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The Factor Structure of Cognitive Reflection, Numeracy, and Fluid intelligence. The evidence from the Polish adaptation of the Verbal CRT.

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Abstract

The Cognitive Reflection Test (CRT) is one of the most popular measures of individual differences in rational thought and decision making. Nevertheless, it overlaps substantially with numeracy and intelligence, which impede the interpretation of results. The present research had two main aims. First, to investigate the generalizability of Verbal CRT—a novel measure of cognitive reflection less confounded with numeracy and math anxiety than numerical CRT—in cultural contexts outside US/UK . Second, to test the factor structure linking traditional—numerical—CRT, Verbal CRT, numeracy and fluid intelligence. In Studies 1a and 1b, we adapted and tested the validity and psychometric properties of Polish versions of tasks and scales. Next, using a large and diverse sample of Polish adults, we tested five models of the factor structure of cognitive abilities and thinking dispositions (Study 2). The most parsimonious and best-fitted model contained three latent variables: Verbal CRT, Numeracy (composed of the items from the Berlin Numeracy Test and traditional—numerical—CRT), and Fluid intelligence. In line with previous research, our results show that Verbal CRT is a valid cognitive reflection measure that provides a clearer interpretation than traditional CRT, even in a different language and cultural context.

Keywords: rationality, cognitive reflection, numeracy, fluid intelligence, decision making

The Cognitive Reflection Test (CRT; Frederick, 2005) is theoretically important and very commonly used measure of individual differences in rational thought. The test comprises verbal problems prompting an intuitive answer that is incorrect. For example, when participants respond to a classic “bat-and-ball” problem (“A bat and a ball cost $1.10 in total. The bat costs $1 more than the ball. How much does the ball cost?”), participants must detect that there is a conflict between their first intuitive response (i.e., 10 cents) and a normative (correct) response (i.e., 5 cents). If the conflict is detected, they engage in deliberative processing to calculate the correct answer and override the initial response.[1]

The Cognitive Reflection Test (as well as its modifications, Primi, Morsanyi, Chiesi, Donati, & Hamilton, 2016; Toplak, West, & Stanovich, 2014) was found to be a significant predictor of rationality and real-life outcomes (for a review, see, Pennycook, Fugelsang, & Koehler, 2015). For example, people who scored higher in the CRT (giving more reflective responses) were less likely to exhibit various biases such as the illusion of control, conjunction fallacy, or overconfidence (Noori, 2016). Additionally, people who scored lower in the CRT preferred immediate but smaller rewards than delayed but larger rewards (i.e., delay discounting effect; Bialek, Bergelt, Majima, & Koehler, 2019; Bialek & Sawicki, 2018). Interestingly, they were also more likely to declare both religious and paranormal beliefs (Pennycook, Ross, Koehler, & Fugelsang, 2017; Sirota & Juanchich, 2018; Toplak et al., 2014). Critically, more reflective participants were less prone to biases (such as denominator neglect, sunk cost bias, or belief bias) even when executive functions or intelligence were controlled (Toplak, West, & Stanovich, 2011; Toplak et al., 2014).

The CRT is theoretically grounded in the dual-process theories (e.g., Kahneman, 2011) that distinguish two systems/types of processing: Type 1 (typically described as fast, heuristic,

[1] Nevertheless research using process-tracing methods revealed that a substantial number of people give the first correct response in the CRT, which questions the generalizability of this mechanism (Bago & De Neys, 2019; Szaszi, Szollosi, Palfi, & Aczel, 2017).

intuitive) and Type 2 (typically described as reflective, slow, computationally expensive). Nevertheless, most of these theories do not acknowledge the role of individual differences but instead focus on general mechanisms. Stanovich, West, and Toplak (2011; 2016), in their tripartite model of thinking, addressed the role of individual differences in these types of processing. They suggested that two main problems might drive individual differences in irrationality. First, people may differ on how much resources they engage in completing a cognitive task (but generally, they are rather cognitive misers, and they do not commit their resources when unnecessary). Second, Stanovich et al. (2016) see the issue of missing (or contaminated) mindware and argue that the mindware for rational thought is specialized - clustered in probabilistic reasoning, causal reasoning, and scientific reasoning. Although CRT was developed as a measure that taps into the process (e.g., conflict detection and overriding incorrect response), it is also moderately dependent on understanding numerical information (Stanovich et al., 2016).

Numeracy confounds traditional CRT

Numeracy (in particular, statistical numeracy; Cokely et al., 2018) is considered to be a cognitive ability critical for decision making (for recent reviews, see Garcia-Retamero, Sobkow, Petrova, Garrido, & Traczyk, 2019; Peters, 2020; Sobkow, Garrido, & Garcia-Retamero, 2020). It remained a significant predictor even when fluid intelligence, working memory, or vocabulary were included in the models (Peters & Bjälkebring, 2015; Skagerlund et al., 2021; Sobkow, Olszewska, et al., 2020).

Because most tests measuring numeracy (e.g., the Berlin Numeracy Test, BNT; Cokely, Galesic, Schult, & Garcia-Retamero, 2012) do not contain lures (easy available incorrect response), they should tap into different aspects of rationality than CRT (Stanovich et al., 2016). Nevertheless, a bulk of the research demonstrated that CRT and numeracy are moderately correlated (Bialek & Sawicki, 2018; Cokely et al., 2012; Del Missier, Mäntylä, &

de Bruin, 2011; Petrova, Traczyk, & Garcia-Retamero, 2019; Sinayev & Peters, 2015; Sirota & Juanchich, 2018; Sobkow, Olszewska, et al., 2020). Additionally, Juanchich, Sirota, and Bonnefon (2020) found that a gender gap (females scoring lower in the CRT than males) is observed because of anxiety-induced miscalculations in females.

This fact impedes our inferences about cognitive mechanisms underlying problem solving and decision making. Do people fail to detect and override the conflict between their intuition and reflection or simply lack relevant mathematical knowledge? The solution to this problem could be to develop measures that disentangle domain-specific knowledge from the process – luring puzzles that do not contain numerical information.

