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An eye-tracking study of the Russian language compound Remote Associates Test problem solving

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Abstract. One of the most widely used tools for measuring convergent thinking is the Remote Association Test (RAT), originally proposed by S. Mednick in accordance with his associative theory of creativity. In a pilot experiment, we studied the oculomotor activity of Russian speaking participants (n=20), who performed the Russian language Compound Remote Associates test in order to identify oculomotor predictors of involvement in the creative process during problem solving. Using linear mixed-effects models for oculomotor data and linguistic characteristics of the stimuli, two significant fixed effects (average compound Zipf-word frequency and number of blinks per second) on increasing the probability of correct response in RAT tasks were found, which is probably related to internal attention involvement while controlling the linguistic factor of the frequency of words-associates that the test participant processes.

Keywords: eye tracking, remote associates test, creativity, convergent thinking, blinking, word frequency, Zipf value

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Introduction

This research represents an eye-tracking study of the Russian Language Compound Remote Associates Test problem solving to reveal oculomotor indices of the creative process typically involved in solving this test.

This test was developed according to the *Associative Theory of Creativity*, proposed by Mednick [1]. This theory suggests that individuals come up with creative ideas when they integrate mutually remote associative components into novel and useful combinations. These components represent lexical-semantic structures. Mednick developed the *Remote Associates Test (RAT)* to assess how many meaningful common and uncommon remote associations participants can generate from the triads of semantically unrelated words at first sight. For example, the triad "*railroad, girl, class"* has such a potential response as "working", since such phrases can be formed with every word from the triad: *working on the railroad, working girl, working class* [2]. Mednick hypothesized that solvers with flatter associative hierarchies could give more correct responses to the triads and a more diverse set of associates (including uncommon) than individuals with steeper associative hierarchies [1]. The original RAT had good reliability (Spearman-Brown .91 and .92) implemented on samples of 215 and 289 college students [2].

Currently, there are several versions of RAT developed by several researchers on the material of different languages: English [3–5]; Russian [6–8]; German [9]; Polish [10]; Italian [11]; Chinese [12, 13]; Finnish [8]; Romanian [14]; Slovak [15], Spanish [16], and other languages.

Typically, RAT consists of 25–40 items with triads of explicitly unrelated words and the participants should come up with the fourth word that is related to each word from the triad in some way. As a rule, the response-word could be related to the stimuli-words via contextual associations (e.g., *pig – mud*), synonymy (e.g., pig – slob), compound word formation (e.g., *pig – pignut*) or a phrase (e.g., *safety* and *pin* forms a noun phrase *safety pin*). The scores are computed according to the number of correct responses.

Mednick's approach for measuring creative (and mostly convergent) thinking and his idea of RAT refer to one of the most widely used conceptual framework in psychological and neurocognitive studies [17–23].

However, the original RAT validity and even the concept of associative hierarchies remain controversial.

There are two main problems in developing RAT items for discussing further: homogeneity/heterogeneity and remoteness of RAT items.

Homogeneity vs. heterogeneity of RAT items

Bowden and Jung-Beeman [3] argue that the original RAT items are heterogeneous in regard to the principle that each triad of stimuli relates to the response word. Specifically, the triad *same, tennis, head* is associated with the solution word *match* via contextual synonymy (*same* and *match* have common meaning "*equal*" in a certain context), noun phrase (*tennis match*), and compounding (*match head*). This heterogeneity of cue-solution linguistic relations can be found both within and across items. The triad-solution relation can also vary on the scale of abstractness (*humor – sense* vs. *apple – tree*), figurativeness (*star – actress* vs. *star – planet*) and other semantic relations. To assess these parameters of RAT items some researchers recruit independent raters. For example, in Marko, Michalko, and Riecansky's study [15], the raters were shortly trained and then asked to assess all RAT cue-solution pairs for different word relations using Likert-scale, e.g. for abstractness (from 0 (concrete) to 4 (highly abstract): *apple – tree vs. humor – sense*), figurativeness (from 0 (literal) to 4 (figurative): *star – dust* vs. *star – actress*), polysemy (from 1 to 3 representing the number of distinct word meanings that associate cue with solution: in the triad *same – tennis – head*, the correct response-word *match* associates to each of the stimulus word via three different meanings).

