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# On the relation between mental ability and speed of information processing in the Hick task: An analysis of behavioral and electrophysiological speed measures

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ABSTRACT

Inspired by Robert Stelmack's research on the electrophysiological foundation of mental ability (MA), the present study investigated whether the well-established negative relation between reaction times (RTs) and MA in four conditions of the Hick task can be explained by faster stimulus classification and consolidation in working memory as measured by the P300 latency in the event-related potential. RTs of 113 female participants aged from 17 to 38 years increased with increasing number of response alternatives in the Hick task. Except for one condition, RTs were negatively and significantly related to MA but this relationship did not increase with task complexity. This pattern of results suggests that speed of response selection does not account for shorter RTs in individuals with higher than lower MA. Against our expectations, however, in none of the four conditions, P300 latency was related to MA. Thus, the negative association between RTs and MA cannot be explained in terms of faster stimulus evaluation and consolidation in working memory. As a tentative explanation of this lack of association, even the most complex condition was not demanding enough to require the inhibitory processes underlying the P300 component in a sufficient extent to reveal MA-related individual differences in P300 latency.


## 1. Introduction

Speed of information processing has been reported to be faster in individuals with higher compared to individuals with lower mental ability (MA) (see Jensen, 2006). This speed difference could be observed in reaction time (RT) measures (Jensen, 1982, 2006) but also in latencies of the event-related potential (ERP) (Stelmack & Houlihan, 1995). In the tradition of Bob Stelmack's life-time work in this field of research, the present study investigated MA-related speed differences in the Hick task and whether the P300 latency in the ERP, an index of the time required for classifying a stimulus independent of the response process (Beauchamp & Stelmack, 2006; Houlihan, Campbell, & Stelmack, 1994), helps to explain these speed differences.

The Hick task is one of the most frequently used tasks in experimental research on MA-related speed differences (Jensen, 2006). In the different conditions of this task, a visual imperative stimulus is presented in one out of one, two, four, or more possible positions. The participant's task is to respond to the stimulus as fast as possible. If there is only one position (0-bit condition), participants simply react to the appearance of the stimulus, whereas they have to make one or two decisions if the stimulus appears in one out of two (1-bit condition) or four (2-bit condition) possible positions, respectively. Hick's law (1952) holds that RT increases linearly with the number of binary decisions across conditions. Hence, the slope of the linear function is a measure of the speed with which a decision is made or, in other words, the correct response is selected. Roth's (1964) report that the slope is steeper in individuals with lower compared to individuals with higher MA led to an enormous number of studies on the relation between RT in the Hick task and MA (cf. Jensen, 1998, 2006). Meta-analyses revealed that MA is consistently, yet only modestly related to RTs in all conditions of the Hick task, while its relation to the slope of Hick's linear function, contrary to initial findings, seems to be rather weak and inconsistent (Neubauer, Riemann, Mayer, & Angleitner, 1997; Sheppard & Vernon, 2008). This pattern of results casts doubt on the notion that higher speed of decision making is responsible for the shorter RT in individuals with higher compared to individuals with lower MA. However, early studies searching for specific processes underlying the relation between MA and RT in the Hick task divided RT experimentally into decision time and movement time (Jensen & Munro, 1979) and found that decision time rather than movement time was related to MA. This result indicates that sensory rather than motor processes are involved in the relationship between MA and RT.

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An alternative approach to examine specific processes underlying the relation between MA and speed of information processing is the investigation of the ERP (for reviews see Stelmack & Beauchamp, 2001; Stelmack & Houlihan, 1995). The ERP is the electrophysiological response to a repeatedly presented stimulus event and is observed in the continuous electroencephalogram (EEG). The P300 component of the ERP is a prominent positive wave with a maximum peak at about 300 ms after stimulus onset. Although the functional meaning of the P300 latency is still controversial (e.g., Verleger, Jaśkowski, & Wascher, 2005), the most common hypothesis holds that it reflects the time needed for stimulus evaluation and updating of mental representations in working memory (Kutas, McCarthy, & Donchin, 1977; Polich, 2007). Furthermore, response selection and execution processes seem not to influence the P300 latency (Doucet & Stelmack, 2000; Kutas et al., 1977; Magliero, Bashore, Coles, & Donchin, 1984).

