = .07$. Moreover, condition effects could only be observed at central and left electrode sites. For P300 latencies we found a pattern of results that again indicated that P300 latencies were marginally shorter in the 2 bit than in the 1 bit condition at frontal electrode sites, $F(1,35) = 3.44$, $p = .072$, $\omega^2 = .07$, and shorter in the 1 bit than in the 2 bit condition at parietal electrode sites, $F(1,35) = 5.20$, $p = .029$, $\omega^2 = .11$. It should be noted that mean RTs in both conditions were close to the P300 time window (391 and 467 ms) and might therefore account for condition effects in terms of differently timed response preparation processes.

Together, the topography effects described for the mean activity in each ERP time window and the significant interactions of the omnibus analysis suggested that conditions in the Hick paradigm differ in several electrophysiological components of information processing. For ERP latencies, however, there seemed to be a caudality-specific pattern of results that is consistent across all ERP components and that suggests that condition differences in ERP latencies are not specific for ERP components.

*In the Sternberg memory scanning task*, we compared mean activity and ERP latencies between conditions in four different time windows. First, we computed another omnibus analysis following the previously described logic with the four within-subject factors ERP component (N150: 115–160 ms, P200: 200–245 ms, N300: 300–360 ms, P300: 400–600 ms), condition (set size 1, set size 3, set size 5), caudality (frontal, central, parietal), and laterality (left, central, right) to test whether condition effects differed between time windows. We observed a significant interaction between ERP component and condition on average activity, $F(6,228) = 8.52$, $\varepsilon = .59$, $p < .001$, $\omega^2 = .17$, as well as significant three-way interactions between ERP component, condition, and caudality, $F(12,456) = 18.92$, $\varepsilon = .36$, $p < .001$, $\omega^2 = .32$, and between ERP component, condition, and laterality, $F(12,456) = 3.79$, $\varepsilon = .23$, $p = .015$, $\omega^2 = .07$. For ERP latencies, we observed a significant main

**Table 3**
Results of the ANOVA with the three within-subject factors condition (1 bit vs. 2 bit), caudality (frontal, central, parietal), and laterality (left, central, right) on a) P200 (175–215 ms) peak latencies, b) N200 (210–240 ms) peak latencies, and c) P300 (360–420 ms) peak latencies in the Hick paradigm. (n = 36).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) P200 | Condition | 1,35 | 13.91 | .001 | – | .27 |
| | Condition × Caudality | 2,70 | 8.42 | .003 | .65 | .17 |
| | Condition × Laterality | 2,70 | <1 | .631 | .93 | .00 |
| | Condition × Caudality × Laterality | 4,140 | <1 | .932 | .69 | .00 |
| b) N200 | Condition | 1,35 | <1 | .813 | – | .00 |
| | Condition × Caudality | 2,70 | 5.35 | .009 | .90 | .11 |
| | Condition × Laterality | 2,70 | 3.84 | .026 | .82 | .08 |
| | Condition × Caudality × Laterality | 4,140 | 5.29 | .002 | .73 | .11 |
| c) P300 | Condition | 1,35 | <1 | .759 | – | .00 |
| | Condition × Caudality | 2,70 | 7.88 | .004 | .64 | .16 |
| | Condition × Laterality | 2,70 | 1.50 | .233 | .81 | .01 |
| | Condition × Caudality × Laterality | 4,140 | <1 | .40 | .68 | .00 |

effect of condition, $F(2,76) = 8.87$, $\varepsilon = .91$, $p = .001$, $\omega^2 = .17$, and a significant interaction between condition and ERP component, $F(6,228) = 4.52$, $\varepsilon = .37$, $p = .011$, $\omega^2 = .08$. See Fig. 4 for the ERPs elicited by stimuli in the Sternberg memory scanning paradigm.

Please see Table 4 for detailed results of the ANOVAs on the average activity for the specific time windows and Table 5 for the detailed results on peak latencies. We found no significant main effects or interactions including condition on the amplitudes or peak latencies of the N150 and P200 component, all $F$s < 3.15, all $p$s > .065, all $\omega^2$s < .06 (see Tables 4 and 5 a) and b)).

We observed a significant main effect of condition on average N300 activity, $\omega^2 = .26$, with greater amplitudes in the set size 3 and set size 5 conditions than in the set size 1 condition, $F(1,38) = 26.31$, $p < .001$, $\omega^2 = .40$, and no difference between amplitudes in the more difficult conditions, $F < 1$. Moreover, a significant interaction between condition and caudality indicated a specific topography of this effect, $\omega^2 = .15$. The condition effects were greatest at central and parietal electrode sites. We also observed a significant interaction between condition and caudality for N300 peak latencies, $\omega^2 = .06$, indicating that N300 latencies became longer with increasing memory set size at central and parietal electrodes, $F(2,76) = 5.07$, $\varepsilon = .97$, $p = .009$, $\omega^2 = 10$.

