PRZEGLĄD PSYCHOLOGICZNY, 2021, TOM 64, Nr 4, 119–133
DOI: 10.31648/przegldpsychologiczny.7885

Temporal resolution working memory and types of errors in the Raven's Advanced Progressive Matrices Test – a pilot study

Krzysztof Tołpa[1] (0000–0001–6223–234X)
Monika Lewandowska[2] (0000–0002–7354–3693)
Jan Nikadon[3] (0000–0002–2038–254X)
Joanna Dreszer[*2] (0000–0002–2809–2934)

ABSTRACT

Aim

The aim of this study was to investigate the relationship between temporal resolution in the millisecond range, working memory and psychometric intelligence, taking into account qualitative analysis of error types in Raven's Advanced Progressive Matrices *RAPM*.

Method

Thirty-six subjects (24 males and 12 females, in age 17–19 years) performed the temporal resolution task, Automated Operation Span Task *Aospan* and *RAPM*. A temporal resolution was measured by the temporal order threshold *TOT* which was estimated using an adaptive algorithm for 75% correctness level.

Results

There was a tendency towards less frequent Wrong Principle *WP* errors in the *RAPM* coexisting with lower *TOT* values: *rho*(34) = 0.46, $p < 0.05$. Moreover, a significant relationship was observed between Aospan and *RAPM* scores, for both percent of correctly recalled letters (*rho*(34) = 0.55, $p < 0.01$) and the percent of correctly recalled sequences (*rho*(34) = 0.43, $p = 0.05$).

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* Correspondence address: Joanna Dreszer – Department of Clinical Psychology and Neuropsychology, Institute of Psychology, Faculty of Philosophy and Social Sciences, Nicolaus Copernicus University in Toruń, 39 Gagarina Street, 87-100 Toruń, Poland.

[1] Department of Cognitive Science, Institute of Information and Communication Research, Faculty of Philosophy and Social Sciences, Nicolaus Copernicus University in Toruń .

[2] Department of Clinical Psychology and Neuropsychology, Institute of Psychology, Faculty of Philosophy and Social Sciences, Nicolaus Copernicus University in Toruń .

[3] Center for Research on Social Relations, Institute of Psychology, SWPS University of Social Sciences and Humanities.

Conclusions
This is the first study demonstrating the relationship between temporal resolution in the millisecond range and the types of errors in a general intelligence test. Individuals with higher *TOT* values showed a tendency to commit more *WP* errors in the *RAPM* indicating difficulty in finding the correct rule of reasoning. Such tendency may reflect less working memory resources allocated to solve the problem.

Keywords: temporal information processing, temporal resolution, general intelligence, working memory

INTRODUCTION

Various behaviors and tasks involving intellectual abilities, as well as other activities of living organisms, proceed and elapse over time. Previous studies have shown an interplay between human intelligence, understood in different ways, and temporal aspects of information processing (Bartholomew, Meck, Cirulli, 2015; Chelonis, Flake, Baldwin, Blake, Merle, 2004; Coyle, Pillow, Snyder, Kochunov, 2011; Helmbold, Troche, Rammsayer, 2006, 2007; Holm, Ullen, Madison, 2011; Jensen, 2005; Karampela, Madison, Holm, 2020; Szymaszek, Sereda, Pöppel, Szeląg, 2009; Rammsayer & Brandler, 2002).

At the beginning of the XX century, Spearman extracted the *g* (general) factor reflecting a common fraction of all abilities, corresponding to intelligence, characterizing general effectiveness in performing different intellectual tasks (Spearman, 1904). The *g* factor is often identified with general fluid intelligence, *Gf* described in the Cattel and Horn model (*Gf-Gc model*, Horn & Cattell, 1967). According to this hypothesis, *Gf* is an ability to identify complex relations between notions or symbols and to perform cognitive operations on them. *Gf* is contrasted with the general crystallized intelligence *Gc,* understood as an ability to use adequately acquired experience and knowledge. The current study aimed to investigate the relationship between *g* factor, working memory and temporal processing in the millisecond range.