As demonstrated by numerous studies, but primarily by Stelmack and his colleagues, the latency of the P300 wave is negatively related to MA in the oddball paradigm (e.g., Bazana & Stelmack, 2002; Beauchamp & Stelmack, 2006; Fjell & Walhovd, 2003; Sculthorpe, Stelmack, & Campbell, 2009; Troche, Houlihan, Stelmack, & Rammsayer, 2009). Investigations using other tasks, however, revealed that this relationship depends on task characteristics and demands. For example, McGarry-Roberts, Stelmack, and Campbell (1992) used simple and choice reaction time tasks as well as linguistic processing tasks and found the P300 latency only in the latter tasks to be shorter in individuals with higher compared to lower MA. Houlihan, Stelmack, and Campbell (1998) reported even a positive correlation between MA and P300 latency in Sternberg's short-term memory scanning task, i.e. longer P300 latencies in individuals with higher compared to lower MA. Using an attentional-blink task, Troche, Indermühle, and Rammsayer (2012) observed shorter P300 latencies in individuals with higher compared to lower MA in easy conditions but longer P300 latencies in the most demanding conditions. Given that the Hick task is one of the most commonly used tasks to investigate MA-related differences in speed of information processing, it is surprising that, to the best of our knowledge, there are no studies that systematically investigated P300 latency across different Hick task conditions.

Therefore, the main goal of the present study was to investigate the relationship between MA and speed of information processing across four conditions of the Hick task as measured by RTs and P300 latencies. For this purpose, we employed a 0-bit, 1-bit, 2-bit, and 2.58-bit condition with one, two, four, and six response alternatives, respectively. We had the following hypotheses:

1. We expected mean RTs to increase linearly with the number of decisions to be made, while mean P300 latencies should not vary across task conditions due to their independence from processes of response selection and execution (Doucet & Stelmack, 2000).
2. Furthermore, we expected the well-known negative association between RTs and MA. This relationship should either
   a) become stronger from the 0-bit to the 2.58-bit condition as reported by previous studies (e.g., Rammsayer & Troche, 2016; Roth, 1964) or
   b) not vary as a function of Hick condition as suggested by Sheppard and Vernon's (2008) meta-analysis.

If hypothesis 2a was supported and the relation between RTs and MA becomes stronger from the 0-bit to the 2.58-bit condition, this result would indicate that primarily the time of decision making and/or response selection accounts for this relationship. P300 latency as a measure of speed of stimulus evaluation and updating mental representations in working memory (Beauchamp & Stelmack, 2006) might also be negatively related to MA. The relation between MA and RTs, however, should not (or only marginally) be explained by P300 latency.

Alternatively, if hypothesis 2b was supported the negative relation between RTs and MA does not increase with increasing number of response alternatives, speed of decision making and/or response selection cannot be considered the source of variance underlying the relationship between RTs and MA. Hence, speed of stimulus evaluation and, primarily, speed of updating mental representations in WM as measured by P300 latency might be a plausible candidate explaining the relationship between RTs and MA provided that P300 latency shows a negative association to MA.

## 2. Method

### 2.1. Participants

The sample consisted of 113 female undergraduate students ranging in age between 17 and 38 years. Mean age was 19.9 (SD = 2.7) years. All participants had normal or corrected-to-normal vision and hearing. None of them reported taking any centrally acting medication or suffering from neurological disorders. Participants were asked not to consume caffeine or nicotine 2 h and alcohol 24 h prior to the EEG recording. As reimbursement, they received either course credit and/or were paid CAD 10 per hour of participation. All participants were informed about the study protocol prior to testing and gave written informed consent. The local ethics committee had approved the study.