Next, we compared conditions and electrode sites for P300 activity. We observed a main effect of condition, $\omega^2 = .36$, that indicated that P300 amplitudes decreased linearly with increasing memory set size, $F(1,38) = 30.84$, $p < .001$, $\omega^2 = .44$. There was also a significant interaction between condition and caudality, $\omega^2 = .31$, as P300 amplitudes only increased at central, $F(2,76) = 15.85$, $\varepsilon = .92$, $p < .001$, $\omega^2 = .28$, and parietal electrode sites with increasing memory set size, $F(2,76) = 49.44$, $\varepsilon = .90$, $p < .001$, $\omega^2 = .56$, but not at frontal electrode sites, $F(2,76) < 1$, $\varepsilon = .80$, $p = .856$, $\omega^2 = .00$. Moreover, P300 peak latencies became longer with increasing memory set size, $\omega^2 = .13$.

The results of these analyses indicated that conditions differ systematically in average activity and suggest together with the specific topographic interactions for each ERP that the neural processing of probe items in different memory set sizes differs in more than one electrophysiological component.

*In the Posner letter matching paradigm*, we compared mean activity and ERP latencies between conditions in four different time windows. Again, we first computed an omnibus ANOVA with the four within-subject factors ERP component (N140: 115–155 ms, P210: 190–235 ms, N300: 240–365 ms, P300: 465–580 ms), condition (PI vs. NI), caudality (frontal, central, parietal), and laterality (left, central, right) to test if condition effects differed between ERPs. The effect of the interaction between ERP component and condition on average activity was marginally significant, $F(3,99) = 3.36$, $\varepsilon = .36$, $p = .072$, $\omega^2 = .06$. We also observed a significant three-way interaction between ERP component, condition and caudality, $F(6,198) = 5.05$, $\varepsilon = .36$, $p < .01$, $\omega^2 = .11$, and a marginally significant three-way interaction between ERP component, condition and laterality, $F(6,198) = 2.55$, $\varepsilon = .44$, $p = .068$,

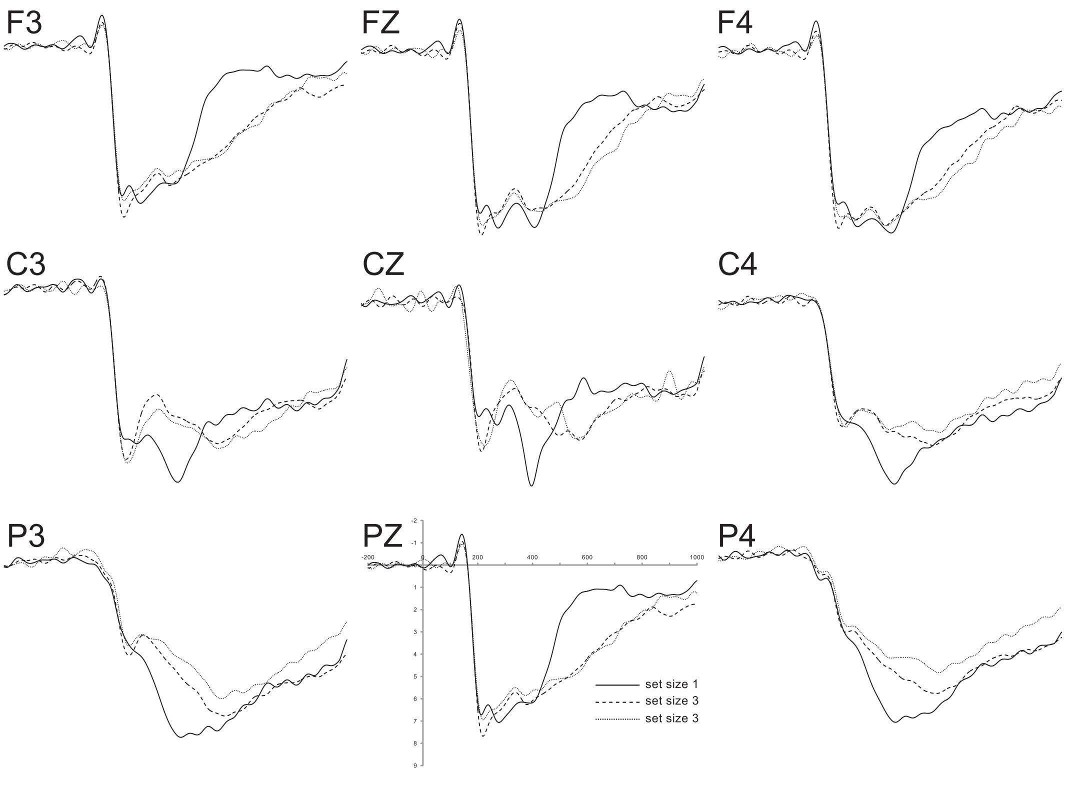


**Fig. 4.** Event-related potentials elicited by the onset of the memory probe for the different memory set sizes in the Sternberg letter matching task. Electrodes are arrayed from most anterior (top) to most posterior (bottom) and from left to right.

