Supplementary materials to a paper

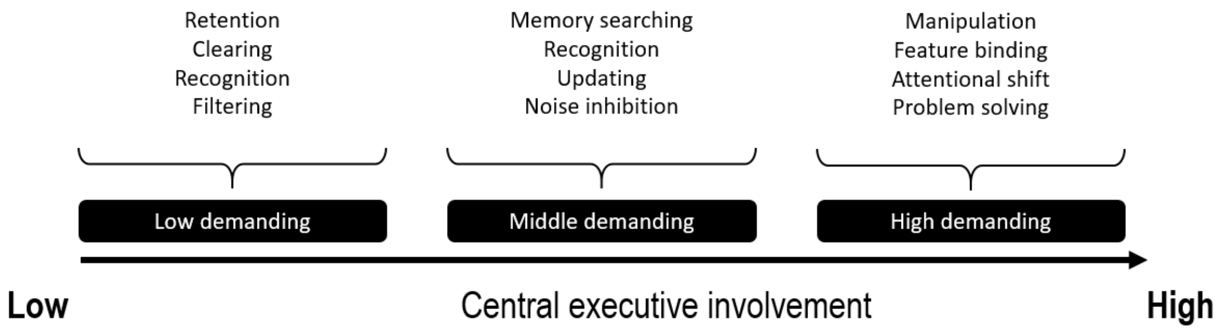
N. Otstavnov, E. Voevodina, S. Mening, R. Urazaeva, T. Fedele (2024). New working memory paradigm for neuroimaging testing of visual and verbal modality under different attentional involvement. *The Psychology. Journal of Higher School of Economics.*

Theoretical assumptions under the paradigm

In order to investigate and isolate the activity of Central Executive (CE), we need to vary the task workload and the amount of resources essential for successful task completion. In particular, one can assume that increasing cognitive load of higher demanding processing operations involve broader resources of CE, which can make its activity trackable (Garavan, 2000). Among processing operations we can name retention, manipulation (Masse et al., 2019) (such as mental rotation or letter alphabetization) (Cannon et al., 2005), recognition (Bledowski et al., 2012), updating, attentional shifting, inhibition of the influence of irrelevant stimulus (Collette & Van Der Linden, 2002), reasoning, problem solving (Logie, 2016), memory search (Vergauwe & Cowan, 2015), filtering the irrelevant information (Conway et al., 2008), multi-modal feature binding (Oberauer, 2005). Such operations can be split into lower demanding operations, which mostly requires passive maintenance of information and a low control from the CE, and high-demanding operations, as the active reorganization (manipulation) of memory representations (D’Esposito et al., 1999; Veltman et al., 2003). Thus, we can place them in one-dimensional scale mapping low to high CE involvement (Supplementary figure 1).

Supplementary figure 1

Processing operations with the corresponding level of central executive engagement



Note. It is important to note that the levels of demand depends on the number of items in working memory.

Based by this schema, we selected a low and a high demanding operation: filtering (maintenance) and manipulation for visual and verbal modalities. In particular, in the low demanding task we asked participants to filter either visual or verbal information from a complex stimulus representation. In the high demanding task, we asked participants to manipulate visual and verbal information by mental rotation or alphabetization, respectively (Davis et al., 2018).

Methods

Selection of cues

Both pro- and retro-cues were presented for 0.5s (Schneider et al., 2016). We aimed to have clear and easy to interpret cues for the task. Thus, we employed visual cues (pictograms) to indicate condition types. Instead of reading a text or a word with automatic processing of it in the same working memory (WM), visual cues allowed simply recognizing the condition and decreasing the task-irrelevant load. We used simplest visual cues that were associated with the condition requirements (Xu & Chun, 2006). Pictograms were taken from the platform *flaticon.com*.

We choose the following cues to indicate task conditions:

- eye – perception condition;
- brain – memorization condition;
- odd letter "A" – simple verbal condition (memorize sequence of letters);
- "navigation" – simple visual condition (memorize spatial location);
- first and last alphabetic letters with arrow "А -> Я" – complex verbal condition (reorder the sequence alphabetically);
- array with 90 degree turn - complex visual condition (rotate the matrix).

Odd letters were used in order not to interfere with the stored consonants letters in WM.

Selection of letters

For the task, we selected Cyrillic letters of equal or approximately equal visual and acoustic complexity. All letters, which can be confused with Latin letters or other symbols (digits), were deleted (Ч – 4, Х – X, З – 3, В – Б, Р – R, С – Ц, Н – Х). We avoid letters, which have additional mounted or protruding elements (Щ, Ц) or contain the parts of another letters (Ь – Ы), as they increase the perception time, which can potentially affect the memorization because of their graphical complexity (Алексеева, 2016). We used Cyrillic letters because the target audience of the experiment were Russian-speaking adults.

In the matrix, we avoid pairing letters, which have phonological (В – Ф, К – Г, Т – Д, Ш – Ж, Г – Т) or visual similarity (П – Г, Г – Т, М – Л, Л – Д), or significant differences in their usage in language (Ляшевская, Шаров, 2009). We also excluded first consonant letter (Б) from the stimulus pool as for participants it would be much easier to order alphabetically this letter than others would. In order to decrease the probability of confusing letters "П" and "Л", we used the font "Century Gothic". Final sample contained 10 letters (ТЛКМ ДПГЖ ШФ).