There are many other linguistic parameters of cue-solution relations that can be taken into account, but the main problem for RAT problems developers is whether heterogeneous or homogeneous the RAT items should be in their linguistic parameters. Several researchers argue that solving RAT-problems with different word relations may load different cognitive systems [24], and, consequently, RAT performance not obligatorily reflects a coherent cognitive ability of a participant.

Thus, many researchers around the world have developed different homogeneous versions of RAT: functional RAT [24], compound RAT [3], visual RAT [8, 25]. There are several functional RATs for the Russian language [6, 7]. A new functional RAT is currently being developed by E. Valueva. A compound RAT in the Russian language does not exist, and it is being developed by Repeykova et al. [26].

Remoteness of RAT cues from solution

Mednick [1] proposed that RAT problem solvers with flatter associative hierarchies outperform ones with steeper hierarchies due to their ability to access and link *remote* concepts or ideas. Hence, the *remoteness* of cues from solution in each triad refers to the principal determinant of the item difficulty, and, consequently, RAT score is supposed to reflect the level of remote associative abilities [27]. In developing new RATs, researchers use several methods to assess the cue-solution remoteness. The most common are the following.

1. Using word association norms for measuring the associative remoteness

One of the methods is developing the word association norms datasets comprised of a rank-ordered frequencies of participants' free associations for a given cue candidate-word (e.g., *chair*). The common, or dominant associate is considered as the most frequently given one (e.g., *table*), whereas the remote associate has low frequency responses (e.g., *committee* or *toilet*). Based on the set of the responses, the associative distance of stimulus-response pairs can be easily calculated as 1 minus the relative frequency of the cases in which a stimulus word evoked a certain associate word. The higher value indicates the higher associative remoteness of two words and the remoteness of each item is the average value of three respective cue-solution distance values.

In a recent study of RAT psychometric evaluation, Marko, Michalko, and Riecansky [15] revealed a single latent factor related to RAT performance. Using linear regression analysis, the authors revealed that the *cue-solution associative remoteness* accounts for ~ 80% of variance in item difficulty of RAT (R^2=.791). Thus, at least partially, the original Mednick's assumption of steeper vs. flatter "associative hierarchies" [1] tends to be supported in empirical studies: RAT performance largely depends on the person's ability to find remote associates between words.

The limitation of this method is that the normative data needs large number of participants because associative data depends on individual and group differences, language development and situational factors.

Hence, we suppose that RAT items require an optimal threshold and variability of remoteness in order to get acceptable reliability and validity of the instrument. This requirement was implemented in our current study using Average Solution Frequency (average Zipf-value) score for each RAT item (see Appendix 2). The relation between item remoteness, difficulty and sensitivity in different versions of RAT still lacks empirical verification [15, 28].

The objective linguistic measures will be controlled in our study of developing the Russian language compound RAT.

Cognitive factors in RAT problem solving

Different versions of RAT have been used to measure several cognitive abilities associated with creativity, including intelligence, insight, memory, problem-solving, and related academic achievement [29].

Some of the first researchers who confirm the link between the RAT scores, ***intelligence*** and ***academic achievement*** were Taft and Rossiter [30]. They revealed positive correlations between the performance on RAT and scores on the Advanced Tests AL and AQ (Form W), including total (r = .57), verbal (r = .60), and quantitative IQ scores (r = .46), scores on Raven's Progressive Matrices (r = .38), speed and accuracy test scores (r = .27), and a number series test scores (r = .41). They also revealed that performance of RAT moderately correlated with academic achievement, including English (r = .40) and Science (r = .32) exam scores in high school students (n = 107). Also, one actively discussed hypothesis refers to the IQ threshold for creative potential [31, 32].

RAT has been widely used in many cognitive studies as a ***convergent thinking*** test of creativity. Performance on the RAT has weak to moderate correlations with performance on divergent thinking tests, e.g. with performance on flexibility (r = .28) and originality (r = .29) of Unusual Uses test [32]. Lee, Huggins, and Therriault [31] provided empirical evidence that performance on the RAT had significant positive correlations with different convergent thinking measures assessing different aspects of analytical and deductive processing (intelligence, working memory, academic achievement). Specifically, RAT scores and the

Raven's Progressive Matrices (measure of fluid intelligence) scores were positively correlated in several studies (*r* ranges from .33 to .47) [31]. Among cognitive factors, ***verbal intelligence*** is assumed as the most reliable measure of assessing the validity of the newly developed RAT. Logically, the RAT problem solving may involve the processes of analysis, generalization and highlighting the common semantic word features, searching for the appropriate lexical representations as candidates from one's passive vocabulary, evaluating word-candidates, decision making and responding. For example, in Lee, Huggins, and Therriault's [31] study, the correlation of vocabulary subset of Wechsler Adult Intelligence Scale and compound RAT was .41.