The Verbal Cognitive Reflection Test (Verbal CRT)

Recently, Sirota et al. (Sirota, Dewberry, Juanchich, Valus, & Marshall, 2021) developed a test containing ten problems that have a similar structure to traditional CRT but are verbal problems only and are thus not confounded with mathematical ability. For example, in a puzzle, "Mary's father has 5 daughters but no sons—Nana, Nene, Nini, Nono. What is the fifth daughter's name probably?" there is an intuitive and luring response: "Nunu" (the correct answer should be "Mary"). In a set of studies, Sirota et al. demonstrated that this test has good internal consistency and validity. Verbal CRT scores predicted the same rationality measures as traditional numerical CRT (e.g., belief bias, denominator neglect, time preference, paranormal beliefs). However, correlations observed between Verbal CRT and math-related measures (i.e., objective numeracy, subjective numeracy, math anxiety) were significantly lower than those for Numerical CRT. Finally, contrary to Numerical CRT, there was no significant gender gap in the performance in Verbal CRT. To summarize, we argue that Verbal CRT could be a milestone in measuring individual differences in cognitive reflection, but further research is needed to test the generalizability of obtained effects in different languages and cultural contexts.

Aims

In the present research, we had two main aims. First, we intended to test whether the effects of Verbal CRT could be generalized outside the US/UK samples. While the traditional CRT was already tested in several countries (see the meta-study by Brañas-Garza, Kujal, & Lenkei, 2019), to our best knowledge, besides native English speaking countries, Verbal CRT was only used in Slovakia (Čavojová, Šrol, & Mikušková, 2022; Mikušková & Čavojová, 2020). However, in the case of these studies, only three Verbal CRT items were included, and they were combined with Numerical CRT into a single index. Thus, our research is the first that aims to adapt and validate this test in a different language than English. The process of adaptation (not only simple translation) seems to be especially important because of the verbal properties of a test that may be highly susceptible to language.

In Study 1a, we developed a Polish adaptation of the Verbal Cognitive Reflection Test. Next, using a large and diverse sample from the general Polish population (Study 2), we tested its psychometric properties (internal structure and validity). We intended to replicate findings from the original research (Sirota et al., 2021) by exploring relationships between Verbal CRT and (ir)rationality-related measures (e.g., belief bias, denominator neglect, time preference), math-related measures (i.e., math anxiety, subjective numeracy, objective numeracy), and gender differences (females scoring lower than males in Numerical, but not Verbal CRT). Because Polish versions of some rationality-related measures were not available, we developed them in Study 1b.

Our second aim was to investigate the factor structure of different cognitive abilities and thinking dispositions (Study 2): statistical numeracy, fluid intelligence, and cognitive reflection (verbal and numerical). Previous research demonstrated that they are correlated with each other. It is uncertain whether these measures tap into different constructs and are complementary to each other, or instead, they could be considered redundant. Previous research (Attali & Bar-Hillel, 2020; Erceg et al., 2020) demonstrated that traditional CRT and numeracy tests compose the same latent factor. At the same time, other researchers integrated Verbal CRT items with numerical ones to obtain an index of cognitive reflection (Čavojová et al., 2022; Mikušková & Čavojová, 2020). Moreover, following the idea of general cognitive capacity, Thompson (2021) combined traditional CRT, numeracy, and IQ tests into a single index.

Finally, a recent meta-analysis (Otero, Salgado, & Moscoso, 2022) investigated whether cognitive reflection is an independent factor among other cognitive abilities. This study revealed that cognitive refection variance was mainly accounted for by a general factor of cognitive intelligence plus a small contribution from the numerical ability. Interestingly, despite theoretical arguments, Otero et al. (2022) found no evidence supporting the existence of a cognitive reflection factor. Nevertheless, the number of studies with the Verbal CRT included in this meta-analysis was very small, so these results should be taken with precaution.

Based on the mixture of theoretical and empirical arguments, we intended to investigate the factor structure of Verbal CRT, Numerical CRT, Berlin Numeracy Test (BNT), and fluid intelligence (measured using Raven-like matrices). We compared five models varying in the number of factors: four, three, or one. The first model would contain four correlated factors for each test separately (i.e., Verbal CRT, Numerical CRT, BNT, fluid intelligence). If this model had the best fit, it would suggest that each of these scales load on distinct latent factors, and they could be complementary in explaining human thoughts and behavior.

In the second model, we assumed the existence of a cognitive reflection factor integrating Verbal and Numerical CRT. We based this model on the assumption that they were constructed using a similar approach – puzzles having luring incorrect answers, and to respond correctly, one should inhibit this intuitive response. Nevertheless, we have inconsistent empirical evidence for the existence of this factor. On the one hand, Čavojová et al. (Čavojová et al., 2022; Mikušková & Čavojová, 2020) successfully merged these two tests. On the other hand, the abovementioned meta-analysis by Otero et al. (2022) did not find this cognitive reflection factor.

In the third model, we assumed the existence of three related factors: Verbal CRT, Numeracy, and Fluid Intelligence. This three-factor structure reflects three characteristics of a rational decision maker (Stanovich et al. (2016)). First, the decision makers should detect the conflict between their response and a response that follows a normative rule. Second, they should have appropriate mindware available during a simulation process. Third, they should have sufficient cognitive capacity to sustain simulation and override incorrect responses. This model fits this interpretation: Verbal CRT taps into individual differences in override/conflict detection, Numeracy is related to specialized mindware, and Fluid Intelligence is responsible for processing efficiency. Moreover, Numerical CRT and statistical numeracy share a substantial proportion of variance (Attali & Bar-Hillel, 2020; Erceg et al., 2020; Otero, Salgado, & Moscoso, 2022). We argue that by comparing models in which items from traditional CRT load the same latent factor as Verbal CRT items (i.e., cognitive reflection factor) with a model in which these conventional CRT items load the same latent factor as items from statistical numeracy test (i.e., numeracy factor), we would be able to determine whether traditional CRT taps into cognitive reflection or rather numeracy.

For the fourth model, we did not have strong theoretical and empirical evidence. Nevertheless, we decided to use it as a control model and compare it with the second and third models. Within this model, BNT and Verbal CRT items would be combined into a single latent factor correlated with Numerical CRT and fluid intelligence. We hypothesized that this model fit would be relatively worse than Models 2 and 3.