**Table 4**
Results of the ANOVA with the three within-subject factors condition (set size 1, set size 3, set size 5), caudality (frontal, central, parietal), and laterality (left, central, right) on a) N150 (115–160 ms) amplitude, b) P200 (200–245 ms) amplitude, c) N300 (300–360 ms) amplitude, and d) P300 (400–600 ms) amplitude in the Sternberg memory scanning paradigm. (n = 39).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) N150 | Condition | 2,76 | <1 | .95 | .66 | .00 |
| | Condition × Caudality | 4,152 | 2.08 | .151 | .32 | .03 |
| | Condition × Laterality | 4,152 | <1 | .813 | .39 | .00 |
| | Condition × Caudality × Laterality | 8,304 | 1.04 | .334 | .16 | .00 |
| b) P200 | Condition | 2,76 | 2.13 | .134 | .86 | .03 |
| | Condition × Caudality | 4,152 | 1.48 | .235 | .34 | .01 |
| | Condition × Laterality | 4,152 | 2.05 | .149 | .37 | .03 |
| | Condition × Caudality × Laterality | 8,304 | 1.19 | .289 | .15 | .00 |
| c) N300 | Condition | 2,76 | 14.41 | <.001 | .93 | .26 |
| | Condition × Caudality | 4,152 | 7.46 | .002 | .42 | .15 |
| | Condition × Laterality | 4,152 | <1 | .595 | .55 | .00 |
| | Condition × Caudality × Laterality | 8,304 | 1.20 | .300 | .19 | .01 |
| d) P300 | Condition | 2,76 | 22.33 | <.001 | .93 | .36 |
| | Condition × Caudality | 4,152 | 18.32 | <.001 | .45 | .31 |
| | Condition × Laterality | 4,152 | <1 | .409 | .49 | .00 |
| | Condition × Caudality × Laterality | 8,304 | <1 | .387 | .23 | .00 |

$\omega^2 = .04$. There was no significant main effect or interaction including condition on ERP peak latencies. See Fig. 5 for the ERPs elicited by stimuli in the Posner letter matching paradigm.

Next, we computed several ANOVAs for the different time windows in the Posner letter matching paradigm. Please see Tables 6 and 7 for all main effects and interactions including the factor condition. There were no significant main effects of condition on ERP amplitudes, all $\omega^2$s < .05, but several interactions between condition and caudality and condition and laterality. Condition differences were most pronounced at frontal electrode sites for the N140, P210 and N300 component. These interactions were not further unraveled, as follow-up tests of condition differences at frontal electrode sites yielded no significant effects, all *F*s < 1.2, all *p*s > .282, all $\omega^2 = .00$. For the P300 component, we observed a specific topography of condition effects that indicated that P300 amplitudes were greater in the PI than in the NI condition and that this effect was greatest at central electrode sites, $\omega^2 = .07$. Moreover, the significant three-way interaction suggested that condition differences were greatest at Cz, $\omega^2 = .05$. As in the overall analyses, there were no main effects or interactions including condition on any of the ERP peak latencies.

Again, the topography differences between condition differences in ERPs and the significant interactions in the omnibus analysis indicated that the PI and NI condition differ in more than one ERP component. These differences were only manifest in average activity, but not in peak latencies.

### 3.3. Factor structure of mental speed

In the next step, we analyzed the factor structure of mental speed and its relation to general intelligence. In order to investigate the factor structure of mental speed, we computed six principal component analyses separately for the six time-domain variables (RT, $v$, $t_0$, P100 latency, N150 latency, P200 latency) across the three ECTs. We then computed individual component scores of the first principal component for all participants to generate six new variables that capture the greatest amount of variance in each set of time-domain variables across ECTs. We repeated this procedure for

**Table 5**
Results of the ANOVA with the three within-subject factors condition (set size 1, set size 3, set size 5), caudality (frontal, central, parietal), and laterality (left, central, right) on a) N150 (115–160 ms) peak latencies, b) P200 (200–245 ms) peak latencies, c) N300 (300–360 ms) peak latencies, and d) P300 (400–600 ms) peak latencies in the Sternberg memory scanning paradigm. (n = 39).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) N150 | Condition | 2,76 | 1.55 | .22 | .85 | .01 |
| | Condition × Caudality | 4,152 | <1 | .758 | .72 | .00 |
| | Condition × Laterality | 4,152 | <1 | .695 | .89 | .00 |
| | Condition × Caudality × Laterality | 8,304 | 1.12 | .351 | .60 | .00 |
| b) P200 | Condition | 2,76 | <1 | .433 | .80 | .00 |
| | Condition × Caudality | 4,152 | <1 | .485 | .51 | .00 |
| | Condition × Laterality | 4,152 | <1 | .782 | .70 | .00 |
| | Condition × Caudality × Laterality | 8,304 | <1 | .578 | .57 | .00 |
| c) N300 | Condition | 2,76 | 2.01 | .143 | .96 | .03 |
| | Condition × Caudality | 4,152 | 3.37 | .019 | .78 | .06 |
| | Condition × Laterality | 4,152 | 2.43 | .064 | .81 | .04 |
| | Condition × Caudality × Laterality | 8,304 | 1.69 | .123 | .76 | .02 |
| d) P300 | Condition | 2,76 | 6.43 | .005 | .82 | .13 |
| | Condition × Caudality | 4,152 | 1.84 | .139 | .82 | .02 |
| | Condition × Laterality | 4,152 | 2.06 | .100 | .85 | .03 |
| | Condition × Caudality × Laterality | 8,304 | <1 | .767 | .76 | .00 |