The formation of incorrect probe for complex verbal condition required to exclude evident obvious answers when the last alphabetic letters (ШФ) are demonstrated in the first places (Ш - - - , - Ш - -) or vice versa. We avoid such situations by creating a rule, when the whole letter set is divided to four groups (ГД-

ЖКЛ-МПТ-ФШ) and letters from one group are never presented in more than one group away (“Г – – – “ and “ – Г – – “ is correct, while “– – Г –“ and “– – – Г” are not).

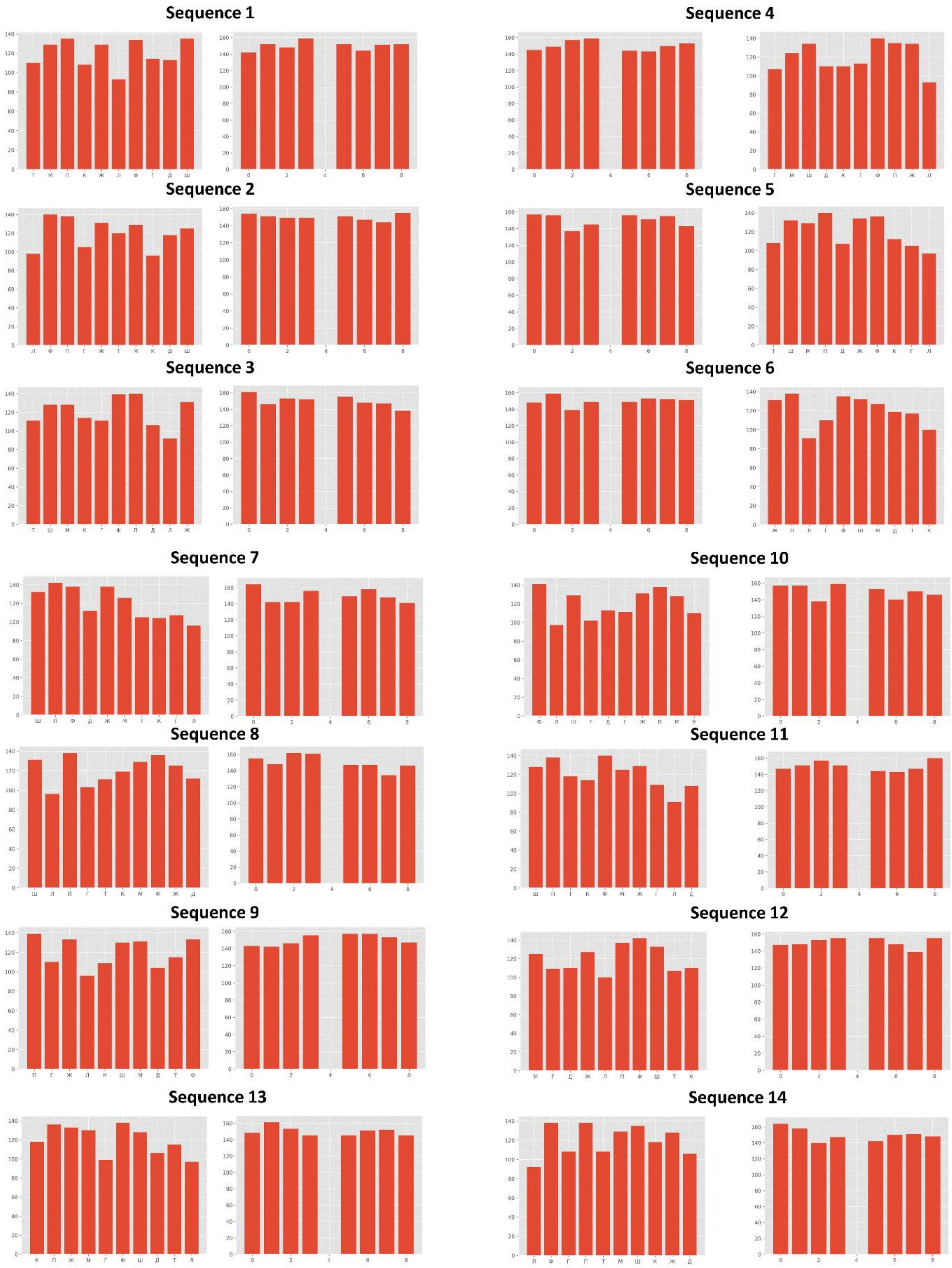
Requirements for the stimulus set

We imposed several requirements to the final stimulus set. (1) Central cell should never include target letters, as it does not change in the visual domain during rotation (rotation is happening about the central cell) and because it is located in the center of visual field, which can ease the memorization and creates a bias (Алексеева, 2013). (2) The sequence should never include letters of adjacent sounds or visual similarity (Г – К, Г – Т, Л – Д, Т – Д, Ш – Ж, К – Л, Л – М) (Baddeley, 1992; Saito et al., 2008). (3) Two consecutive matrices should have no repetitions of letters and no more than two coinciding cells. (4) Half of the probes should be correct and half – incorrect. (4) Spatial patterns with squares in the corner or only corner cells or a cross should be excluded. (5) Matrices should not include frequently used combinations of letters, which can form acronyms and thus bias memorization.