Finally, we tested whether these specific cognitive abilities could be reduced to one general factor. Stanovich et al. (Stanovich, West, & Toplak, 2011, 2016) argue that standard intelligence tests such as Raven Progressive Matrices or Wechsler Adult Intelligence Scale do not measure adaptiveness, wisdom, or good judgments essential for rationality and decision making. Thus, rationality should be separate from intelligence. If the single-factor model showed the best fit, it would be an argument against this notion and for merging various cognitive tests into a single index (as in Thompson, 2021).

Study 1a

The study aimed to develop a Polish version of Verbal CRT (Sirota et al., 2021) as well as investigate its factor structure and internal consistency.

Method

Participants

The final sample contained 156 psychology students (20 males, 132 females, 4 missing; M_{age} = 26.8; SD_{age} = 8.9). See Supplementary Table S1 for exclusions criteria.

Materials and Procedure

Participants completed ten items from the Verbal CRT (Sirota et al., 2021) in Polish in a random order using an online platform. The items were in an open-ended response format. Original items were back-translated and tested in a pilot study. We decided to slightly modify the meaning of the tenth item (for Polish translation, see Supplementary Table S2). After solving each Verbal CRT item, participants rated their familiarity.

Results

Descriptives

The difficulty (% of correct responses) of items varied from 48.7% (VCRT8) to 83.3% (VCRT5), their intuitiveness (% of incorrect intuitive responses) varied from 14.1% (VCRT5) to 41.7% (VCRT7) and familiarity from 0% (VCRT4) to 19.4% (VCRT6) (see Supplementary Table S2, for details).

Factor structure and internal consistency

We conducted a Confirmatory Factor Analysis using Diagonally Weighted Least Squares (DWLS) estimation (Mîndrilă, 2010)—with a one latent factor using the JASP software (version 0.14; JASP Team, 2020). Despite satisfactory fit of this model $\chi^2(35) = 32.226$, p = .603, RMSEA = .000 (90% CI [0.000, 0.051]); *p*close = .944; TLI = 1.000; SRMR = .062, we decided to exclude two items (VCRT2 & VCRT10) due to their low factor loadings (.119 and .283, respectively). After removing these two items, another CFA was carried out (see Supplementary Table S3). The model containing eight items, fitted well $\chi^2(20) = 15.929$, p = .721, RMSEA = .000 (90% CI [0.000, 0.053]); *p*close = .940, TLI = 1.000, SRMR = .055 and had good internal consistency, McDonald's ω = .714 (.646, .782).

Discussion

We developed a version of the Polish Verbal CRT (Sirota et al., 2021) that contains eight problems (two problems from the original scale were excluded because of low factor loadings). Despite cultural and language differences that may impede the test's psychometric characteristics, we found that a one-factor model containing eight items fitted the data well and had good internal consistency. Moreover, problems had relatively low familiarity and provoked intuitive incorrect responses. However, in the case of some items, we observed popular incorrect responses that were coded as "other" based on the original scoring key. Still, these responses could also be considered intuitive in a Polish context (see the Discussion of Study 2 for a more extensive interpretation of intuitiveness). Our results indicate the test's usefulness for studying individual differences in override/conflict detection. Nevertheless, it is worth noting that this preliminary study was conducted only on a student sample that was not balanced in gender (this was because the vast majority of psychology students in our sample were females).

In the next study (1b), we adapted, to the Polish language and culture, measures of (ir)rational thought that would subsequently be used to test the construct validity of Verbal CRT.

Study 1b

Method

Participants

The final sample contained 220 students (193 females; M_{age}= 25.7, SD_{age} = 7.2 years; see Supplementary Table S1 for exclusions criteria). The post-hoc sensitivity analysis conducted using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) revealed that assuming α = .05 and 1 - β = .80, using the obtained sample size, we were able to detect a small effect (ρ = .19) similar to those observed in other studies on CRT.

Materials and procedure

Participants completed a set of tasks in Polish (see the OSF project https://osf.io/2pcdq/ for exact wording in Polish and English) in a random order using an online platform. This set contained CRT and measures that were shown to be related to cognitive reflection in previous research. Five of these measures were used in the original study on the development of Verbal CRT: Belief Bias, Denominator Neglect, Risk Preference, Time Preference, and Rational-Experiential Inventory (Sirota et al., 2021). The two others were related to superstition (Sosnowski & Wiech, 2006) and religious beliefs (Pennycook et al., 2017).

Numerical Cognitive Reflection Test. Participants completed the seven-item open-ended version of the Cognitive Reflection Test (Toplak et al., 2014). Despite the Polish translation of this test being used in previous research (Czerwonka, 2016; Sleboda & Sokolowska, 2017; Sobkow, Olszewska, et al., 2020), no validated and published version of this test is available in Polish. Thus, we decided to investigate the factor structure and internal consistency of this test. After completing this test, participants were asked to indicate familiarity with the items.

Belief Bias. We used six syllogisms translated from Sirota et al.'s study (2021). In each problem, participants read two premises (e.g., "Premise 1: All things that are smoked are good for the health. Premise 2: Cigarettes are smoked"), a conclusion (e.g., "Conclusion: Cigarettes are good for the health") and were asked to indicate whether the conclusion follows (or does not follow) logically. These items involved a conflict between the logical validity of a syllogism and the believability of the conclusion. The Belief Bias index was recoded in such a way that a higher score indicated more biased judgments.

Denominator Neglect. We used five denominator neglect problems translated from Sirota et al.'s study (2021). In each problem, participants were asked to choose between drawing tickets from two bowls: smaller (e.g., "contains 10 tickets: 1 ticket marked 'winner' and 9 blank tickets") or larger (e.g., "contains 100 tickets: 8 tickets marked 'winner' and 92 blank tickets"). They indicated their preference using a 6-point scale (1 – "I would definitely pick from the small bowl", to 6 – "I would definitely pick from the large bowl"). Denominator neglect appears when people do not pay adequate attention to denominators (the number of all tickets in bowls) but instead focus on numerators (the number of winning tickets) in their judgments. The items were averaged and coded so that the higher the score, the higher the denominator neglect (higher preference for the bowls containing more winning tickets but with a lower probability of winning).