Metalinguistic awareness is also supposed as one of the main factors influencing performance on RAT. *Metalinguistic awareness* refers to the ability to consciously reflect on the nature of language: the abilities to understand implied meanings, formal structures like phonemes, syntax, the ability to make morphological analysis, etc. The development of metalinguistic awareness is assumed to consist of cognitive control (selecting and coordinating the relevant pieces of information that is necessary for comprehending the language manipulation) and analyzed knowledge (recognizing the meaning and structure of the "manipulated" language) [33]. For example, compounding morphology is highly prevalent for some languages, and native speakers could be tested on their ability to manipulate familiar morphemes to form compound words [34]. It is assumed as the essential ability for performance on the compound RAT for languages with complex morphology, and we suppose professional linguists and students of philological departments will outperform non-linguists on this test due to their metalinguistic awareness.

On the one hand, according to Mednick [1], RAT was developed to measure creative thinking without any specific knowledge in test takers. On the other hand, domain specificity implies pre-existing knowledge and experience within a particular domain in order to successfully produce creative work [35]. The assumption is that the more knowledge one possesses and the better one understands the relationships between pieces of information within a domain, the greater the likelihood one has of generating a creative idea. Thus, in solving linguistic RAT problems, individuals need to know all the potential word solutions according to their literacy level, vocabulary size, ability to find similarities in semantics of the triads, make morphological analysis and word formation operations etc.). On the contrary, it is assumed that domain-relevant knowledge or special skills are beneficial for creative thinking to a certain extent: the prior cultivation of established pathways for knowledge or skills implementation can prevent creative thinking when individuals expose to "design fixation" in creative problem solving [36]. Domain-general vs. domain-specific measures of creativity are still discussed.

The ***cognitive process*** of RAT problem solving could be measured by neurocognitive techniques as a fine-grained measurement of creative process. In a systematic review, Wu et al. [23] revealed a growing number of neurocognitive studies of remote association, insight problem-solving, general creative process from 2000 to 2019. Using RAT problems, the researchers have been explored the processes of how participants solve problems through remote association with the focus on participants' response to semantic search during the think-aloud RAT problem solving and reply performance. Also, such studies help researchers to estimate RAT items' difficulty and understand what cues in the triad are supposed to be problematic.

Some scholars posit that similar problem-solving processes are involved in the RAT and ***insight*** problem solving during experiments. Both problems can mislead participants with dominant but incorrect representations. The spontaneous association of closely dominant lexical representations may lead participants to an impasse that prevents them from solving the problem. They may get stuck in the easy retrieval representations and fail to find the solution for RAT item. Remote and original ideas should be connected to solve the RAT problem. Usually, participants cannot state the problem-solving process. "Aha!" experience may occur only after a participant solved the RAT problem.

The remoteness principle can be described not only using word-associates but also using analogies from different domains. The idea is that the more creative the person is, the less effects of local, or closely related piece of knowledge on one's solution we can observe. But often experts retrieve representations from their domain of expertise more easily than from more distant domains [28]. Some practitioners use abstraction method, or moving up the idea space "tree" to the node ("creative hack") where more remote but plausibly related relevant analogies from other domains can be found. Linsey et al. [37] used the *WordTree* digital tool to develop the engineers' abstraction that enable them to identify distant-domain analogies as part of the ideation process. Beda et al. [28] describe this technique from the perspective of RAT problems: a remote association is assumed as a "creative hack" that enables problem solver to leave a fixated area to some unexplored one in the idea space (Fig. 1).