It is believed that neuronal correlate of the *g* factor may be connected with the mechanism affecting temporal information processing *TIP*, described as an internal oscillator (e.g. Drake, Jones, Baruch, 2000). The functioning of this hypothetical clock mechanism may be responsible for the temporal framing of cognitive processes (Block, 1990; Fraisse, 1984; Gibbon, 1991; Ivry & Spencer, 2004; Pöppel, 1994, 1997, 2004) encompassing language abilities, planning and execution of movement, attention and working memory, as well as intellectual abilities (Habib, 2021; Hove, Gravel, Spencer, Valera, 2017; Jabłońska et al., 2020; Madison, Forsman, Blom, Karabanov, Ullén, 2009; Oroń, Szymaszek, Szeląg, 2015; Rammsayer & Brandler, 2002, 2007; Spencer & Ivry, 2005; Szeląg et al., 2014; Szymaszek et al., 2009; Tallal, 1980; Troche & Rammsayer, 2009; Ulbrich, Churan, Fink, Wittmann, 2009; Ullén, Forsman, Blom, Karabanov, Madison, 2008; Wittmann, von Steinbüchel, Szeląg, 2001).

Existing evidence on the relationship between *TIP* and general intelligence can be found among the studies concerning mental speed, i.e. speed and efficiency of information processing measured by reaction time (e.g. Der & Deary, 2017; Jensen, 1993; Miller & Vernon, 1996) and inspection time (*IT*, Duan, Dan, Shi, 2013; Grudnik & Kranzler, 2001; Nettelbeck & Lally, 1976; Petrill & Deary, 2001). It is reasonable to assume that the negative correlations between reaction time and *g* factor, observed regardless of the subjects' age, reflect an increased pace of cognitive processes in individuals with a higher intelligence level (Der & Deary, 2017; Jensen, 1982). Similar observations were made in the studies on *IT*, where visual stimuli were presented in a form of two vertical lines connected by a horizontal one (Deary, 1995, 2000; Grudnik & Kranzler, 2001; Kranzler & Jensen, 1989; Nettelbeck & Lally, 1976; O'Connor & Burns, 2003). The length of one vertical line is always constant while the other one is changing. The task is to determine which line is longer (left or right) (e.g. Deary, 2000). In the auditory form of the *IT* paradigm (e.g. Deary, 1995, 2000; O'Connor & Burns, 2003) subjects are asked to identify the order of two short tones differing in frequency. In this paradigm, the stimulus exposure time is constant, while an interval between the stimuli is changing. *IT* is defined as the shortest exposure time for which the individual is able to achieve a minimum of 90% of correctness. Shorter *IT* values, both visual and auditory, have been correlated with higher psychometric intelligence (Grudnik & Kranzler, 2001). These results may suggest more efficient differentiation of short stimuli by individuals with higher intellectual abilities. It is worth noting that the aforementioned studies utilized various, commonly used measures of intelligence (*Wechsler Intelligence Scale, Raven's Progressive Matrices, Cattell Culture Fair Intelligence Test,* etc.) where quantitative methods of data analysis were applied.

The studies by the Rammsayer's group (Pahud, Rammsayer, Troche, 2018; Rammsayer & Brandler, 2002, 2007; Troche & Rammsayer, 2009) aimed to verify the temporal resolution power hypothesis, according to which, the internal oscillator pace, interpreted as reflecting the features of neuronal networks performance (frequency of neuronal transmission, oscillations and synchronization rate) is higher in the individuals with higher scores in the general or fluid intelligence tests. This is linked with faster and more efficient information processing as well as smaller susceptibility to distraction. Rammsayer & Brandler (2007) analyzed the outcomes of eight tasks involving various levels of time experience in the range of milliseconds (e.g. temporal duration judgment, simultaneity judgment, differentiation of rhythms, temporal order judgment) and battery of tasks measuring reaction times. These analyses showed temporal *g* highly correlated with psychometric *g* factor, which may provide a better explanation for the differences in the functioning of individuals with higher intellectual capacity than the mental speed hypothesis.