Risk Preference. We used eight risk preference problems translated from Sirota et al.'s study (2021). In each task, participants were asked to indicate whether they prefer the sure (e.g., "£1,000 for sure") or risky option (e.g., "A 90% chance of £5,000"). In a Polish version of the task, participants were presented with rewards in Polish currency. All items were in the gain domain, and risky options had consistently higher expected values than sure options. Risky choices were summed, resulting in an index of risk preference (the higher the score, the higher the risk preference).

Time Preference. We used five items measuring time preference translated from Sirota et al.'s study (2021). In each task, participants were asked to indicate whether they preferred a reward that would be received immediately (e.g., "£3400 this week") or after a delay (e.g., "£3800 in four weeks"). Similarly, participants were presented with rewards in Polish currency. Delayed choices were summed, resulting in an index or time preference (the higher the score, the higher the preference for larger but delayed rewards).

Rational-Experiential Inventory (REI). We used the twenty-four-item version of the Rational-Experiential Inventory (Ayal, Rusou, Zakay, & Hochman, 2015; Pacini & Epstein, 1999) translated by Sleboda and Sokolowska (2017). This questionnaire is based on the cognitive experiential self-theory (Epstein, 1994) that acknowledges the individual differences in two types of processing: experiential (holistic, affective, and more rapid) and rational (analytic, logical, and slow). This inventory contains two main scales: Rational and Experiential. Higher scores indicated higher rational and experiential processing styles, respectively.

Superstition. Because beliefs could be specific to culture, we decided to use a scale measuring superstition that was developed in Poland (Sosnowski & Wiech, 2006). The version of the scale used in this study contained five items, such as "Knocking on unpainted wood results in bad luck,” and participants responded using a four-point scale (from 1 – do not agree to 4 – agree). A higher score indicated higher superstition.

Religious Beliefs Scale. Previous research demonstrated that cognitive reflection is also related to religious beliefs (Pennycook et al., 2017). In this study, we used a Polish translation of the Religious Beliefs Scale by Pennycook et al. (2017). Participants responded to six items (e.g., “There is a life after death”) using a 5-point scale (1 – strongly disagree, 5 – strongly agree). The higher score indicated firmer religious beliefs.

Results

Numerical CRT

In the first step, we decided to analyze the psychometric properties of the numerical CRT items. The difficulty (% of correct responses) of items varied from 30.9% (NCRT1) to 56.8% (NCRT7), their intuitiveness (% of incorrect intuitive responses) varied from 22.3% (NCRT4) to 54.1% (NCRT1) and familiarity from 7.7% (NCRT7) to 27.3% (NCRT1) (see Supplementary Table S4).

We also conducted a Confirmatory Factor Analysis with a one latent factor using DWLS estimation in the JASP software. Despite satisfactory fit of this model $\chi^2(14) = 13.923$, $p = .455$, RMSEA = .000 (90% CI [0.000, 0.065]); *p*close = .850; TLI = 1.000; SRMR = .047, we decided to exclude one item (NCRT6) due to its low factor loading (.157). After removing this item, another CFA was carried out (see Supplementary Table S5). The model containing six items fitted well, $\chi^2(9) = 8.234$, $p = .511$, RMSEA = .000 (90% CI [0.000, 0.071]); *p*close = .825, TLI = 1.000, SRMR = .041, and had good internal consistency, McDonald’s $\omega = .743$ (95% CI [.690, .795]).

Correlations between measures

The six-item version of Numerical CRT was very highly correlated with the original seven-item version of the scale (r = .97, see Supplementary Table S6). Thus, we decided to present and discuss only relationships with a shorter 6-item scale.

Consistent with previous research, we found a moderate correlation between Numerical CRT and Belief Bias (r = -.502; p < .001), weak between CRT and Denominator Neglect (r = -.267; p < .001), Time Preference (r = .258; p < .001), Superstition (r = -.295; p < .001), REI Experiential (r = -.302; p < .001) and very weak between CRT and Risk Preference (r = .160; p = .018). We also found a positive correlation between CRT and REI Rational (r = .261; p < .001). Surprisingly, contrary to Pennycook et al. (2017), cognitive reflection was not related to religious beliefs in our sample (r = -.093; p = .172).

Discussion

We found that the Polish version of the Cognitive Reflection Test fits well with the one-factor model and has good internal consistency. Nevertheless, we decided to drop one item because of the low factor loading. Eliminating this item did not change the pattern of correlations with other rationality-related measures.

Similar to previous research, we found that cognitive reflection was negatively associated with belief bias (Erceg et al., 2020; Sirota et al., 2021; Sirota & Juanchich, 2018), denominator neglect (Sirota et al., 2021; Sirota & Juanchich, 2018), and superstition/paranormal beliefs (Primi et al., 2016; Sirota et al., 2021; Sirota & Juanchich, 2018). Moreover, individuals who scored higher in CRT preferred higher but later rewards (Bialek et al., 2019; Bialek & Sawicki, 2018; Sirota et al., 2021) as well as higher but uncertain rewards (Sirota et al., 2021), which indicates the validity of the Polish translation of the abovementioned measures.

Study 2

Because of the preliminary nature of Study 1a, further research investigating the psychometric characteristics of the Polish version of Verbal was needed. The second study aimed to validate the Polish version of the Verbal CRT developed in Study 1a using a larger, more diverse sample and construct validity measures (designed in Study 1b). Moreover, we also investigated the factor structure of cognitive reflection, numeracy, and fluid intelligence measures by comparing several competing models using Confirmatory Factor Analysis.

Method

Participants

Five hundred and eighty-three (321 females, 55.1%) users of the Polish research panel participated in the study. The sample largely varied in age (from 18 to more than 55 years) and education (from primary to master's degree). We intended to recruit as many participants as possible under the restrictions of the budget. We planned to achieve at least 500 to obtain accurate estimates in the Confirmatory Factor Analysis (Irwing & Hughes, 2018). Sensitivity analysis with G*Power (Faul et al., 2009) showed that assuming $\alpha = .05$ and $1 - \beta = .80$; with the obtained sample size, the study could detect a very small effect size ($\rho = .10$) for a linear correlation, and detect a small effect (Cohen's $d = .21$) for gender differences.