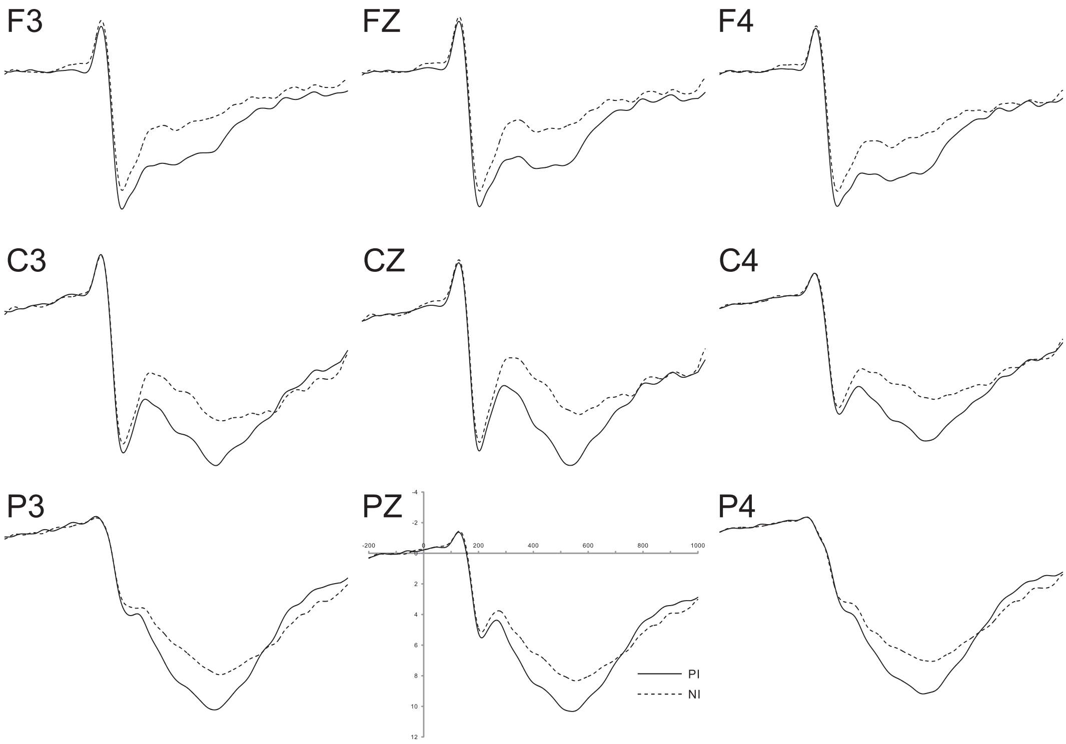


**Fig. 5.** Event-related potentials elicited by the onset of the letter pair in the PI condition (PI = physical identity; solid lines) and the NI condition (NI = name identity; broken lines) in the Posner letter matching task. Electrodes are arrayed from most anterior (top) to most posterior (bottom) and from left to right.

intelligence test scores and extracted a general intelligence factor. Table 8 shows the variables entered into each PCA and the amount of variance explained by the respective first principal component. We then entered these seven component score variables into further analyses to explore the factor structure of mental speed. Correlations between these seven component scores are shown in Table 9. If the factor structure of mental speed is unitary, all component score variables should load onto one mental speed variable that should have a great eigenvalue and explain a substantial amount of variance in speed and latency parameters.

To explore this idea, we conducted a hierarchical PCA of the six time-domain component scores and identified two components explaining 76% of variance based on the scree plot (Cattell, 1966) and the parallel analysis criterion (Horn, 1965). These two components had eigenvalues of 3.32 and 1.21. Component loadings after an oblique rotation of the two factors are shown in Table 10. All ERP latencies loaded strongly onto

**Table 6**
Results of the ANOVA with the three within-subject factors condition (Physical Identity vs. Name Identity), caudality (frontal, central, parietal), and laterality (left, central, right) on a) N140 (115–155 ms) amplitude, b) P210 (190–235 ms) amplitude, c) N300 (240–365 ms) amplitude, and d) P300 (465–580 ms) amplitude in the Posner letter matching paradigm. (n = 35).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) N140 | Condition | 1,33 | <1 | .712 | – | .00 |
| | Condition × Caudality | 2,66 | 2.22 | .139 | .62 | .04 |
| | Condition × Laterality | 2,66 | <1 | .377 | .95 | .00 |
| | Condition × Caudality × Laterality | 4,132 | 2.68 | .045 | .84 | .05 |
| b) P210 | Condition | 1,33 | <1 | .535 | – | .00 |
| | Condition × Caudality | 2,66 | 7.37 | .007 | .58 | .16 |
| | Condition × Laterality | 2,66 | <1 | .480 | .77 | .00 |
| | Condition × Caudality × Laterality | 4,132 | 2.04 | .122 | .67 | .03 |
| c) N300 | Condition | 1,33 | 1.15 | .292 | – | .00 |
| | Condition × Caudality | 2,66 | 5.91 | .015 | .61 | .13 |
| | Condition × Laterality | 2,66 | <1 | .573 | .69 | .00 |
| | Condition × Caudality × Laterality | 4,132 | 2.79 | .043 | .77 | .05 |
| d) P300 | Condition | 1,33 | 2.53 | .121 | – | .04 |
| | Condition × Caudality | 2,66 | <1 | .424 | .61 | .00 |
| | Condition × Laterality | 2,66 | 3.64 | .038 | .88 | .07 |
| | Condition × Caudality × Laterality | 4,132 | 2.84 | .037 | .83 | .05 |