### 2.2. Assessment of psychometric intelligence

A short-version of Cattell's Culture Fair Test 20-R (CFT 20-R; Weiß, 2006) was used as a measure of MA. It comprises three subtests (series, classifications, and matrices) with 15 items and one subtest (topologies) with 11 items. Weiß (2006) reported a test-retest reliability of $r_{tt} = 0.85$ after two months. Testing of intelligence took place in individual or group testing sessions (max. 10 participants) one to 14 days before the experimental session. The four subtests were submitted to a principal component analysis. Component scores on the first unrotated component were used as estimators of the individual level of psychometric intelligence.

### 2.3. Hick task

#### 2.3.1. Apparatus and stimuli

The present Hick reaction time task was adapted from Neubauer (1991). The visual stimuli were presented on a Dell Trinitron 19″ monitor with a screen resolution of 1024 × 768 pixel and a refresh rate of 75 Hz. Stimulus presentation and response recording was controlled by Eprime 2.0 and a Cedrus® response pad (RB-840; accuracy of ±1 ms). Stimuli were white-framed rectangles (1.8 cm × 1.35 cm) and white plus signs ("+", 0.6 cm) presented on a black background.

#### 2.3.2. Procedure

The task consisted of a 0-bit, 1-bit, 2-bit, and 2.58-bit condition. Each condition contained 32 experimental trials preceded by written instructions and 10 practice trials. The conditions differed in the number of white-framed rectangles that were continuously presented on the monitor screen as depicted in panels a to d of Fig. 1. In each trial, a plus sign appeared in the center of one of the presented rectangles with a random delay of 1000 ms, 1333 ms, 1666 ms or 2000 ms. The participants' task was to respond to this plus sign as quick as possible (while avoiding errors) by pressing a response button. The response buttons were arranged in correspondence to the arrangement of the rectangles in the 2.58-bit condition (see panel d of Fig. 1). Responses were given with the index finger of the right hand in the 0-bit condition, the index fingers of the right or left hand in the 1-bit condition, the index or middle fingers of the right or left hand in the 2-bit condition, and with the index, middle-, or ring fingers of the right or left hand in the 2.58-bit condition. The plus sign remained on the screen until the response

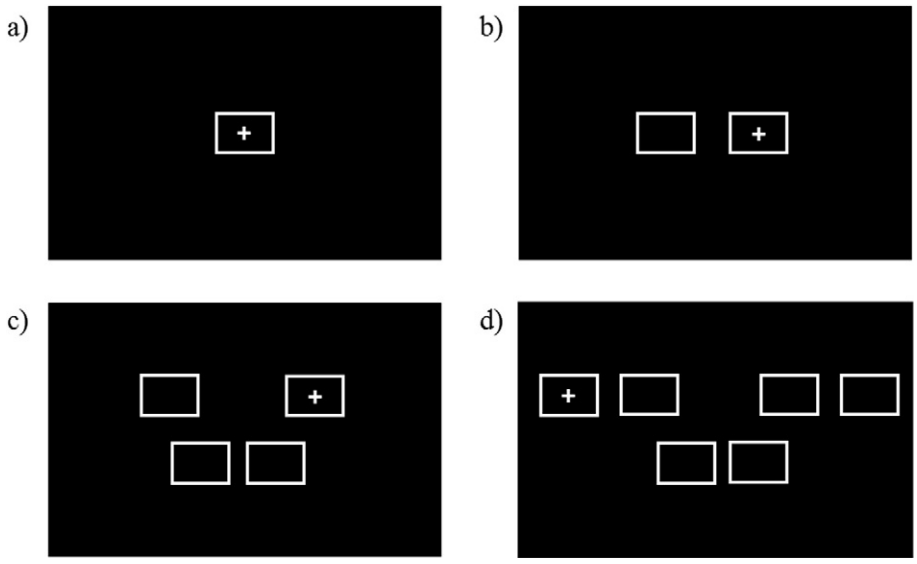


**Fig. 1.** Example trial for the 0-bit (panel a), 1-bit (panel b), 2-bit (panel c), and 2.58-bit condition (panel d) of the Hick task.

was given. Then, the next trial started. The order of conditions was counterbalanced across participants. RTs and errors were recorded as dependent variables. Only correctly responded trials with RTs between 90 ms and 1500 ms were included in data analyses.