Materials and Procedure

Participants completed a set of measures in a random order containing the eight-item version of Verbal CRT, Numerical CRT, as well as Belief Bias, Denominator Neglect, Time Preference, Rational-Experiential Inventory, and Superstition. Additionally, participants completed a measure of fluid intelligence and solved tasks and questionnaires that tapped into individual differences in numerical cognition: statistical numeracy, subjective numeracy, and math anxiety. Finally, at the end of the study, participants indicated familiarity with Verbal and Numerical CRT items (Supplementary Tables S2 and S4).

Statistical numeracy. We used the Berlin Numeracy Test (BNT; Cokely et al., 2012) as a measure of statistical numeracy. BNT contains four tasks requiring the use of statistical and probability information, such as “Imagine we are throwing a five-sided die 50 times. On average, out of these 50 throws how many times would this five-sided die show odd number?”. Possible scores on the test ranged from 0 to 4 points, with higher scores indicating higher statistical numeracy. The Polish version of this test has been successfully used in multiple studies (e.g., Sobkow, Fulawka, Tomczak, Zjawiony, & Traczyk, 2019; Sobkow, Olszewska, et al., 2020; Sobkow, Zaleskiewicz, Petrova, Garcia-Retamero, & Traczyk, 2020).

Subjective numeracy. Subjective numeracy was measured by the 8-item Subjective Numeracy Scale (Fagerlin et al., 2007). Participants answered each question using a 6-point scale to assess their perceived numerical abilities (e.g., “How good are you at working with percentages?”) and preference for numerical information (e.g., “How often do you find numerical information to be useful?”). Higher scores indicated being more confident with numbers. The Polish version was successfully used in previous research (e.g., Sobkow et al., 2019; Sobkow, Olszewska, et al., 2020; Sobkow, Zaleskiewicz, et al., 2020; Traczyk, Sobkow, et al., 2018).

Math anxiety. We used the Polish version of the Abbreviated Math Anxiety Scale (Cipora, Willmes, Szwarc, & Nuerk, 2018), containing nine items. In each item, participants were asked to indicate their level of anxiety felt when learning math or being tested in math using a five-point scale. Higher scores indicated higher math anxiety.

Fluid intelligence. To measure fluid intelligence, we used four matrix reasoning items chosen from the International Cognitive Ability Resource (ICAR; Condon & Revelle, 2014).

Reasoning problems were presented in the form of three-by-three matrices of elements with one missing element. Participants were instructed to identify the rule underlying the matrix and select one of the six response elements that satisfied the rule. Higher scores indicated higher fluid intelligence.

Results

The validity of the Polish version of Verbal CRT

Correlations. The general pattern of correlations between Verbal CRT and other measures indicated its validity (Table 1). Verbal CRT was positively correlated with Numerical CRT, statistical numeracy, fluid intelligence, Rational scale from REI, subjective numeracy, and Time Preference. Moreover, we observed negative correlations with math anxiety, Belief Bias, Denominator Neglect, and Superstition.

---- Table 1 ----

Next, we compared the correlation coefficients between Numerical and Verbal CRT (Supplementary Table S7). Importantly, correlations with measures related to numeric competencies and math emotions were significantly weaker for Verbal CRT than for Numerical CRT. Moreover, we found no significant difference for Superstition. However, even though Verbal CRT was significantly correlated with Belief Bias, Denominator Neglect, Time Preference, these correlation coefficients were significantly weaker than those for Numerical CRT.

Gender differences. We found that females scored significantly lower than males on Numerical CRT (M_{females} = 1.42; SD_{females} = 1.58; M_{males} = 2.34; SD_{males} = 1.98; $t(581) = 6.225$, $p < .001$, $d = 0.518$) but not in Verbal CRT (M_{females} = 3.19; SD_{females} = 2.43; M_{males} = 3.41; SD_{males} = 2.56; $t(581) = 1.067$, $p = .286$, $d = 0.089$). Additionally, we have conducted the "two-one-sided t-test” procedure for gender differences in Numerical CRT and Verbal CRT

(TOST, Lakens, 2017). We assumed the smallest effect size of interest as d = 0.3, and determined the upper and lower equivalence bound as d = -0.3 and d = 0.3. The analysis revealed that, in the case of Verbal CRT, the effect of gender is not significantly different from zero but also not equal to zero. However, in the case of Numerical CRT we observed clear evidence that the effect is not only significantly different from zero but also not equal to zero (Supplementary Figures S1 & S2). Finally, for Verbal CRT we found partial scalar invariance across the gender (for details, see Supplementary Table S8)

The factor structure of cognitive abilities and thinking dispositions

Finally, we investigated the factor structure of cognitive abilities and thinking dispositions. Using Confirmatory Factor Analysis and DWLS estimation method, we compared five models that included separate items (coded as 0 – incorrect response, 1 – correct response). In all tested models, we allowed for covariances between latent factors, and all variables were standardized. In the first model, all items were linked to four factors according to the scales that they were taken from: Verbal CRT, Numerical CRT, Berlin Numeracy Test, and International Cognitive Ability Resource. This model fitted well, $\chi^2(203) = 156.923$, $p = .993$, RMSEA = .000 (90% CI [0.000, 0.000]); *p*close = 1.00; TLI = 1.000; SRMR = .033.

Nevertheless, we intended to build the most parsimonious model. Thus, we defined and tested four other models: Model 2, in which items from Numerical and Verbal CRT were included as one latent variable (Cognitive Reflection), Model 3 in which Numerical CRT and statistical numeracy items composed one latent variable (Numeracy), and Model 4 in which Verbal CRT and Berlin Numeracy Test composed one latent variable. Finally, we tested Model 5, in which all task-based individual differences items composed one latent factor

(Cognitive Ability). The fits of Models 2, 4, and 5 were worse than Model 1 (Table 2)[2]. Nevertheless, Model 3's (with Numerical CRT and statistical numeracy as one factor – Numeracy, see Figure 1) fit was equally good as Model 1: $\chi^2(206) = 161.773$, $p = .990$, RMSEA = .000 (90% CI [0.000, 0.000]); *p*close = 1.00; TLI = 1.000; SRMR = 0.034. Thus, we decided to choose a simpler model.