Stimulus quality assessment

The quality of the stimulus set was evaluated by the criterion of the usage of letter and matrix cells in a balanced way. If any letter or cell appeared in the generated stimulus set more frequently than the two standard deviation of the set average, the whole stimulus set was rejected. Additionally, we visually checked the frequency of each letter and cell usage and included to the final stimulus material only those sets, which have the most balanced histograms (Supplementary figure 2).

Balance for letter and cell usage for stimulus set



Dealing with guesses

We conducted a repeated measures analysis for correct responses in each condition. We deleted responses faster than 400ms as they were considered as a guess rather than a retrieval (Llorens et al., 2023). Additionally we conducted the analysis with less conservative cutoff interval of 300ms, however, the results remained the same (only one correct response changed in simple verbal condition). Table 1 represents the outcomes of the post-hoc comparison.

- Accuracy: Modalities ($F_{(1,31)} = 8.77$, $p_{GGcorrected} < 0.01$); Load ($F_{(1,31)} = 57.63$, $p_{GGcorrected} < 0.01$); interaction ($F_{(1,31)} = 4.85$, $p_{GGcorrected} = 0.04$);
- Median response time: Modality ($F_{(1,31)} = 41.37$, $p_{GGcorrected} < 0.01$); Load ($F_{(1,31)} = 143.15$, $p_{GGcorrected} < 0.01$); interaction ($F_{(1,31)} = 5.60$, $p_{GGcorrected} = 0.02$)).

Table 1

Post hoc comparisons for the accuracy and response times with 300 ms cutoff interval

Condition A	Condition B	T value	P value
	Accuracy		
Simple verbal	Simple visual	-0.66	0.99
Complex visual	Simple visual	-4.60	< 0.01**
Complex verbal	Simple verbal	-7.54	< 0.01**
Complex verbal	Complex visual	-3.61	0.01**
	Response time		
Simple verbal	Simple visual	4.67	< 0.01**
Complex visual	Simple visual	7.09	< 0.01**
Complex verbal	Simple verbal	10.63	< 0.01**
Complex verbal	Complex visual	5.67	< 0.01**

Note. Asterisk indicates p-value equal or less than 0.05, double asterisks indicates p-value less than 0.01.

Normality testing and data transformation

Original accuracy values did not follow Gaussian distribution. Normality (Shapiro-Wilk test) was violated in two conditions: $W_{simple\ visual} = 0.92$ ($p = 0.03$), $W_{simple\ verbal} = 0.87$ ($p < 0.01$), $W_{complex\ visual} = 0.94$ ($p = 0.08$), $W_{complex\ verbal} = 0.94$ ($p = 0.07$). Normality test based on the skew and kurtosis confirmed the normality violation ($Z_{simple\ visual} = 5.20$, $p = 0.07$; $Z_{simple\ verbal} = 10.56$, $p < 0.01$; $Z_{complex\ visual} = 2.95$, $p = 0.23$; $Z_{complex\ verbal} = 4.44$, $p = 0.11$) (D'Agostino, 1971).

Original median response values partly followed Gaussian distribution. Normality (Shapiro-Wilk test) was violated in one conditions: $W_{simple\ visual} = 0.93$ ($p = 0.06$, $W_{simple\ verbal} = 0.94$ ($p = 0.06$), $W_{complex\ visual} = 0.86$ ($p < 0.01$), $W_{complex\ verbal} = 0.97$ ($p = 0.46$)). Normality test based on the skew and kurtosis confirmed the normality violation ($Z_{simple\ visual} = 3.41$, $p = 0.18$; $Z_{simple\ verbal} = 9.21$, $p = 0.01$; $Z_{complex\ visual} = 23.92$, $p < 0.01$; $Z_{complex\ verbal} = 4.95$, $p = 0.08$) (D'Agostino, 1971).