The temporal task, used in the present study, resembles the auditory inspection time evaluation since it requires identifying the order of two rapid, subsequent visual stimuli. The obtained results: temporal order threshold *TOT*, is defined as the shortest interval between two stimuli, necessary for the correct identification of their temporal order. Indirect evidence for the relationship between *TOT*s and general intelligence is provided by the studies on healthy aging (Kołodziejczyk & Szeląg, 2008; Skolimowska, 2011; Surwillo, 1964, 1973 In the case of higher *TOT*s, preferring a significantly slower pace of incoming sensory stimuli and the movement execution at a comfortable pace are observed and noticed easily in everyday life. Interestingly, centenarians with higher intellectual ability are also characterized by faster and more efficient temporal processing than their peers with a lower intelligence level (Kołodziejczyk & Szeląg, 2008). These outcomes are interpreted in terms of slowing of the internal clock mechanism with aging (Surwillo, 1964, 1973).

It is also possible to determine the similarities between the developmental changes of fluid intelligence (Horn & Cattell, 1967) and the pace of the hypothetical internal clock (Vanneste, Pouthas, Wearden, 2001). Age-related decline of fluid intelligence has been well-documented and linked to the atrophic changes in the brain (Salthouse, 2011). However, these similarities should be interpreted with caution since intelligence in the aforementioned studies was only a covariant (Salthouse, 2001) and aging-related processes are connected with the changes in the central nervous system *CNS* functioning and cognitive domains, which may lead to reduced performance of tasks measuring *TIP* and general intelligence. As Salthouse (2011) suggests, the relationship between aging, cognitive decline and associated brain changes is not entirely clear.

Fluid intelligence is closely connected with working memory reflecting an ability to keep attention focused on the activated elements of short-term memory and to perform operations on them (Engle, Laughlin, Tuholski, Conway, 1999; Engle, 2018). Working memory is, therefore, necessary for problem-solving measured by the intelligence tests. Working memory may explain the relationship between the temporal resolution power factor and intelligence (Troche & Rammsayer, 2009, Zajac & Burns, 2011). Temporal resolution and working memory are separate, however, interrelated constructs, especially, when the temporal generalization task is used to measure temporal processing (Zajac & Burns, 2011). It has been shown that 35% of the relationship between temporal resolution and general intelligence could be explained by the working memory factor. Moreover, temporal resolution more strongly correlated with working memory and speed of information processing than with intelligence Other studies have demonstrated a complete mediation of the relationship between temporal resolution and intelligence by the working memory (Troche & Rammsayer, 2009).

One of the purest measures of the *g* factor is the Raven's Progressive Matrices test (Raven, 1971), in which individuals are asked to identify the relationship between elements of patterns in the matrix and choose the missing element from provided options. The most frequently reported measure of this test performance is the total number of correct responses. However, the results can be analyzed qualitatively, by identification of the types of committed errors (Raven, 1971). Forbes (1964) distinguished four types of errors made in the *RAPM*: 1) Incomplete Solution (Incomplete Correlate, *IC*) which occurs when an individual is unable to identify all variables necessary to solve a problem. As a consequence, the chosen answer is partially correct; 2) Arbitrary lines of reasoning (Wrong Principle, *WP*) – errors occurring when an individual cannot identify any variable necessary to solve a problem. The rule of reasoning used to choose an answer is qualitatively different from the correct one; 3) Overdetermined choices (Confluence of Ideas, *CF*) occur when an individual does not realize that some elements are irrelevant to the problem or do not change. In this case, the chosen response is excessively complex, contains too many elements; 4) Repetitions *RP* occurs when an individual chooses an answer identical to the figures in the cell adjacent to the empty one. Babcock (2002) analyzed the tendency to make errors of different types, depending on the level of intelligence – low ability (1–10 points), medium ability (11–17 points), high ability (18–31 points) separately for the age category of 18–30, 31–59 or 60–90 years old. She observed that high ability subjects more frequently tended to make the *IC* error than those with medium ability. The latter subjects had a higher tendency to make *IC* errors than low ability individuals. The reverse trend was observed for the *WP* errors. People with medium and high ability usually follow correct lines of reasoning. Their errors may result from insufficient identification of all relevant variables. Low ability subjects do not seem to make a specific type of error – instead, their errors are probably an effect of a random choice of answers.