---- Table 2 ----

---- Figure 1 ----

Discussion

Two main conclusions could be drawn from Study 2. First, the Polish version of Verbal CRT exhibits good validity and internal consistency (nevertheless, we observed some issues with the coding scheme of the intuitive responses that might be prone to cultural context). Second, the most parsimonious and well-fitted model contained three latent factors: Verbal CRT, Numeracy (composed of items from BNT and Numerical CRT), and Fluid Intelligence.

In our research, we used the most common method for scoring the CRT (the sum of correct responses). Nevertheless, for some researchers, the number of intuitive errors or the proportion of intuitive (heuristic) among all incorrect responses could be equally important (Erceg & Bubić, 2017). We found very strong negative correlations between the two scoring procedures: the sum of correct responses and a sum of incorrect intuitive responses. Moreover, the general pattern of correlations between reflectiveness and intuitiveness scores

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[2] We also compared models using the Satorra-Bentler method (Scaled Difference in χ^2s - SDCS; Brown, 2015;). See Supplementary Table S9 for results. We found significant differences between Model 1 and Model 2 ($T_S(3) = 46.12$; $p < .001$), Model 4 ($T_S(3) = 67.16$; $p < .001$), as well as Model 5 ($T_S(6) = 78.29$; $p < .001$). Importantly, the difference between Model 1 and Model 3 was not statistically significant, $T_S(3) = -17.52$; $p = 1.00$.

and other measures was largely the same (see Supplementary Table S10). Thus, the intuitiveness score of the Polish version of Verbal CRT suggests similar construct validity as the reflectiveness score.

On the other hand, after a careful inspection of the incorrect responses, we found that in the case of the Polish version of Verbal CRT, in six out of eight items, the majority of incorrect responses were coded as intuitive based on the original scoring key. We found alternative responses in the two remaining items that may also be considered intuitive. In particular, in the case of VCRT3, many participants indicated that survivors should be buried "where their family decides" or "in their homeland" (in the original scoring key, only "USA" was coded as an intuitive answer). While in the VCRT9 item, many Polish participants gave a "yes" response to a question: "Would it be ethical for a man to marry the sister of his widow?". There are differences between countries in the foundations of their moral judgments (Graham et al., 2011; Haidt, Koller, & Dias, 1993) that can probably affect intuitive responses. For example, it might be acceptable for some people to marry the sister of a former (deceased) wife, and some non-reflective participants could understand this item in that way. The differences between cultures and languages may affect intuitive responses; thus, researchers for whom this index is significant could consider revising a scoring key for intuitive incorrect responses. Nevertheless, we argue that these differences do not influence the reflectiveness score and our main conclusions.

Despite language and cultural differences as well as a shorter form of the test, the pattern of relationships observed for the Polish version of Verbal CRT was largely the same as in the original version of the test (Sirota et al., 2021). In particular, Verbal CRT (the reflectiveness score) was negatively related to measures of (ir)rationality: Belief Bias, Denominator Neglect, Superstition, and positively with Time Preference and self-report rationality. Importantly, even when we observed significant correlations with math-related measures (statistical numeracy, subjective numeracy, and math anxiety), they were significantly weaker than those for Numerical CRT. Moreover, similarly to previous research (Juanchich et al., 2020; Sirota et al., 2021), we found a significant gender difference in performance in the Numerical CRT (with males scoring significantly higher than females). Still, there was no such clear difference for Verbal CRT. It is worth highlighting that the "two-one-sided t-test" procedure showed that the difference between women's and men's scores is not significantly different from zero nor equivalent to zero. For meaningful interpretation of the gender differences, we also established measurement invariance for Verbal CRT. The results showed partial scalar invariance across the gender. Despite some limitations, Verbal CRT (in both the original and Polish versions) seems to be a good measure of cognitive reflection that is less contaminated with numerical abilities and emotions than the traditional—numerical—CRT.

Similar effects were also present when we analyzed the structure of our main variables. Because we intended to build the simplest model, we merged Numerical CRT items with Verbal CRT (Cognitive Reflection factor, Model 2) or with Berlin Numeracy Test items (Numeracy factor, Model 3). When Numerical CRT was a part of Numeracy, the model fitted the data better than when it was a part of Cognitive Reflection. Thus, we replicated previous findings (Attali & Bar-Hillel, 2020; Erceg et al., 2020), showing that CRT and math-related measures are empirically indistinguishable and compose one latent factor. These results indicate that the traditional—numerical—CRT taps into aspects of rationality related to knowledge to a greater extent than the process.

General Discussion

The present research had two main aims: to validate the Polish version of the Verbal CRT and to investigate the factor structure of numeracy, cognitive reflection, and fluid intelligence measures. The main findings summarizing the psychometric properties of our instrument in the context of previous research can be found above (the Discussion of Study 2). In the

General Discussion, based on the several theoretical models (e.g., the tripartite model, the Cattel-Horn-Carroll model of cognitive abilities, and the skilled decision theory), we will provide an interpretation of the best model describing the factor structure of cognitive abilities and thinking dispositions. Finally, we will discuss limitations, directions for future research, and practical implications of our results.

Interpretation of structural models

In the present research, we found that the best model (the most parsimonious but still well fitted) included three factors: Verbal CRT, Numeracy, and Fluid Intelligence. Importantly, we decided to choose this model, relying not only on the empirical evidence but also on the theoretical arguments.