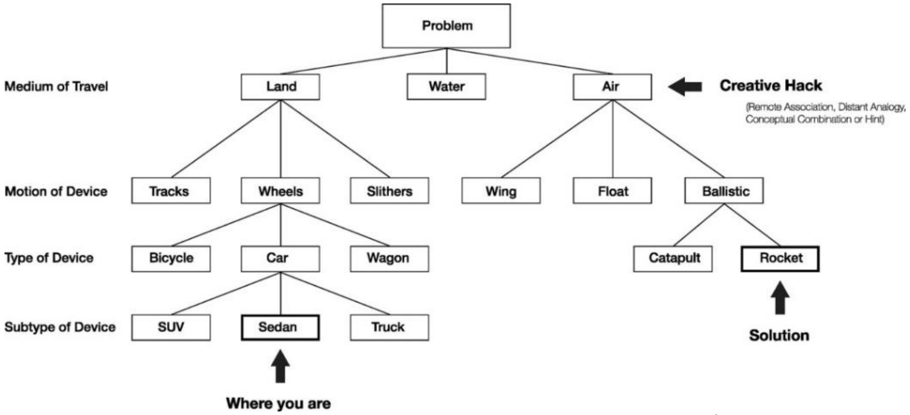

Fig. 1. The remoteness principle in the idea space [28][1]

Inspired by this technique, we used the idea of *WordTree* visualization to describe the patterns of the compound RAT cue-solution remoteness in this study.

[1] Under a Creative Commons license.

The creative process during RAT problem solving involves two stages: (1) an ***initial divergent stage of idea generation*** and (2) a ***convergent stage of solution matching and evaluation***.

In neurocognitive experiments, the cognitive processes of solving RAT problems were typically tested through four stages of creative acts [38], including:

1) *preparation* (when the problem is investigated by participants);

2) *incubation* (when the problem is analyzed unconsciously);

3) *illumination* (when participants' ideas come together to give a possible solution);

4) *verification* (when the solution is checked by participants).

These stages could be tested in different paradigms: behavioral, eye-tracking, EEG, etc.

Eye movements and the RAT cognitive processes

Recently, several studies observed objective psychophysiological indices of cognitive processes during RAT problem solving using ***eye-tracking technology*** [39–42].

This technology allows detecting individual internal cognitive mechanisms in different RAT designs.

When solving RAT problems (e.g., a compound RAT) in eye-tracking studies, participants are usually presented triads of words, and solution words may be presented or not presented according to the research design. The main eye reaction patterns include *eye movements* (*fixations and saccades), blinks, and pupil constriction/dilation*.

In Salvi and Bowden's review [39], ***eye movements*** and ***blinking*** are discussed as the psychophysiological reactions that influence creative thinking.

Human neural networks that enable individuals searching for information in the visual environment may influence other neural networks that enable them to search for non-visual information stored in long-term memory. Salvi and Bowden [39] posit that when individuals retrieve information from memory, imagine something, solve problems or think in a creative way, they often shift their gaze from the environment to an empty space or a blank on the screen. This mechanism is assumed to be related to ***internal attention***. There are some empirical evidences that individual differences in eye movements are influences by the memory demands during problem solving. For example, Glenberg et al. [43] found that when participants try to answer questions with moderate difficulty, they tend to avert the gaze from engaging visual stimuli. The authors explained this effect as the following: typically, people are engaged in remembering when they monitor the environment for unrelated but meaningful events. If the remembering task seems to be difficult, then the visual attention resources are temporarily distracted from the visual environment to the recollection process.

In psychology and cognitive neuroscience, the existence of two types of attentional mechanism of information processing is widely used and discussed [44, 45]. Bottom-up (external) information comes from the environment through the senses and this kind of attention is external (bottom-up) attention. This type of attention retrieves the information from the outside and also operates with the selection and modulation of sensory information: e.g., in visual, audio, tactile representation etc. [45]. Internal (top-down) attention operates with internal representations (thoughts, concepts, recollection of events etc.). It is assumed that loads on external and internal attention are mutually exclusive and these two types of attention have the same limits of capacity: e.g., if an individual is immersed in own thoughts, one's attention to the external environment should be reduced and vice versa.

Thus, fixations *on* as well as saccades *to* a stimulus (e.g., a cue-word in RAT) may facilitate the retrieval of necessary information from this stimulus (phonological, morphological, lexical representations), whereas eye movements *away* from the stimulus or fixations on the empty space or blank shift individual attention away from the visual environment, inhibit further processing of the stimulus, and allow weaker (more remotely linked) internal concepts to become "highlighted" [39].

A number of behavioral and neurophysiological studies came to the same result: at the moments of individual engagement in internal attention, the processing of external stimuli is suppressed. Reducing distractors from the environment may enhance internal concentration [46–52].