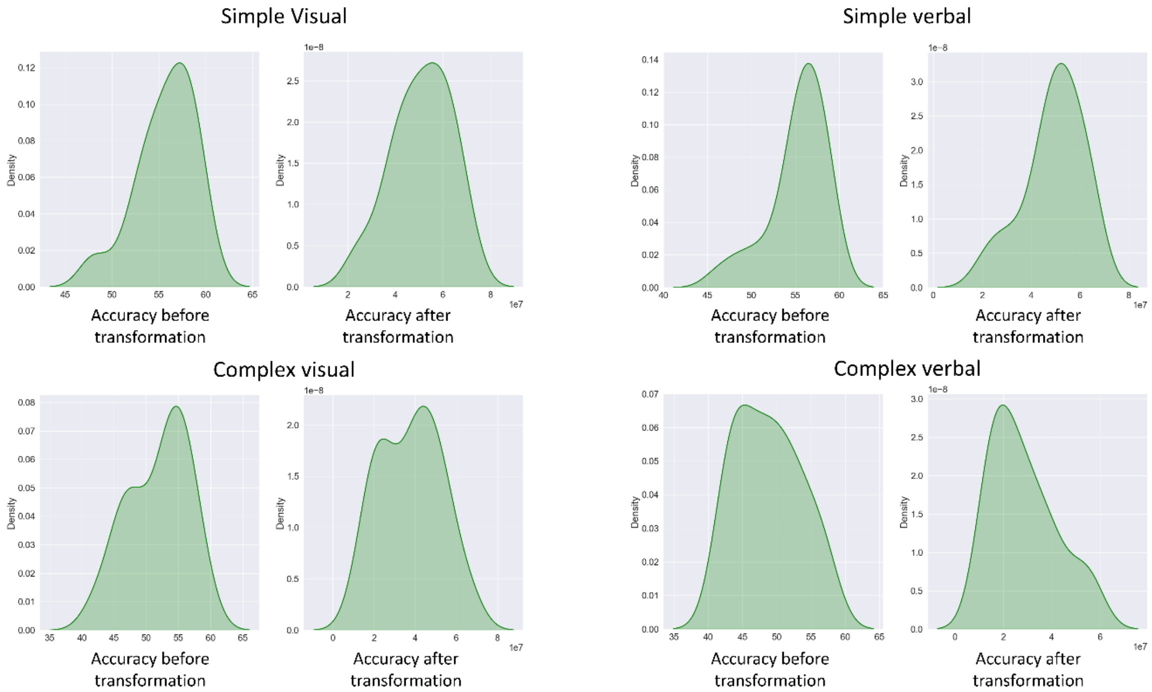
In order to apply analysis of variance we transformed data with Box-Cox transformation in a way that accuracy and median response time follow approximately normal distribution. We applied scipy.stats.boxcox function from scipy package (1.10.0) for accuracy (log-likelihood = 4.80) and response time (log-likelihood = -0.76) remaining default lambda. After transformation both the accuracy data and median response time followed the normal distribution (accuracy: $Z_{simple\ visual} = 1.23$, $p = 0.54$; $Z_{simple\ verbal} = 3.63$, $p = 0.16$; $Z_{complex\ visual} = 3.07$, $p = 0.21$; $Z_{complex\ verbal} = 3.57$, $p = 0.17$; response time: $Z_{simple\ visual} = 1.03$, $p = 0.59$; $Z_{simple\ verbal} = 1.15$, $p = 0.56$; $Z_{complex\ visual} = 0.79$, $p = 0.67$; $Z_{complex\ verbal} = 1.84$, $p = 0.40$).

Homogeniety (Levene's test) was not violated for both accuracy and response time ($W_{accuracy} = 1.01$, $p = 0.39$; $W_{response\ time} = 0.51$, $p = 0.67$). Sphericity (Mauchly's test) was not violated: $\chi_{accuracy}{}^{2}{}_{(5)} = 2.64$, $p = 0.75$; $\chi_{response\ time}{}^{2}{}_{(5)} = 7.67$, $p = 0.18$. Thus, we decided to proceed with parametric statistical methods.

Accuracy density for each condition before and after transformation are depicted in Supplementary figure 3. Response time density for each condition before and after transformation are depicted in Supplementary figure 4.