We argue that this three-factor structure, on the one hand, reflects three characteristics of a rational decision maker postulated by Stanovich et al. (2016): Verbal CRT taps into individual differences in override/conflict detection, Numeracy is related to specialized mindware, and Fluid Intelligence is responsible for processing efficiency. On the other hand, these three factors are also consistent with the Cattell-Horn-Carroll model (McGrew, 2009) – one of the most acknowledged models on the structure of cognitive abilities. In the second striatum of this model, among other broad abilities, one could find Fluid reasoning (“use of deliberate and controlled mental operations to solve novel problems that cannot be performed automatically”, p.5), Comprehension-knowledge (“breadth and depth of acquired knowledge of the language, information, and concepts of a specific culture”, p.5) and Quantitative knowledge (“store of acquired mathematical knowledge, not reasoning with this knowledge”, p. 5). We could find some similarities between these three broad abilities and the results of our study: Fluid reasoning resembles the Fluid intelligence factor, Comprehension-knowledge could be related to Verbal CRT, and, Quantitative knowledge to Numeracy factor.

Nevertheless, this conceptual fit is not perfect, and we argue both Numeracy and Verbal CRT tap skills going beyond those measured by classic intelligence tests.

For example, in their skilled decision theory, Cokely et al. (2018) proposed that the Decision Making Skill should be placed in the second stratum of Carroll's model, next to other broad cognitive abilities. The Decision Making Skill is based on "practical logical inductive reasoning skills" and statistical numeracy. Cokely et al. (2018) argue that cognitive processes in people with high statistical numeracy go beyond performing calculations and resample those that could be observed in experts. In particular, during problem solving (or decision making), they draw from vast amounts of knowledge chunks stored in the long-term memory (instead of precisely and iteratively calculating all the possible outcomes) that enable them to overcome limitations of working memory capacity. Moreover, according to this theory, people with higher statistical numeracy are metacognitively savvy - they accurately evaluate and integrate thoughts, feelings, and values as well as monitor and calibrate their confidence.

Interestingly, in all of the abovementioned effects, numeracy was measured using math tests in which participants were asked to calculate correct responses. However, according to Peters et al. (Peters, 2020; Peters & Bjälkebring, 2015), this approach is insufficient and taps into only one numeracy aspect – objective numeracy. They argue that besides objective numeracy, decision making also depends on subjective assessment of numeric competencies and approximate numeracy related to evolutionarily old number sense.

Subjective numeracy may be described as a self-representation of "me as a math person"/"me as not a math person" (Peters, 2020) and regulate motivation to solve numerical problems. People with lower subjective numeracy may avoid numerical information and may not engage in processing it. Despite the good predictive power of the Subjective Numeracy Scale (which goes beyond measures of objective numeracy), it is not clear what is an "active ingredient" in this instrument (e.g., numeric self-efficacy, math self-concept, or rather math anxiety). Thus, further research should disentangle these mechanisms and develop measures that could provide a more precise interpretation of the results.

Finally, decision making may also depend on the third type of numeric competencies – approximate numeracy (or ANS acuity; Peters, 2020; Peters & Bjälkebring, 2015). Approximate numeracy reflects the intuitive and imprecise sense of numeric magnitudes. Although the measure of approximate numeracy was not included in the present study, recent research has demonstrated its good predictive power (especially for real-life outcomes, see, for example, Sobkow, Olszewska, et al., 2020 and Sobkow, Zaleskiewicz, et al., 2020). Thus, future research and theoretical models should try to include this ability as well.

Limitations

In this research, we aimed to address some limitations that were stressed in the original work (Sirota, et al., 2021). For example, we have included a large sample of non-English-speaking participants, and we have conducted a preliminary study to adapt Verbal CRT items. Nevertheless, this investigation still suffers several limitations. First, as mentioned above, researchers adapting Verbal CRT (or using our adaptation of a test) should be careful when interpreting intuitiveness scores or could consider developing new scoring keys for intuitive incorrect responses. The intuitive aspects seem to depend more on culture or language than reflective ones. Moreover, the current study was conducted in Poland, and further studies should also aim to replicate these effects in more distant (non-WEIRD: Western, Educated, Industrialized, Rich, & Democratic; Henrich, Heine, & Norenzayan, 2010) and non-Christian cultures such as India, China, and South Africa.

Second, contrary to the original study, we found only partial invariance between genders in the Polish version of Verbal CRT. Moreover, we did not find clear evidence for the lack of gender differences in Verbal CRT. Nevertheless, in the case of Numerical CRT, these differences were evident. Thus, we argue that results in the Numerical CRT seem to be biased by the participants' gender, while in the case of the Polish version of Verbal CRT, this bias is probably diminished. Future research should aim at better understanding differences in the gender gap between different measures of cognitive reflection.

Third, to achieve a large and diverse sample allowing for complex analyses, we have conducted our study using an online setting using a commercial research panel. Despite the benefits, this approach also had some disadvantages. For example, we used a public-domain measure of intelligence (ICAR) that could be used in online research. Moreover, the study contained eleven quite demanding and long-lasting measures. For brevity, we decided to use only four items from the ICAR (those available in the supplementary materials; Condon & Revelle, 2014). Nevertheless, researchers who want to delve into the relationships between numeracy, cognitive reflection, fluid intelligence, and other domain-specific cognitive abilities should consider using more advanced and comprehensive measures, preferably in the laboratory setting.

Finally, the design of our studies could also be improved in several ways. For example, one could use the CRT version developed by Primi et al. (2016), which might be better for younger and less educated samples than the version of the CRT by Toplak et al. (2014), or could consider non-randomized order of tasks. In our design, some participants could complete math anxiety or subjective numeracy measures just after solving the difficult Berlin Numeracy Test, which might affect the results of these self-report scales. Nevertheless, we argue that these changes should not influence our general pattern of results. Primi et al.'s test is still based on processing numerical information. At the same time, even though SNS and AMAS scales were affected by the previous exposure to BNT, this effect was random, so the order of measures should not affect our main conclusions.

Practical implications

Besides theoretical insights, our research could also have important practical implications. For example, it may help researchers choose adequate measures for their studies. In particular, we found that traditional—numerical—CRT is not a pure measure of the ability to detect and override conflict but rather a mixture of numeracy and cognitive reflection. Nevertheless, suppose one is not interested in a deep understanding of psychological mechanisms and only wants to control individual differences using a single measure. In that case, the Numerical CRT (particularly the version by Primi et al., 2016, developed using the Item Response Theory and validated in diverse samples) is probably the best choice. However, researchers who aim to delve into cognitive processes and disentangle the effects of numeracy from cognitive reflection could use a numeracy measure that does not encompass luring items (for example, the Berlin Numeracy Test) and the Verbal CRT.