**Table 7**
Results of the ANOVA with the three within-subject factors condition (Physical Identity vs. Name Identity), caudality (frontal, central, parietal), and laterality (left, central, right) on a) N140 (115–155 ms) peak latencies, b) P210 (190–235 ms) peak latencies, c) N300 (240–365 ms) peak latencies, and d) P300 (465–580 ms) peak latencies in the Posner letter matching paradigm. (n = 35).

| ERP component | Variable | *df* | *F* | *p* | ε | $\omega^2$ |
|---|---|---|---|---|---|---|
| a) N140 | Condition | 1,33 | <1 | .580 | – | .00 |
| | Condition × Caudality | 2,66 | <1 | .794 | .61 | .00 |
| | Condition × Laterality | 2,66 | 1.07 | .321 | .61 | .00 |
| | Condition × Caudality × Laterality | 4,132 | <1 | .413 | .62 | .00 |
| b) P210 | Condition | 1,33 | <1 | .471 | – | .00 |
| | Condition × Caudality | 2,66 | 3.14 | .066 | .75 | .06 |
| | Condition × Laterality | 2,66 | 2.69 | .086 | .84 | .05 |
| | Condition × Caudality × Laterality | 4,132 | 1.41 | .243 | .82 | .01 |
| c) N300 | Condition | 1,33 | 1.17 | .288 | – | .00 |
| | Condition × Caudality | 2,66 | <1 | .629 | .98 | .00 |
| | Condition × Laterality | 2,66 | 1.04 | .356 | .94 | .00 |
| | Condition × Caudality × Laterality | 4,132 | 1.87 | .148 | .65 | .03 |
| d) P300 | Condition | 1,33 | 3.01 | .092 | – | .06 |
| | Condition × Caudality | 2,66 | <1 | .443 | .73 | .00 |
| | Condition × Laterality | 2,66 | <1 | .614 | .85 | .00 |
| | Condition × Caudality × Laterality | 4,132 | <1 | .832 | .80 | .00 |

the first rotated component that was also loaded by drift rates. All behavioral time domain component scores loaded more strongly on the second component that was marked by RT component scores. Because greater (i.e., slower) ERP latencies were associated with greater component scores in the first component, we reversed the polarity of the first component so that greater component scores indicated smaller (i.e., faster) ERP latencies. Subsequently, we labeled the two components 'processing speed' and 'behavioral speed', respectively. The two components were correlated, $r = .36$.

We extracted individual component scores for these two hierarchical components and computed a hierarchical second-order PCA of these two components and the intelligence component scores. Correlations between the three variables were $r = .54$, $p < .001$ (*g* and processing speed), $r = .52$, $p = .001$ (*g* and behavioral speed), and $r = .36$, $p = .028$ (processing and behavioral speed). The PCA of these correlates yielded a single second-order component based on the scree plot (Cattell, 1966) and the parallel analysis criterion (Horn, 1965) with an eigenvalue of 1.98 onto which all hierarchical first-order components loaded (see Table 11 for factor loadings). This component explained 66% of variance in first-order factor scores. *g* component scores had the greatest loadings on this component, followed by neural and behavioral speed with highly similar loadings.

**Table 8**
Sources of entered variables for the six speed, latency, and intelligence variables and the amount of variance explained by the first principal components of each PCA.

| Variable name | Source of entered variables | % of variance explained by first principal component |
|---|---|---|
| *g* | APM, knowledge test | 78% |
| Median RT | All ECTs and conditions | 62% |
| $v$ | All ECTs, estimated across conditions | 42% |
| $t_0$ | All ECTs, estimated across conditions | 51% |
| P100 latency | Hick paradigm and Sternberg memory scanning task, all conditions | 37% |
| N150 latency | All ECTs and conditions | 45% |
| P200 latency | Sternberg memory scanning and Posner letter matching task, all conditions | 69% |

*Note.* $v$ = drift rate; $t_0$ = response-time constant.

In the last step, we computed correlations between the two speed components and APM and knowledge test scores to investigate whether correlations were greater for *gf* or *gc*. Correlations were generally greater for *gf* than for *gc*: Correlations between APM scores and speed components ranged from $r = .53$ to .54, while correlations between knowledge test scores and speed components ranged from $r = .35$ to .39.

### 3.4. The effects of latencies on g are mediated by RTs

Next, we analyzed if reaction times mediate the relationship between ERP latencies and intelligence test scores. For all mediation analyses, we used the component scores we computed in the PCA.

As Fig. 6 illustrates, the relationship between ERP latencies and intelligence was mediated by reaction times. A bootstrap analysis with $m = 5000$ resamples yielded a significant indirect effect of P100 latencies through RTs on intelligence test scores, CI 95% (−0.44, −0.01). We found that RTs also partially mediated the effect of N150 latencies on intelligence test scores. We observed a significant indirect effect when we computed a bootstrap analysis with $m = 5000$ resamples, CI 95% (−0.41, −0.02). Lastly, we tested if RTs also mediated the effect of P200 latencies on g. Again, the bootstrap analysis with $m = 5000$ resamples indicated a significant indirect effect, CI 95% (−0.43, −0.04).