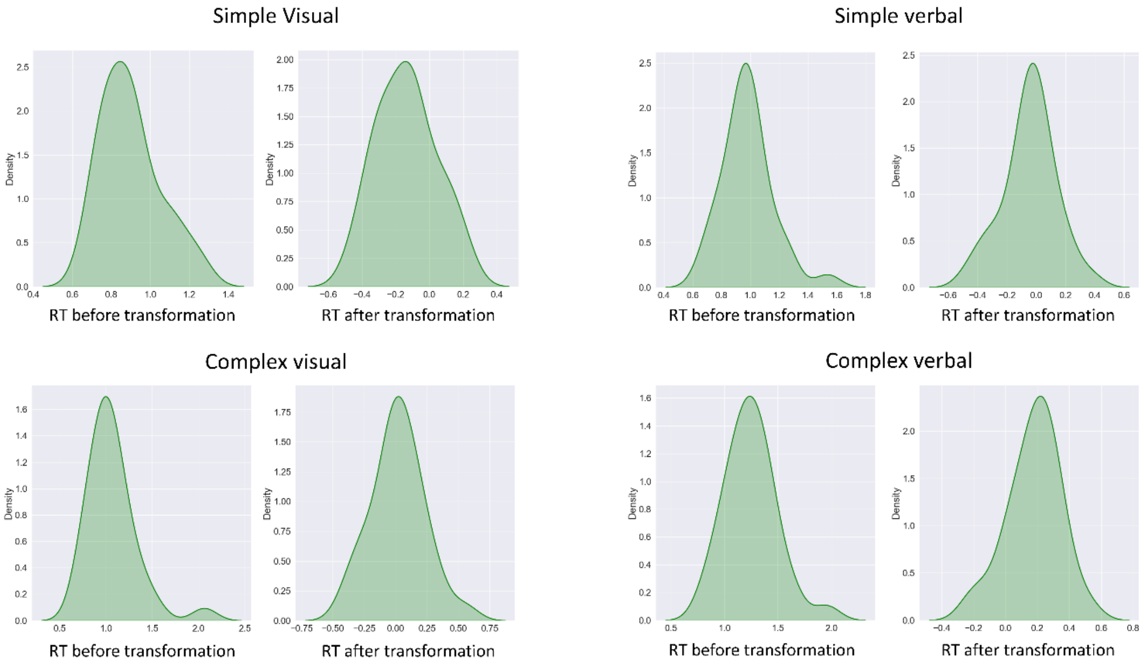
Supplementary figure 3

Accuracy density for each condition



Supplementary figure 4

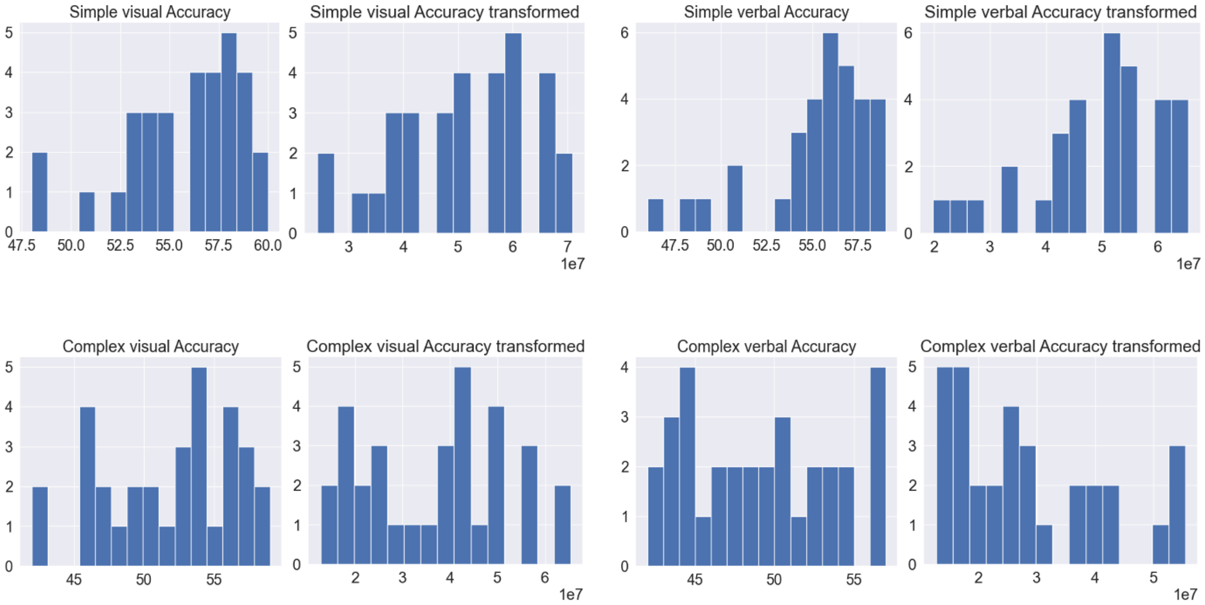
Median response time density for each condition



Accuracy histogram for each condition before and after transformation are depicted in Supplementary figure 5. Response time histogram for each condition before and after transformation are depicted in Supplementary figure 6.