The aim of the current study was to investigate the relationship between temporal resolution, types of errors in the fluid intelligence test and working memory. We hypothesized that the measure of temporal resolution would correlate with the scores from the intelligence and working memory tasks. Taking into account studies conducted by Babcock (2002) we expected to observe the relationship between *TOT* and the tendency to make *IC* and *WP* errors. According to the authors' knowledge, this is the first study investigating temporal processing in the millisecond range in relation to the qualitative analysis of the *RAPM* outcomes.

METHOD

Participants

The study involved 39 subjects (25 males and 14 females), aged 17–19 years (M = 18.44, SD = 0.55), students of high schools in Toruń. All subjects were in generally good health, attended school regularly, and had a normal or corrected-to-normal vision. Subjects were recruited through direct advertisements in high schools or posted on social media. Before the procedure, each participant provided informed consent to take part in the study. In the case of adolescents, informed consent was given by their parents or guardians. The study was approved by the Bioethics Committee of the Nicolaus Copernicus University in Toruń.

The results of 36 subjects (24 males, 12 females) 17–19 years old (*M* = 18.44, *SD* = 0.56) were included into the statistical analysis. Two participants were classified as outliers. One of them achieved a score higher than three standard deviations for the deviation from chance selection for the *WP* error. The other one did not achieve the correctness of 75% and the *TOT* was equaled to less than zero. The last individual was excluded from the analysis because of the lack of any errors made in the *RAPM*, which made it impossible to interpret the measure of deviation from chance selection for the given error.

Procedures

Temporal resolution

Temporal order judgment task was used to estimate temporal resolution. The task is an example of a two-alternative forced-choice procedure (*2AFC*). Subjects are required to identify the temporal succession of two stimuli, presented in short, changing intervals. Interval duration was calculated by an adaptive algorithm based on *Updated Maximum Likelihood* estimation (Shen, Dai, Richards, 2015). The following configuration was used: maximal and initial duration of the interval was 150 ms and minimal duration of the interval – 1 ms.

The procedure was controlled by the minicomputer Raspberry Pi 3 Model B SBC (Bulk) equipped with a mini controller Arduino Genuine Zero. The stimuli were generated using a LED Maxim Integrated MAX16822BEVKIT + controller. Two LED CREE diodes were a stimulation source with a maximum luminance of 350 lm. The diodes were attached to the right and left side of the screen, on which the fixation cross was presented. The response pads were connected to the computer *via* optical fibers. The duration of the single trial was 3 s. The stimuli were presented for 40 ms, first on one side and after the interval of changing duration, on the other side of the screen. Subjects sat in the distance of 1 m in front of the screen. The task was to report the side on which the stimulus was presented first, by pressing the button on the response pad with a thumb in the proper hand.

The subjects performed a training session to familiarize themselves with the procedure. In the main task, they were asked to focus their sight on the fixation cross to avoid the influence of different possible strategies used to identify the temporal order. Right after completing the task subjects filled in the questionnaire about their experience during the experiment and strategies used to perform the task.

As a result of the temporal order judgment task, *TOT* was determined individually in each participant. *TOT* is defined as the minimal inter-stimulus-interval for the 75% correctness level (Jabłońska et al., 2020; Szeląg et al., 2011, Szeląg, Jabłońska, Piotrowska, Szymaszek, Bednarek, 2018). *TOTs* were calculated based on the *post hoc* estimation of psychometric curves of each individual using the Psignifit 4 toolbox in Matlab (Schütt, Harmeling, Macke, Wichmann, 2016). *TOT*s were estimated using all trials applied and the number of the trials differed between subjects, ranging from 20 to 120. Even in the case of the smallest number of trials, in the subjects who were included in the study sample, *TOT* could be determined.

Working memory

To measure the working memory span the Automated Operation Span Task *Aospan* was used (Unsworth, Heitz, Schrock, Engle, 2005). The subjects were asked to perform arithmetic operations and to remember a series of letters in an alternating manner. The training session preceded each proper task. The length of the letter sequence was random and ranged from 3 to 7 elements. Subjects performed 15 trials in total, each consisting of a sequence of letters to remember and mathematical operations. Each sequence length was presented 3 times. *Aospan* is a part of battery PEBL 2.1 (Mueller & Piper, 2014). The task was performed on a laptop with a screen resolution of 1366 x 768. A laser mouse was used to give responses during the task. Two measures were calculated: percent of correctly recalled sequences and percent of correctly recalled letters.