## 4. Discussion

The present study sheds light on the neuro-cognitive processes of mental speed. The results indicate that so-called elementary cognitive tasks (ECTs) are not as elementary as presumed but that they tap several functionally different neuro-cognitive processes. As expected, we found that there is no unitary construct of mental speed, but that there are several distinct speeded processes involved in elementary

**Table 9**
Product–moment correlations (rank correlation coefficients in parentheses) between the six mental speed component scores (RT, v, t0, P100 latency, N150 latency, P200 latency) and g.

| ECT | RT | $v$ | $t0$ | P100 | N150 | P200 | $g$ |
|---|---|---|---|---|---|---|---|
| RT component scores | 1 | | | | | | |
| $v$ component scores | −.74*** (−.79***) | 1 | | | | | |
| $t_0$ component scores | .72*** (.65***) | −.34* (−.37*) | 1 | | | | |
| P100 latency component scores | .53** (.38**) | −.38* (−.41*) | .11 (.02) | 1 | | | |
| N150 latency component scores | .50** (.35*) | −.38* (−.32*) | .19 (.06) | .54*** (.48**) | 1 | | |
| P200 latency component scores | .46** (.40*) | −.46** (−.44**) | .18 (.11) | .25 (.25) | .80*** (.80***) | 1 | |
| $g$ | −.55*** (−.56***) | .50** (.56***) | −.42* (−.38*) | −.49** (−.44**) | −.53** (−.50**) | −.45** −(.45**) | 1 |

*Note.* $v$ = drift rate; $t_0$ = response-time constant.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

cognitive tasks. Moreover, our results show that an increase in the difficulty and complexity of these ECTs affects several of these processes simultaneously. If we consider, for example, our results for the Sternberg memory scanning paradigm, we see that conditions in this task differed in several behavioral and electrophysiological parameters. As expected, diffusion model analyses revealed that drift rates decreased and response-time constants increased with increasing memory set size, which indicates that conditions differ both in the speed of decision making (reflected in the changes in the $v$ parameter) and in the speed of encoding, memory access, and/or in the speed of movement times (reflected in the changes in the $t_0$ parameter). Moreover, changes in memory set size also had an effect on several ERP components in the stream of information processing, namely the N300 component, which is associated with spatial, structural and categorical incongruences of visual stimuli (Demiral, Malcolm, & Henderson, 2012; Hamm, Johnsin, & Kirk, 2002), and the P300 component, which is associated with stimulus evaluation and categorization and is known to be sensitive to stimulus probability, subjective uncertainty and resource allocation (Luck, 2005). All in all, we can conclude that the traditional difference and slope measures of ECTs do not only capture variance from a single cognitive process, but that they reflect a multitude of different processes.

Condition differences in ERP amplitudes and latencies were mostly consistent with previous research on these tasks, although there are only few studies with comparable designs. In the Hick paradigm, we observed significantly greater P200 amplitudes for the 1 bit than for the 2 bit condition, which is consistent with the results reported by Falkenstein, Hohnsbein, and Hoormann (1994) who analyzed ERPs in 2- and 4-choice RT tasks and found that P200 amplitudes were greater in the 2-choice than in 4-choice condition. Moreover, they reported that P390 amplitudes were greater in the 2-choice than in the 4-choice condition for all electrode sites, while we found this effect only at central electrode sites and observed a reversed effect at frontal electrode sites. McGarry-Roberts et al. (1992) reported greater P300 amplitudes in a choice reaction time task than in a simple reaction time task, which may indicate that the more complex RT task resulted in greater P300 amplitudes. As McGarry-Roberts et al. (1992) only used a 2-choice CRT and no 4-choice CRT and only entered the Pz electrode into the statistical analyses, their results are not directly comparable to our results that showed a very specific topography. In the present study, we found an effect of choice alternatives on P300 latencies with a specific topography in the way that P300 latencies were larger for the 2 bit than for the 1 bit condition at parietal electrode sites, while this effect was reversed at frontal electrode sites. Falkenstein et al. (1994) found a similar effect

**Table 10**
Component loadings for the principal component analysis with oblimin rotation of time-domain component scores.

| | First-order component | |
|---|---|---|
| | 1 | 2 |
| RT component scores | −.29 | −.83 |
| $v$ component scores | .40 | .55 |
| $t_0$ component scores | .20 | −.94 |
| P100 latency component scores | −.59 | −.20 |
| N150 latency component scores | −.96 | .04 |
| P200 latency component scores | −.93 | .10 |

*Note.* Because greater (i.e., slower) ERP latencies were associated with greater component scores in the first component, we reversed the polarity of the first component so that greater component scores indicated smaller (i.e., faster) ERP latencies.

**Table 11**
Component loadings for the principal component analysis of the two hierarchical mental speed factors and g.

| | G |
|---|---|
| $g$ | .87 |
| Processing speed | .80 |
| Behavioral speed | .77 |

*Note.* Lowercase $g$ designates general intelligence extracted from the PCA of APM and knowledge test scores, whereas uppercase $G$ is the second-order component derived from speed and intelligence components.