According to the results of eye-tracking studies, people produce more gaze aversions ("looking away" effect) when they try to solve a difficult cognitive task, and this effect has a functional consequence on memorization. For example, Glenberg et al. [43] found that participants improved their accuracy in solving problems with moderate difficulty when their eyes were closed. Also, eye blink rates analysis may provide more evidence for this pattern. Blinking physically blocks incoming information for a short period, generates a suppression of vision associated with an inhibitory signal sent out by the brain [53] both before and after the time of actual eyelid closure [54–56]. Increasing eye blink rates may also be related to directing individual's attention internally, enhancing a more complex cognitive mechanism of attention not merely the interruption of visual input [57, 58]. Holland and Tarlow [59] suggested that eye blinks emerge during cognitive shifts between different ideas. On the contrary, both the number of blinks and blinks duration decrease as a function of more intense cognitive load [60–62], concentration on the task, e.g. during solving mathematical tasks [59]. Several researchers found that blinking measures were associated with such internal processes as divergent thinking and creativity [41], insight problem solving [52], discrepancy between external and internal workloads [63], mind wandering [64].

Ueda et al. [41] revealed that, compared to the resting state, increased ***eye blink rates*** during the two creative tasks performance were correlated with the production of more alternative uses on the Alternate Uses Task (39.2 times per minute, SD = 22.1) and slower solutions on the RAT (38.7 times per minute, SD = 21.1). Eye blink rates were significantly higher in AUT and RAT compared to the resting state: AUT: $t(55) = 6.58$, $p < .001$, $r = .66$; RAT: $t(54) = 6.40$, $p < .001$, $r = .65$. Ueda et al. [41] hypothesized that the slower RAT solutions reflected a more divergent search for solution variants that could be related to the *insight approach* to solve RAT problems. For the last one, no data for comparing eye blink rates in correct vs. incorrect trials or using correct answer as dependent dichotomous variable in regression analysis was provided because the authors analysed eye blink rates only for trials in which participants were not able to find correct answers for up to 60 seconds. Also, no significant correlation was found between the total number of solved RAT items by a certain participant and eye blink rates suggesting that solution rate is possibly too coarse a measure to be used in studies of the RAT problem solving.

In the study of Salvi et al. [52], participants were asked to divide compound RAT solutions into those produced via analysis or via insight. During the preparation stage, before problems eventually solved by insight, participants demonstrated higher blink rate as well as longer duration of blinks but also fewer fixations as compared to problems eventually solved by analysis. Another finding was that immediately prior to solutions, participants had longer blinks and averted their gaze from the problem more frequently during solving RAT by insight compared to analytical way.

In an EEG study of the compound RAT performance, Jung-Beeman et al. [46] found increased alpha-frequency activity over the right occipital-parietal cortex 1500 ms prior to insight solutions compared to analytic solutions. This activity is assumed to indicate active suppression of input [65] and implicit effort to reduce bottom-up visual processing for performing more abstract, internal processing [66]. The activation of alpha-band is also linked to the eye movements and blinking restriction [49, 67].

To sum up, it can be argued that eye blinks and fixations are associated with different process of solving RAT problems. When participants are not engaged in analytical but likely in divergent thinking, the number of eye blinks (per s./min) tends to increase but the number of fixations on RAT stimuli tends to decrease (probably, with more and long fixations on empty space). This cognitive process appears most likely due to defocusing from the RAT problem, indicating internally focused attention on finding compound words as mediated links between RAT cues and final responses. When participants are engaged in this process, they are assumed to solve a currently processed RAT problem with sudden insight most likely. These psychophysiological patterns relating to disengagement from the visual environment may be linked to the imagination and creativity by diminishing visual processing of stimuli and thus reducing strong (explicit) associations, and switching to internal attention for searching of weaker (implicit) associations between RAT stimuli [39].

In our pilot eye-tracking study, both eye blink rates and fixation rates were used as predictors and the correct response for each RAT trial was used as the dependent variable in the logistic regression analysis.

Interhemispheric interaction is one of the neural mechanisms assumed to be involved in creative thinking. Some theories of creative thought imply that the successful interhemispheric coordination is a critical component to the creative process [68] and that contributions from each hemisphere are distinct, but necessary to complete most creative tasks. One eye tracking technique for testing interhemispheric coordination is *bilateral eye movements* that induce cognitive enhancements for episodic memory, attention, and divergent thinking. Fleck and Braun [40] revealed that bilateral and right-centre eye movements exhibited enhanced performance on the solution/non-solution judgement to a target word in 7 seconds after compound RAT performance. The bilateral condition demonstrated the best performance for solution targets and the right-centre condition presenting the best performance for non-solution targets. There was medium effect size of main effects for visual field ($F(1, 115) = 8.086$, mean standard error [MSE] = 0.011, $p = .005$, $\eta^2 = .066$. Although this intervention is not used in our empirical study, the potential influence of interhemispheric asymmetry is worth studying in future.