Psychometric intelligence

The Raven's Advanced Progressive Matrices *RAPM* was used to measure psychometric intelligence. For each subject, a total number of correct response was calculated as well as the tendency to commit errors. Various types of errors are not equally distributed in the test. Thus, we used the indicator proposed by Babcock (2002) in a form of a deviation from chance selection for each error type. It is calculated as follows:

1. The errors are classified into different categories and a total number of each error type in each problem is provided.
2. The number of each error type only in the incorrectly solved problems is determined.
3. A total number of errors is calculated and the result is multiplied by 7. The obtained value represents the total number of distractors in the problems, in which errors have been made.
4. Individual probability of committing an error of each type by chance is determined. To achieve this, the value from step 2 is divided by the value from step 3.
5. The number of each error type made by an individual is determined.
6. Determining the proportion of each error type (value from step 5) to the total number of errors is calculated for each individual.
7. An individual deviation from chance selection for each error type is established. Individual probability of making each error type by chance only (value from step 4) is subtracted from the individual proportion of each error type made by a subject (value from step 6). A positive value of this indicator means that an individual made a particular error type above a chance level. A negative value indicates that subject made that particular error type below a chance level.

In the present study, we used the classification of error types proposed by Babcock (2002) for problems 1–31 and by Israel (2006) for problems 32–36. The values required to obtain the deviation from a chance level for each error type were calculated using a self-developed script written in Matlab.

Statistical analysis

To investigate the relationship between time information processing, working memory and intelligence the pairwise Spearman's *rho* correlations with FDR correction for multiple comparisons were computed for the following measures: *TOT*, percent of correctly recalled sequences, percent of correctly recalled letters in a sequence in the *Aospan* task, the total number of correct responses in the *RAPM* and the deviations from chance selection for each error type in the *RAPM*. The analysis was conducted using the R software.

RESULTS

TOT correlated significantly only with the deviation from chance selection of *WP* error: *rho*(34) = 0.46, $p < 0.05$. The relation between *TOT* and the *Aospan* task results was non-significant: for the percent of correctly recalled letter sequences letters *rho*(34) = 0.18, p = 0.62 and for the percent of correctly recalled letters: *rho*(34) = 0.03, p = 0.89. Moreover, there was no meaningful relationship between the *TOT* and *RAPM* outcomes: *rho*(34) = -0.18, p = 0.62.

The Aospan task results were associated significantly with the RAPM scores: for the percent of correctly recalled sequences the correlation coefficient was at the edge of statistical significance: *rho*(34) = 0.43, p = 0.05 and for the percent of correctly recalled letters: *rho*(34) = 0.55, $p < 0.01$. Both measures of Aospan were highly correlated: *rho*(34) = 0.78, $p < 0.01$.

Furthermore, there was a significant relationship between two indicators of the tendency to make errors in the *RAPM* – a deviation from chance selection for the *WP* error and a deviation from chance selection for the IC error: *rho*(34) = -0.47, $p < 0.05$.

DISCUSSION

The current pilot study aimed to investigate whether the qualitative analysis of *RAPM* results (analysis of error types) may contribute to a better understanding of the relationship between general intelligence, temporal information processing and working memory. We observed expected, and consistent with previous studies, correlations between working memory and intellectual abilities (e.g. Engle et al., 1999; Engle, 2018; Troche & Rammsayer, 2009). *TOT* values did not correlate significantly with a total score in *RAPM* and the results of the *Aospan* task. The qualitative analysis of intelligence test performance demonstrated the relationship between the *TOT* and a tendency to make *WP* error type. This outcome may reflect different rules of reasoning in individuals who obtained low and high *TOT* values.

Babcock (2002) reported that high ability individuals, who scored in *RAPM* between 18 and 31 points, showed a tendency to commit *IC* (incomplete correlate) errors and at the same time not make *WP* (wrong principle) errors. In the presented study the lowest score achieved by subjects was 18 points. Thus, all our individuals can be classified into the high ability group. Despite the fact that the relationship between *TOT* and the total score of *RAPM* was nonsignificant, we showed a correlation between the *TOT* and deviation from chance selection for *WP* error. This may suggest that individuals with high intellectual ability and increased *TOT* values (less efficient temporal information processing in the millisecond range), while solving *RAPM* problems, may use the lines of reasoning qualitatively different from correct ones.