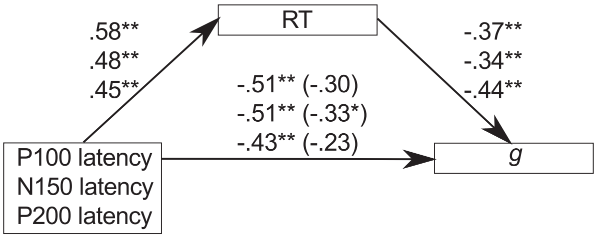


**Fig. 6.** Standardized regression coefficients for the association between ERP latencies and general intelligence mediated by reaction times. The standardized regression coefficients between ERP latencies and general intelligence controlling for reaction times are in parentheses. $^*p < .05$. $^{**}p < .01$.

with a very specific topography as the P390 component peaked later in the 4-choice than in the 2-choice task at Pz, and McGarry-Roberts et al. (1992) also reported longer P300 latencies for the CRT task in comparison to the SRT task at Pz. There was also a latency shift in the N200 peak reported by Falkenstein et al. (1994), but it did not display the specific topography effects of the present study.

In the Sternberg memory scanning paradigm, we found that P300 amplitudes decreased and P300 latencies increased with increasing memory set size, which is consistent with the majority of the studies analyzing the electrophysiological activity in this paradigm (Brookhuis, Mulder, Mulder, & Gloerich, 1983; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Gomer, Spicuzza, & O'Donnell, 1976; Houlihan et al., 1998; Pelosi, Hayward, & Blumhardt, 1998), although some studies found no difference in P300 latencies across conditions (Pelosi et al., 1992) or substantial interindividual differences in condition effects on P300 latencies (Pelosi, Hayward, & Blumhardt, 1995).

To our knowledge, there are no previous EEG-studies specifically aimed at analyzing the Posner letter matching paradigm. McGarry-Roberts et al. (1992) used a comparable paired-stimuli task, in which two words were presented subsequently and participants had to decide whether the target stimulus was a) physically or b) semantically the same (i.e., a synonym) as the prior presented first stimulus. Please note that the experimental setup (presenting subsequent instead of parallel stimuli) as well as the stimulus material (words instead of letters) and the depth of semantic processing (word meaning instead of letter identification) varied substantially from the present study. Still, the authors reported greater P300 amplitudes to the target stimulus for the physical similarity task than for the semantic similarity task, which is consistent with the results of the present study as we also found greater P300 amplitudes in the physical identity condition than in the name identity condition. McGarry-Roberts et al. (1992) also reported longer P300 latencies in the semantic similarity task than in the physical similarity task, while we found no latency shift in the data. This discrepancy may be due to a multitude of reasons as their paradigms varied substantially from ours.

Nearly all of these studies analyzed a smaller number of time windows and fewer ERP components than the present study and generally focused on one or two major components (often the P300). Therefore, it is not possible to relate our results for all time windows to previous research, as the stream of information processing during ECTs has not yet been analyzed electrophysiologically in such detail. Moreover, in several of these previous studies only very few electrodes were used, often only the midline electrodes (Fz, Cz, Pz), making it difficult to compare condition effects with a specific topography to these studies, as in many of the previous studies condition effects were only analyzed at one electrode (e.g., Pz for the P300 component) and the topographic characteristics of condition effects were not considered.

Furthermore, we could show that a single broad general mental speed factor is substantially associated with general intelligence, because a second order factor analysis of two more specific speed factors and general intelligence yielded a single broad factor marked by general intelligence. Thus our results indicate that although there are several functionally distinct processes involved in ECTs, it is the common time-domain variance shared by all these components that is associated with general intelligence. This does not imply that more specific speed components do not share unique variance with intelligence, but it does imply that the association between mental speed and mental abilities could in most part be due to a single shared source of variance. This result is consistent with the few studies that reported associations between RTs in different elementary cognitive tasks (Burns & Nettelbeck, 2003; Hale & Jansen, 1994; Neubauer & Bucik, 1996; Neubauer et al., 2000). In his reanalysis of the reaction time data reported by Kranzler and Jensen (1991), Carroll (1991) also found a broad general factor in addition to narrower task-specific factors with substantial variable loadings reflecting *decision time* (in contrast to an orthogonal factor of *movement time*). In our study, movement times (captured in the $t_0$ parameter) did not span a distinct factor, but loaded onto the behavioral speed factor that showed substantial loadings on the second-order mental speed factor. One difference between the movement speed factor in Carroll's (1991) reanalysis and movement speed measured as $t_0$ might be that $t_0$ does not only capture movement speed, but also stimulus encoding and memory-related processes (Ratcliff & McKoon, 2008), which might be more closely related to a general mental speed factor. Taken together, our findings suggest that there is indeed a single broad mental speed factor across different tasks and across both behavioral and electrophysiological measurements, a general factor that is significantly associated with general intelligence.