### 2.4. Electrophysiological recording

During the Hick task the EEG was continuously recorded using a Neuroscan NuAmps amplifier and an electrode cap (EasyCap© International) with 28 Ag/AgCl electrodes referenced to the ear lobes. AFz served as ground electrode. The electrooculogram (EOG) was derived from two electrodes placed on the supra- and infraorbital ridges of the right eye (vertical EOG) and from two electrodes placed 2 cm external to the outer canthus of each eye (horizontal EOG). Impedances were kept lower than 5 kΩ.

EEG and EOG were digitized at a rate of 1000 Hz, offline filtered (1 to 15 Hz) and visually inspected for movement and sweat artifacts. The impact of the EOG was reduced by a regression-based ocular blink reduction (Semlitsch, Anderer, Schuster, & Presslich, 1986). The EEG was segmented based on markers from the Hick task referring to the onset of the plus sign. The segments consisted of a pre-stimulus interval of 100 ms and a post-stimulus interval of 800 ms. Each segment was baseline corrected for the pre-stimulus interval. An automatic artifact rejection excluded segments with voltage changes exceeding ±50 μV/200 ms. Finally, the segments of each condition were averaged for each participant leading to the ERP.

Using a semi-automatic peak detection, the largest positive deflection between 200 ms and 650 ms after stimulus onset in the individual ERP was determined. Afterwards, the peaks were visually inspected and, if required, manually adjusted. This peak was regarded as P300 amplitude and the time interval between stimulus onset and this peak as P300 latency.

## 3. Results

### 3.1. Behavioral data

Descriptive statistics of standardized CFT scores, RT and percentage of errors for each of the four Hick task conditions are presented in Table 1. Planned comparisons revealed that, as predicted by Hick's law, RTs increased significantly from the 0-bit to the 1-bit condition, $t(112) = 18.28$, $p < 0.001$, $d = 1.26$, from the 1-bit to the 2-bit condition, $t(112) = 17.96$, $p < 0.001$, $d = 1.40$, and from the 2-bit to the 2.58-bit condition, $t(112) = 10.70$, $p < 0.001$, $d = 0.79$ (see Fig. 2). Percentage

**Table 1**
Means (M), standard deviations (SD), minimum and maximum of RTs and P300 latencies in the four conditions of the Hick task as well as CFT 20-R scores and Pearson correlations between these variables.

| | M | SD | Min | Max | Correlations with RTs | | | | Correlations with P300 latencies | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 0-bit | 1-bit | 2-bit | 2.58-bit | 0-bit | 1-bit | 2-bit | 2.58-bit |
| RT in the Hick task [ms] | | | | | | | | | | | | |
| 0-bit condition | 285 | 41 | 205 | 433 | – | | | | | | | |
| 1-bit condition | 342 | 49 | 242 | 559 | 0.74*** | – | | | | | | |
| 2-bit condition | 424 | 67 | 298 | 686 | 0.55*** | 0.70*** | – | | | | | |
| 2.58-bit condition | 476 | 65 | 340 | 644 | 0.58*** | 0.64*** | 0.69*** | – | | | | |
| P300 latency in the Hick [ms] | | | | | | | | | | | | |
| 0-bit condition | 280 | 40 | 210 | 441 | −0.02 | −0.04 | −0.05 | −0.10 | – | | | |
| 1-bit condition | 318 | 32 | 229 | 404 | 0.18* | 0.22** | 0.21* | 0.16* | 0.04 | – | | |
| 2-bit condition | 322 | 34 | 223 | 404 | −0.05 | −0.02 | −0.06 | −0.09 | 0.16* | 0.34*** | – | |
| 2.58-bit condition | 327 | 34 | 234 | 399 | 0.04 | 0.08 | 0.08 | 0.05 | 0.01 | 0.30*** | 0.31*** | – |
| CFT scores[a] | 98.2 | 11.9 | 74 | 130 | −0.22** | −0.23** | −0.11 | −0.23** | 0.06 | −0.01 | 0.08 | 0.09 |