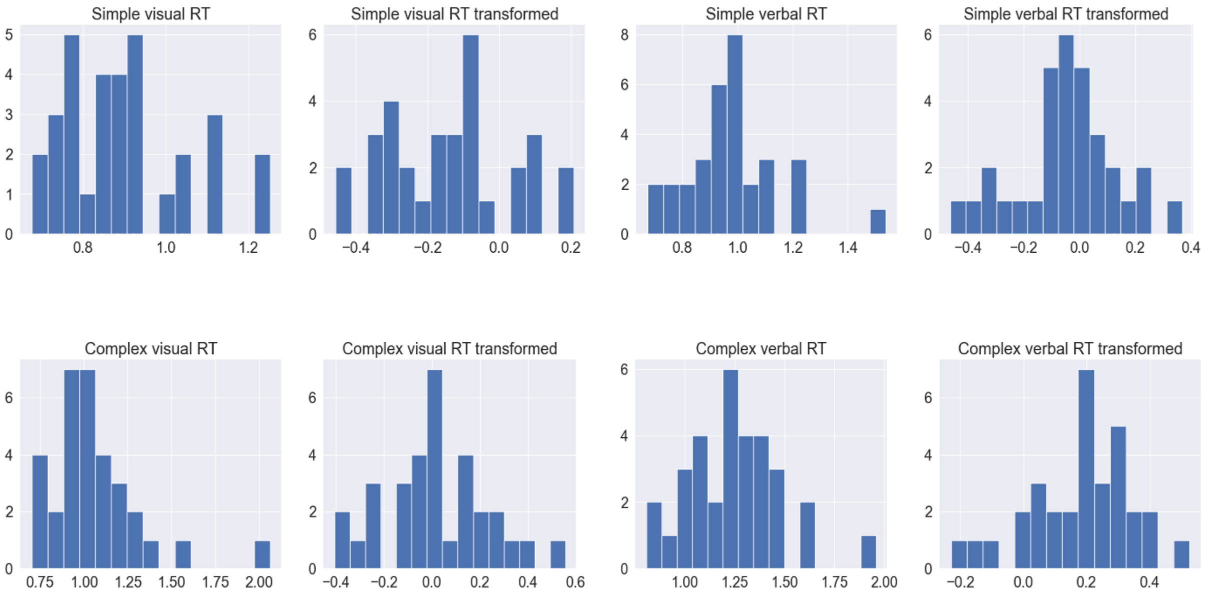
Supplementary figure 5

Accuracy histogram for each condition



Supplementary figure 6

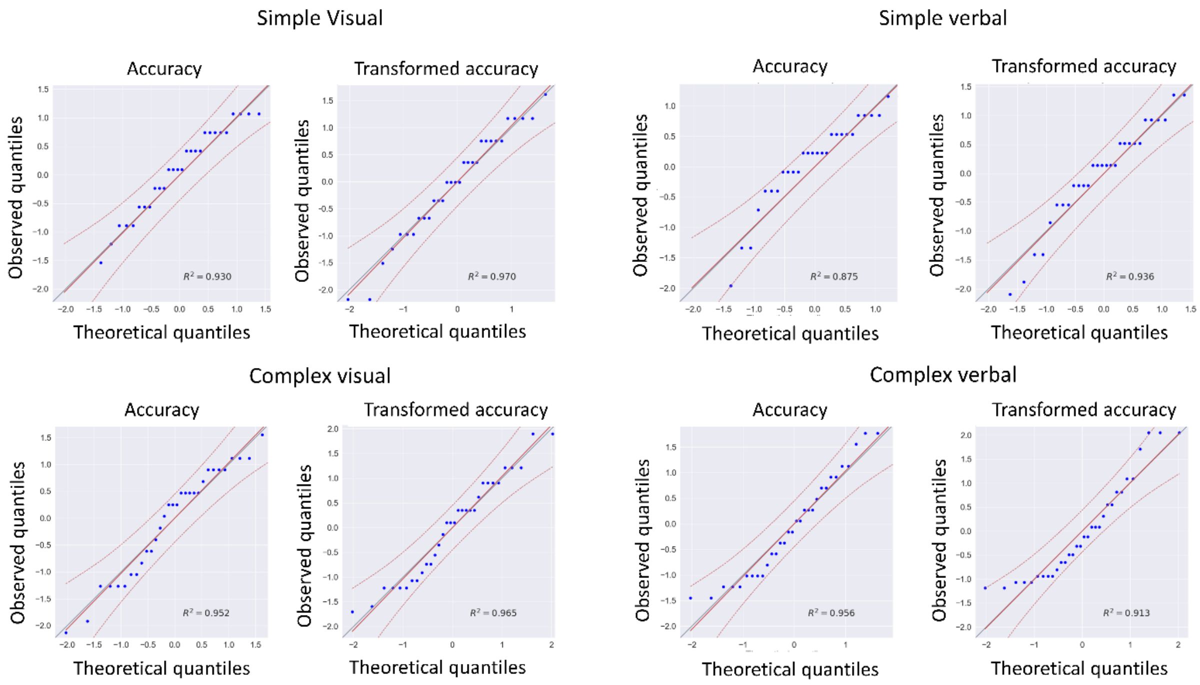
Median response time histogram for each condition



Accuracy Q-Q plots for each condition before and after transformation are depicted in Supplementary figure 7. Response time Q-Q plots for each condition before and after transformation are depicted in Supplementary figure 8.