The associations between RTs, ERP latencies and general intelligence in this study are substantially greater than the initially quoted average correlation of $r = -.24$ between RTs and mental abilities in Sheppard and Vernon's (2008) review or the weak negative associations between ERP latencies and intelligence reported in the literature (Houlihan et al., 1998; McGarry-Roberts et al., 1992; Pelosi et al., 1992; Schulter & Neubauer, 2005). There may be two reasons why the magnitude of the associations in the present study is greater than in the literature: Jensen (2006) argued that characteristics of the participant sample may affect the size of the association between RTs and mental abilities. We deliberately recruited a heterogeneous community sample to avoid any restriction in the variance of the cognitive variables, because a lack of variation in one or more variables may decrease the co-variation between variables. Moreover, the number of trials used in the three paradigms was higher than most trial numbers in the literature, which may have increased the reliability of the ERP latencies that are known to sometimes have low to moderate reliabilities even when the number of trials is relatively large (Cassidy, Robertson, & O'Connell, 2012).

What is intriguing about our findings is that the association between ERP latencies and mental abilities was mediated by reaction times. This mediation supports the hypothesis that individual differences in psychophysiological information processing speed are manifested in behavioral reaction times and may in this way contribute to individual difference in general intelligence. In other words, individual differences in the onset of early ERP components such as the P100 or P200, which are components that occur nearly immediately after stimulus presentation in the chronometry of neurocognitive information-processing, predict individual difference in reaction times that occur about half a second later. This result suggests that higher speed of neurocognitive information-processing may contribute to advantages in the speed of cognitive information-processing, decision, and memory processes. These advantages in the speed of different cognitive processes may then enhance performance on psychometric intelligence tests and explain the association between early ERP latencies and mental abilities.

### *4.1. Limitations*

Some limitations have to be considered before strong conclusions may be drawn. First, the sample size with $N = 40$ participants is rather large for an electrophysiological study, but it is too small for complex multivariate analyses such as multiple regression and structural equation modeling. Moreover, the stability of the factor structure we extracted has to be replicated in further studies before drawing any final conclusions, although our results are generally consistent with earlier studies on the factor structure of RTs in elementary cognitive tasks.

Second, it is unclear if ERP latencies and diffusion model parameters show enough stability over measurement occasions to qualify as trait-like variables. There are no systematic studies on the stability of diffusion model parameters except for one study that reported between-session stabilities of $r \geq .65$ for drift rate and non-decision time parameters in a lexical decision task (Yap, Balota, Sibley, & Ratcliff, 2012). A first study on the temporal stability of ERP components reported strong test–retest correlations for ERP amplitudes ranging from $r = .63$ to .89 and varying test–retest correlations for ERP latencies ranging from $r = .19$ to .89 (Cassidy et al., 2012). Both measures can only explain inter-individual differences in intelligence if they show sufficient psychometric stability.

Third, the RTs of the 1 bit condition we adopted from Neubauer et al. (1992) did not follow Hick's law, but were instead significantly larger than the RTs in the 2 bit condition. We therefore did not include behavioral and electrophysiological data from this condition in further analyses. Still, this divergence from the data reported by Neubauer et al. (1992) is surprising. The standard deviation in this condition was twice as large as the standard deviations in the other conditions, which indicates a great increase in difficulty or complexity. Moreover, individual differences in the understanding of the rather complex instructions of the task or in the ability to adapt to position changes might have affected RTs to a great degree. It should be noted that the sample in the original study by Neubauer et al. (1992) consisted only of children (11 to 15 years old) who got feedback immediately after each trial. Therefore, either the age difference or the direct feedback might explain why no such phenomenon was reported in the original study. A thorough validation of the modified paradigm with several control conditions would be needed to understand which cognitive processes are involved in the strangely behaving original 1 bit condition.

### *4.2. Conclusion*

The aim of the present study was to decompose the stream of information processing in elementary cognitive tasks in order to identify processes that might contribute to the association between mental abilities and mental speed. By combining diffusion model analysis with ERP methodology, we showed that ECT conditions differ in several neuro-cognitive parameters. Therefore, we would not recommend the use of difference scores in further studies, not only because they suffer from severe psychometric problems such as low reliabilities (Jensen, 1998), but also because they do not seem to measure what they are supposed to. According to our results, difference parameters are likely to capture several different sources of variance and are probably *not* singling out specific cognitive processes such as the speed of information uptake. Instead, we propose using diffusion models and electroencephalography in order to single out specific components of information processing for further analyses.

Future studies should include several measurement occasions to test whether a general mental speed factor qualifies as a trait-like variable. Only a factor that captures a certain amount of trait-like performance is suited to be considered as an explanation of general intelligence. Moreover, future studies should also include a broader battery of intelligence tests to investigate if mental speed is more strongly associated with general intelligence (as our data would suggest) or with specific mental abilities, which we could not test in the present study.

Our study is one of the few studies that reported consistent negative correlations between ERP latencies and intelligence across different tasks and different time windows. In contrast to most other studies, we recruited a community sample in order to avoid restricted variance in the cognitive performance variables and their electrophysiological correlates. Moreover, each of our tasks had a large number of trials to increase the reliability of the notoriously unreliable ERP latencies. We could show that there is a general mental speed factor across different tasks and different measures of speed that is associated with general intelligence. Moreover, we found that the association between ERP latencies and intelligence is mediated by reaction times. These results illustrate the benefits of the application of diffusion models and ERPs in research on the chronometry of mental abilities. All in all, we found that more intelligent individuals do not only show faster behavioral reactions, but that they have a general advantage in all neuro-cognitive speed-related processes.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.intell.2015.05.002.

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