Conclusions

In the present studies, we have investigated the generalizability of the effects of Verbal CRT in a Polish population. Our results showed that the Polish adaptation of Verbal CRT is a valid measure of cognitive reflection: it predicted various measures of (ir)rational thought, but simultaneously it was less contaminated with math-related abilities and emotions than traditional CRT. Nevertheless, researchers should be careful when interpreting intuitive responses in this test because they might be prone to cultural differences.

Additionally, our studies shed new light on this topic by providing evidence about the structure of these abilities and thinking dispositions. We found the support for the three-factor model of cognitive abilities and thinking dispositions: Verbal CRT, Numeracy (composed of the items from the Berlin Numeracy Test and traditional—numerical—CRT), and Fluid intelligence. This knowledge may help researchers better understand why different individuals act more or less rationally and design tailored interventions.

Disclosure statement

No potential competing interest was reported by the authors.

IRB Statement

This research was approved by the Ethical Committee at Wroclaw Faculty of Psychology, SWPS University (Poland)

Data availability statement

The data that support the findings and exact wording of materials (in Polish and in English) are openly available in the Open Science Framework platform at https://osf.io/2pcdq/.

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Table 1. Pearson's correlations among measures used in Study 2.

	Variable	M (SD)	McDonald's ω (95% CI)	1	2	3	4	5	6	7	8	9	10	11
1	Verbal CRT	3.29 (2.49)	.799 (.775, .824)	—										
2	Numerical CRT	1.83 (1.83)	.767 (.738, .797)	.48***	—									
3	Statistical numeracy (BNT)	0.86 (1.09)	.607 (.553, .660)	.38***	.63***	—								
4	Fluid intelligence (ICAR)	1.48 (1.19)	.487 (.419, .554)	.28***	.48***	.36***	—							
5	REI Rational	40.42 (6.16)	.806 (.782, .829)	.19***	.36***	.30***	.19***	—						
6	REI Experiential	40.17 (6.28)	.825 (.804, .846)	.04	-.09*	-.10*	<.01	.27***	—					
7	Math anxiety (AMAS)	24.43 (8.39)	.910 (.899, .921)	-.24***	-.38***	-.34***	-.18***	-.47***	-.02	—				
8	Subjective numeracy (SNS)	30.19 (8.84)	.836 (.817, .856)	.17***	.44***	.35***	.24***	.45***	-.06	-.40***	—			
9	Belief Bias	5.13 (2.05)	.661 (.621, .701)	-.27***	-.40***	-.36***	-.25***	-.13**	.11**	.11**	-.26***	—		
10	Denominator Neglect	2.61 (1.22)	.805 (.779, .830)	-.28***	-.36***	-.33***	-.16***	-.17***	.13***	.20***	-.25***	.23***	—	
11	Superstition	11.66 (4.27)	.896 (.883, .909)	-.25***	-.30***	-.25***	-.17***	-.15***	.11**	.19***	-.24***	.25***	.21***	—
12	Time Preference	1.53 (1.53)	.716 (.681, .752)	.15***	.31***	.28***	.18***	.22***	-.02	-.15***	.23***	-.20***	-.12**	-.21***

Note: * $p < .05$; ** $p < .01$; *** $p < .001$

Table 2. Model comparison of the structure of cognitive abilities and thinking dispositions.

	χ^2	RMSEA	TLI	SRMR	Standardized estimates between latent factors
Model 1 (Four factors): • Verbal CRT • Numerical CRT • Statistical numeracy • Fluid intelligence	$\chi^2(203) = 156.923$, $p = .993$	RMSEA = .000 (90% CI [0.000, 0.000]); *p*close = 1.00	1.000	0.033	Verbal CRT ↔ Numerical CRT = .618 Numerical CRT↔ Statistical numeracy = .921 Numerical CRT↔ Fluid intelligence = .755 Verbal CRT↔ Statistical numeracy = .556 Verbal CRT↔ Fluid intelligence = .449 Statistical numeracy ↔ Fluid intelligence = .646
Model 2 (Three factors): • Cognitive Reflection: Verbal CRT + Numerical CRT • Statistical numeracy • Fluid intelligence	$\chi^2(206) = 526.986$, $p < .001$	RMSEA = .052 (90% CI [0.046, 0.057]); *p*close = 0.293	0.949	0.061	Cogitive Reflection ↔ Statistical numeracy = .793 Cognitve Reflection ↔ Fluid intelligence = .660 Statistical numeracy ↔ Fluid intelligence = .645
Model 3 (Three factors): • Verbal CRT, • Numeracy: Statistical numeracy + Numerical CRT • Fluid intelligence	$\chi^2(206) = 161.773$, $p = .990$	RMSEA = .000 (90% CI [0.000, 0.000]); *p*close = 1.00	1.000	0.034	Numeracy ↔Verbal CRT = .610 Numeracy ↔ Fluid intelligence = .735 Verbal CRT↔ Fluid intelligence = .449
Model 4 (Three factors): • Verbal CRT + Statistical numeracy • Numerical CRT • Fluid intelligence	$\chi^2(206) = 432.849$, $p < .001$	RMSEA = .043 (90% CI [0.038, 0.049]); *p*close = 0.970	0.964	0.057	Numerical CRT↔Verbal CRT + Statistical numeracy = .764 Numerical CRT↔ Fluid intelligence = .757 Verbal CRT + Statistical numeracy ↔ Fluid intelligence = .557
Model 5 (One factor): • Verbal CRT, Numerical CRT, Statistical numeracy, Fluid intelligence	$\chi^2(209) = 582.935$, $p < .001$	RMSEA = .055 (90% CI [0.050, 0.061]); *p*close = .046	0.942	0.064	-

Note: All of the variables were standardized.

Figure 1. The three-factor model of cognitive abilities $\chi^2(206) = 161.773$, $p = .990$, RMSEA = .000 (90% CI [0.000, 0.000]); *p*close = 1.00; TLI = 1.000; SRMR = 0.034.