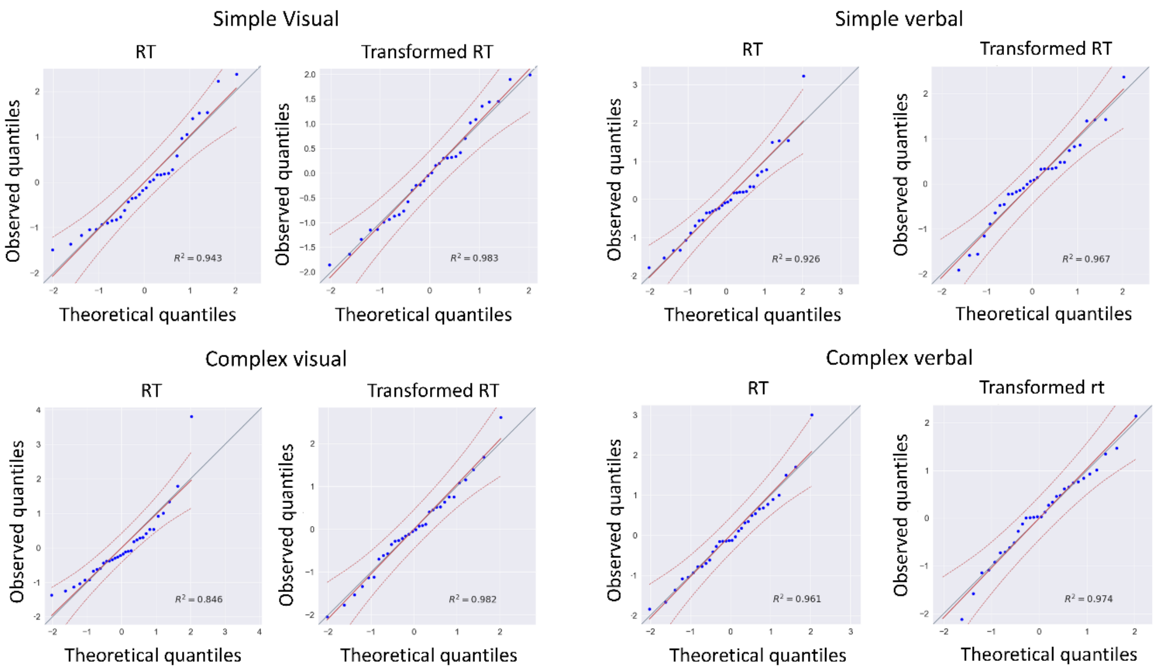
Supplementary figure 7

Accuracy Q-Q plots for each condition



Supplementary figure 8

Median response time Q-Q plots for each condition



Results of accuracy comparison between Gender.

We checked the gender differences in accuracy and median response time by the three-way mixed ANOVA with two within group factors (Modality and Load) and one between group factor (Gender). The mixed-model ANOVA revealed no effect of Gender on accuracy ($F_{(1, 30)} = 0.161$, $p = 0.691$, power = 0.067). Two-way ANOVA in male population revealed no effects of Modality ($F_{(11)} = 3.71$, $p = 0.08$), significant effect of Load ($F_{(11)} = 15.74$, $p < 0.01$) and significant interaction of these two factors ($F_{(11)} = 12.13$, $p < 0.01$). Post-hoc comparison in the male population revealed no differences between simple visual and simple verbal conditions ($T_{(11)} = 0.56$, $p = 0.99$, CLES = 0.57). Significant differences were observed between simple verbal and complex verbal condition ($T_{(11)} = -5.57$,

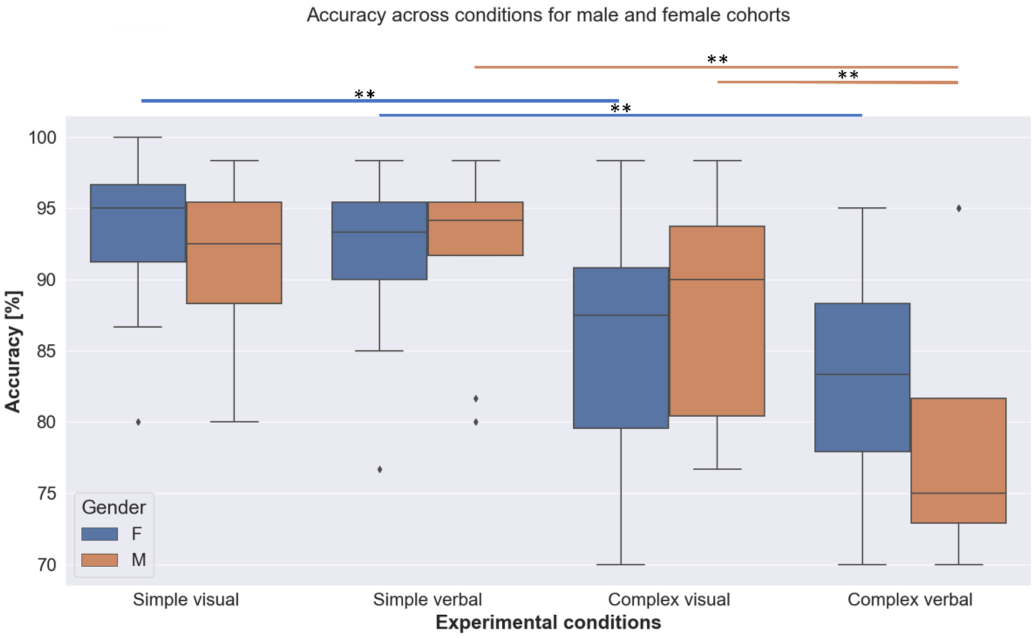
$p < 0.01$, CLES = 0.13). No differences were observed between simple and complex visual conditions ($T_{(11)} = -1.427$, $p = 0.70$, CLES = 0.37). No significant differences were observed between complex visual and complex verbal conditions ($T_{(11)} = -3.32$, $p = 0.04$, CLES = 0.22).

Two-way ANOVA in male population revealed significant effects of Modality ($F_{(19)} = 5.07$, $p = 0.03$), significant effect of Load ($F_{(19)} = 42.02$, $p < 0.01$) and no interaction of these two factors ($F_{(19)} = 0.09$, $p = 0.77$). In the female population no differences between simple visual and simple verbal conditions were observed ($T_{(19)} = -1.33$, $p = 0.74$, CLES = 0.40). Significant differences were observed between simple and complex verbal condition ($T_{(19)} = -5.26$, $p < 0.01$, CLES = 0.14). Significant differences were observed between simple and complex visual conditions ($T_{(19)} = -5.15$, $p < 0.01$, CLES = 0.14). No differences were found between complex visual and complex verbal conditions ($T_{(19)} = -2.00$, $p = 0.31$, CLES = 0.39).