* $p < 0.05$ (one-tailed).
** $p < 0.01$ (one-tailed).
*** $p < 0.001$ (one-tailed).
[a] Descriptive statistics refer to the IQ-standardized CFT scores while for correlational analyses, the component scores from the principal component analysis on the four CFT subtests were used.

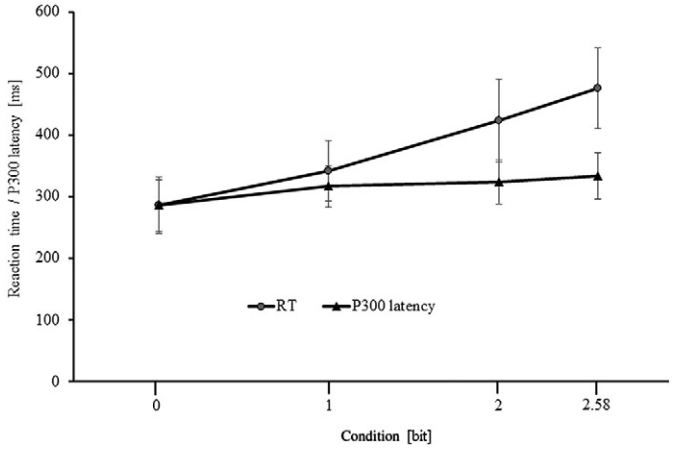


**Fig. 2.** Mean reaction times and P300 latencies (±standard deviations) in the four conditions of the Hick task.

of errors increased significantly from the 0-bit (M ± SD: 0.0 ± 0.0%) to the 1-bit condition (0.7 ± 1.4%), $t(112) = 5.43$, $p < 0.001$, $d = 0.71$, from the 1-bit to the 2-bit condition (2.5 ± 3.2%), $t(112) = 5.67$, $p < 0.001$, $d = 0.73$, but not from the 2-bit to the 2.58-bit condition (3.0 ± 3.4%), $t(112) = 1.12$, $p = 0.26$, $d = 0.15$.

As can be taken from Table 1, correlations between CFT component scores and RTs in the four Hick task conditions were negative and statistically significant for the 0-bit, 1-bit, and 2.58-bit condition but not for the 2-bit condition. Even though these correlations are rather weak, they do not substantially differ from the correlation coefficients reported in the meta-analysis by Sheppard and Vernon (2008) with the exception of the 2-bit condition. Furthermore, it is obvious that the correlations do not systematically increase from the 0-bit to the 2.58-bit condition.

### 3.2. Electrophysiological data

Grand averages for the ERPs in the four Hick task conditions can be taken from Fig. 3. The pronounced positivity about 300 ms after stimulus onset is interpreted as P300 component. The P300 amplitude was significantly smaller in the 0-bit condition than in the 1-bit condition, $t(112) = -5.75$, $p < 0.001$, $d = 0.59$, with mean amplitudes of 8.86 (±3.50) μV and 10.94 (±3.52), respectively. The mean P300 amplitude in the 2-bit condition was 10.78 (±3.73) μV and did not significantly differ from the amplitude in the 1-bit condition, $t(112) = 0.58$, $p = 0.56$, $d = 0.04$, nor in the 2.58-bit condition, $t(112) = 1.86$, $p = 0.07$, $d = 0.15$, which had a mean amplitude of 10.24 (±3.50) μV.