Taking into account existing evidence on the relationship of intelligence and working memory, the observed effect may be a consequence of fewer attention and memory resources necessary to identify the patterns correctly and keep the information in mind to perform the operations (Chuderski, 2015). The study by Jarosz & Wiley (2012) has shown that performance in problems in which the most frequent error was *WP* correlates stronger with working memory factor than performance in the problems where the most frequent error was *IC*. This observation may suggest that tendency to commit *WP* type errors is the most dependent on the working memory functioning (Chuderski, 2015). In the present study, significant relationship between the tendency to make *WP* errors and working memory was not observed. On the other hand, previous studies have revealed that working memory may be a mediator of the relationship between temporal resolution and intelligence. It is, therefore, reasonable to assume that in the highly intelligent group the tendency to make *WP* errors is mostly dependent on temporal information processing. Inclusion of subjects with lower intelligence levels in the analysis may result in the observation of a significant relationship between working memory and tendency to make *WP* errors. Assuming the results of the present study were replicated, the qualitative analysis of intelligence tests could provide a more sensitive (than total score) indicator of individual differences in intellectual abilities and temporal information processing.

The absence of correlation between the temporal resolution measures and *RAPM score*, observed in this study, may result from the specificity of the temporal judgment task. It can also be a consequence of the fact, that only high ability individuals participated in the study (and therefore there was a relatively low variance of results). Here, it is worth noting that despite evidence suggesting that temporal resolution and intelligence are positively associated with each other (e.g. Troche & Rammsayer, 2009), this relationship was not always evident (Rammsayer & Brandler, 2002). The temporal order judgment task engages a specific type of temporal processing underlying processes linked to language, such as speech production and reading. Thus, there may be a third factor mediating the relationship between temporal resolution and general intelligence, such as attention or speed of information processing (Pahud, 2017).

Additionally, we would like to highlight the difficulties of interpretation of the deviation from a chance selection of the error. Firstly, to be included in the analysis, an individual has to make an error. In other words, subjects with high intelligence, who make no errors, have to be excluded from the analysis. Secondly, the deviation from chance selection indicates a tendency to make errors of a particular type. It does not inform, then, about the actual number of errors made. High values may be obtained for a small number of errors (even for a single error) when the probability of making an error of a particular type in a matrix is low. Thus, the observed results are affected by random confounding variables, especially in the case of high ability individuals, who rarely commit errors.

Limitations and future directions

The main limitation of the current study is a relatively small sample size. It does not allow to implement a statistical model with more than a single predictor. Hence, to investigate the relations between the variables of interest only the correlation analysis was performed. In future studies in this area, the number of men and women should be similar. A higher number of males in the present study does not allow to generalize the effects to the entire population. Furthermore, it should be noted that the analyzed sample is relatively homogenous. Again, to generalize conclusions of the study over the population, the results should be replicated on the more diverse sample. Future studies should also take into account more than single measures of working memory, general intelligence and temporal resolution to increase the reliability of the study.

Additionally, one should be aware of the limitations of classifications of errors in *RAPM* adopted from Forbes (1964). Apart from not equal numbers and distribution of errors of particular type across problems in the test, studies also point out unclear rules according to which the wrong answers are created (Chuderski, 2015). As a result, there are differences in the numbers of incorrect lines of reasoning across the types of errors, which make the tendency to make errors of a particular type even more difficult to interpret. To address this problem intelligence tests are modified to control a number of lines of reasoning in the possible responses. Replication of the current study while controlling incorrect lines of reasoning should also increase the reliability of the study and allow for more advanced data analysis.

SUMMARY

According to the authors, this is the first, preliminary report of the relationship between the perception of the temporal order of stimuli presented with rapid succession and types of errors in the Raven's Matrices test. Considering the aforementioned limitations, the presented results should be interpreted with caution. Yet, it seems that the qualitative analysis of intelligence test results may be useful for a better understanding of the relationship between cognitive functioning and temporal aspects of information processing.

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Acknowledgements

The presented study is a part of project no. 2015/18/E/HS6/00399 supported by the funds of the National Science Centre.