The results are visually represented in Supplementary figure 9. The accuracy (mean and standard deviation) for each cohort are presented in Table 1 of the manuscript.

Supplementary figure 9

Accuracy across conditions for male and female population expressed as percentage of correct responses



Note. Asterisk indicates p-value equal or less than 0.05, double asterisks indicates p-value less than 0.01.

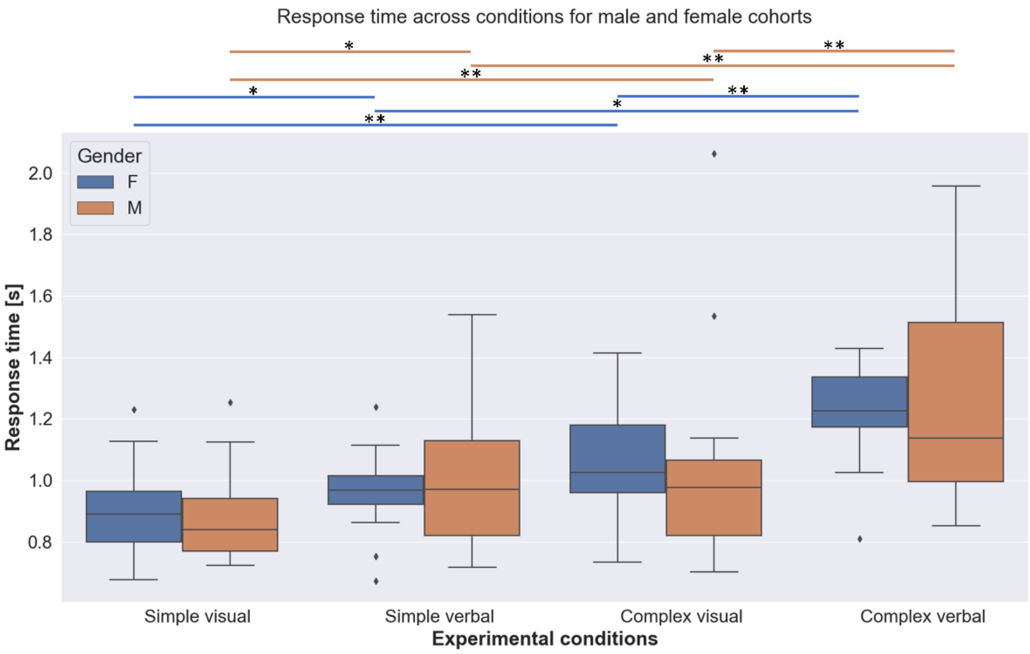
Results of the median response time comparison between Gender.

The mixed-model ANOVA revealed no effect of Gender on accuracy ($F_{(1, 30)}$ = 0. 062, p = 0.81, power = 0.057). Two-way ANOVA in male population revealed significant effect of Modality ($F_{(11)} = 22.39$, $p < 0.01$), significant effect of Load ($F_{(11)} = 74.72$, $p < 0.01$) and no interaction of these two factors ($F_{(11)} = 1.11$, $p = 0.31$). Post-hoc comparison in the male population revealed significant differences between simple visual and simple verbal conditions ($T_{(11)} = 3.54$, $p = 0.03$, CLES = 0.64). Significant differences were observed between simple and complex verbal condition ($T_{(11)} = 5.32$, $p < 0.01$, CLES = 0.72). Significant differences were observed between simple and complex visual conditions ($T_{(11)} = 3.795$, $p = 0.02$, CLES = 0.67). Significant differences were observed between complex visual and complex verbal conditions ($T_{(11)} = 3.31$, $p = 0.04$, CLES = 0.71).

Two-way ANOVA in female population revealed significant effects of Modality ($F_{(19)} = 19.96$, $p < 0.01$), significant effect of Load ($F_{(19)} = 78.39$, $p < 0.01$) and significant interaction of these two factors ($F_{(19)} = 6.37$, $p = 0.02$). In the female population significant differences between simple visual and simple verbal conditions were observed ($T_{(19)} = 3.14$, $p = 0.03$, CLES = 0.66). Significant differences were observed between simple and complex verbal condition ($T_{(19)} = 9.41$, $p < 0.01$, CLES = 0.91). Significant differences were observed between simple and complex visual conditions ($T_{(19)} = 5.93$, $p < 0.01$, CLES = 0.76). No differences were found between complex visual and complex verbal conditions ($T_{(19)} = 4.61$, $p < 0.01$, CLES = 0.79). The results are visually represented in Supplementary figure 10. The response time (median and standard deviation) for each sample are presented in Table 1 of the manuscript.

Supplementary figure 10

Median response time (expressed in seconds) across conditions for male and female population.



Note. Asterisk indicates p-value equal or less than 0.05, double asterisks indicates p-value less than 0.01.

We found no main Gender effect on accuracy and response time. Interestingly, analysis of each gender cohort revealed balanced performance in visual modality across attentional involvement in male, and balanced performance in complex condition across modalities for female. However, such gender differences should be considered with a caution due to a limited sample size for three-way analysis. Addressing gender differences in the architecture of WM components is an interesting framework for the further research with the paradigm during neuroimaging study.

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