The P300 latency (for descriptive statistics see Table 1) was significantly shorter in the 0-bit condition than in the 1-bit condition, $t(112) = 8.09$, $p < 0.001$, $d = 1.05$. However, P300 latency did not increase significantly from the 1-bit condition to the 2-bit condition, $t(112) = 0.97$, $p = 0.17$, $d = 0.12$, nor from the 2-bit to the 2.58-bit condition, $t(112) = 1.39$, $p = 0.08$, $d = 0.15$. Thus, in contrast to RT, P300 latency was not sensitive to the experimental manipulations except for the difference between the simple reaction time task (i.e. 0-bit condition) and the choice reaction time tasks (i.e. 1-bit, 2-bit, and 2.58-bit condition, see Fig. 2).

As can be seen from Table 1, P300 latency in the 0-bit condition was significantly correlated with the P300 latency in the 2-bit condition only. P300 latencies in the other conditions, however, were all significantly correlated with each other. Furthermore, only in the 1-bit condition P300 latency correlated significantly with RTs in all four Hick task conditions. Finally, no significant relation between P300 latency and CFT component scores could be observed in any of the Hick conditions. Given this lacking association between P300 latency and MA, a mediation analysis of the relation between RT and CFT component scores controlled for the influence of the P300 latency was superfluous.

## 4. Discussion

The present study investigated whether the association between MA and RT in the Hick task can be explained by faster stimulus evaluation and updating mental representations in working memory in individuals with higher compared to lower MA as measured by the P300 latency. In line with our first hypothesis, RTs in the Hick task increased linearly with the number of required decisions as proposed by Hick's law (1952). Supporting the second hypothesis, RTs were negatively related to MA, although not significantly in the 2-bit condition. A systematic

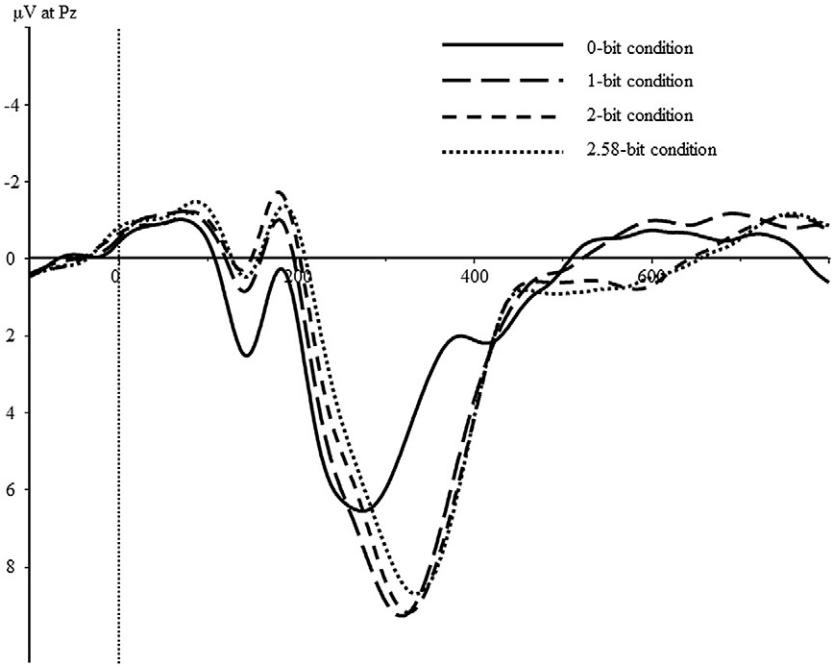


**Fig. 3.** Grand average waves for the ERPs in the four Hick task conditions at Pz electrode site. The zero point of the time scale refers to the onset of the plus sign. Negative is plotted upwards.

and significant increase of the correlation between MA and RTs across the task conditions was not observed supporting hypothesis 2b rather than 2a. P300 latency increased from the 0-bit to the 1-bit condition but was independent from further increases in demands on decision making. Most importantly and in contrast to our expectations (see the expectations following our hypothesis 2b), the P300 latency was not associated with MA in any task condition and, thus, could not contribute to the explanation of the relation between MA and RTs in the Hick task.

The main demand of the Hick task is to select the correct response out of one, two, four, or six response alternatives. This leads to the well-known increase of RT across task conditions described by Hick's law – also evident in the present data. The relationship between MA and RT, however, did not vary systematically across the task conditions. Except for the 2-bit condition, no significant differences between correlation coefficients were observed. Thus, it seems likely that neither speed of making simple decisions nor response selection accounts for the relation between MA and RT in the Hick task. Therefore, we investigated whether processes not influenced by task manipulation might be alternative candidates and used the ERP technique to index these processes. The P300 latency is the most prominent wave in the ERP and the component, which has been most frequently reported to be related to MA (cf. Stelmack & Beauchamp, 2001; Stelmack & Houlihan, 1995). It should be noted, however, that only for the oddball task a consistent relationship seems to exist (Bazana & Stelmack, 2002; Beauchamp & Stelmack, 2006; Sculthorpe et al., 2009; Troche et al., 2009), while in other tasks no consistent or rather unexpected patterns of correlations between P300 latency and MA were found (e.g. Houlihan et al., 1998; McGarry-Roberts et al., 1992). In the present study, the increase from the 0-bit to the 1-bit condition might reflect the qualitative change from a simple to a choice RT task associated with more uncertainty of the target's localization and higher complexity of the stimulus material (e.g., Johnson, 1986). There was, however, no further increase in P300 latencies from the 1-bit to the 2-bit nor from the 2-bit to the 2.58-bit condition. This latter finding corroborates the notion that the P300 latency is independent from processes of response selection (Doucet & Stelmack, 2000) and is consistent with the notion that P300 latency can be interpreted as an index of speed of stimulus evaluation (Houlihan et al., 1994) and updating the mental representations in working memory (Polich, 2010). In no task condition, however, the P300 latency was associated with MA. Hence, these results did not meet with our expectation of speed of stimulus evaluation and updating mental representations in working memory contributing to faster RTs in individuals with higher compared to lower MA.

Polich (2007) hypothesized that the P300 component reflects the inhibition of task-irrelevant, extraneous brain activity to facilitate the transmission of information from frontal to parietal brain locations. From this point of view, the P300 latency is not an additive part of RT. Rather, the P300 component is a process accompanying the processing of a stimulus. This hypothesis might explain the inconsistent results on the relationship between P300 latency and RT as also evident in the present study and which should be clearly higher if individual differences in P300 latency were an additive part of individual differences in RT.

Polich's hypothesis also provides an explanation for the inconsistent results regarding the relationship between MA and P300 latency. P300 amplitude and latency are sensitive to task demands and instructions (cf. Stelmack & Houlihan, 1995) so that the inhibitory role of the P300 component varies from task to task and its accompanying function might be of particular importance when accuracy is required, for example, to detect targets among distractors. In line with this assumption is the finding by Pfefferbaum, Ford, Johnson, Wenegrat, and Kopell (1983) that the P300 latency is lower in sensitivity for task manipulations in tasks with speed compared to accuracy instructions. In the present Hick task, a speed instruction was emphasized and P300-related processes were of minor importance for responding to the stimuli – as can be seen from the non-significant correlations between P300 latency and RT as well as from the finding that in the 0-bit condition mean P300 latency was almost of the same length as mean RT. If the processes related to the P300 component, however, are not vitally important for efficiently performing the Hick task, it is not surprising that no indication was found for any involvement of the P300 latency-related processes in the observed RT differences between high- and low-MA individuals across the increasing levels of task complexity.

To sum up, shorter RTs in the Hick task were associated with higher MA in the present study and these associations did not increase with the increasing number of decisions required by different task conditions. The time for stimulus evaluation as indicated by the P300 latency was not consistently related to RT nor to MA and, thus, provides no explanation for the speed advantage of individuals with higher compared to individuals with lower MA in the Hick task.

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