The sequence of RAT stimuli in word triads may influence the performance of test as well. Huang, Liu, and Chen [69] found that the first two words of the same category in each triad (e.g., "doctor, nurse" that represent the hyperseme "medical staff" or contextual category "hospital") are *fixation words*. These words lead participants to an impasse. The third word (e.g., ("tour guide") is a *keyword* as it differs conceptually from the first two words. If the keyword is put in the middle of the two fixation words ("doctor, tour guide, nurse"), participants will be more likely to come up with the association between "doctor" and "tour guide" and solve the problem successfully. Although this effect seems controversial, it led us to the prediction that RAT cues in the eye-tracking experiment should be presented in different sequence to avoid the visual-spatial influences (i.e., some cue always goes first, then the second and third ones, and this word order may evoke an ordinary reading-rereading processes but not problem solving). From the neurocognitive point of view, this seems reasonable because if a participant looks at a location that was previously occupied by a visual cue, one can recall both visual (*where to look*) and conceptual information (*why to look*): participant can fixate the first word not because of its semantics or frequency of occurrence effect but due to reading strategy. Thus, in our study we use both visual-spatial remoteness of RAT cues and different sequences of RAT cues to reduce the reading strategy effect.

Thus, the RAT problem solving consists of different cognitive processes that may involve the integration of convergent, divergent and analytical thinking, insight problem solving (including preparation, incubation, illumination and verification stages), shifting from external to visual internal attention and vice versa, word recognition, lexical access, morphological processing and recollection of necessary concepts. The current study may reveal implicit oculomotor indices of the creative process typically involved in solving the RAT.

An eye-tracking study of the Russian language compound RAT

Method. This study is implemented in an experimental paradigm for solving RAT problems using an eye-tracking device.

Participants. The sample of 20 Russian speaking participants (all females) between 18 to 49 years of age ($M = 24.35$, $SD = 8.79$) was recruited among university students and lecturers to complete 20-item compound RAT problems in a pilot eye-tracking experiment. 17 participants from 20 were assigned as linguists.

Stimuli. Relying on the methodological approach of Bowden and Jung-Beeman [3] and the language specific principles, in this research the Russian language compound RAT is proposed. In Russian (as in English) a compound word is formed with two or more stems but there are certain criteria to distinguish compound words from collocations.

1. One of the main criteria is the compound word's morphological non-separability (*цельнооформленность*), which means the morphological characteristics of the word belong to one of the components (as a rule, the second): *светобоязнь* (Nominative), *светобоязни* (Genitive), *светобоязни* (Dative), *светобоязнью* (Instrumental) etc. In compound Russian words, a connecting vowel is often used after the stem of the first component (see the previous example) but no such vowel can be used as well (*фотопечать, фотолюбитель*).

2. The next criterion is that Russian compound words cannot be written or printed as open compounds in English (*ice cream, ice water or water ice*): only closed (e.g., *железнодорожник – railroader*) or hyphenated (e.g., *премьер-министр – prime minister*) compounds can be used in Russian.

Thus, these two main grammatical criteria distinguish a compound word from collocations in Russian, and they were implemented in developing the compound RAT.

To create compound words as potential solutions of RAT, the derivational model "Compound words derived from predicative phrases (control term is the verb)" (S+V) was used . When such combinations are transformed into a compound word, the substantive component, as a rule, takes the first position and represents different actants of the verb:

сердцебиение (сердце бьётся и биение сердца)
heartbeat (the heart beats and the beat of a heart)

A classical compound RAT consists of word triads (three cues), three (or more) potential solutions (compound words) and one correct response.

According to the S+V model, the sample of the RAT item is the following:

Verb 1, Verb 2, Verb 3
Solution 1 (Noun+Verb1), Solution 2 (Noun+Verb2), Solution 3 (Noun+Verb3)
Response (Noun)

An example of the Russian compound RAT item solution:
The triad of stimuli: *отражать (reflect) бояться (fear) рассеивать (scatter)*

The solutions*: светоотражение (light reflection),*
светобоязнь (fear of light), светорассеяние (light scattering)[1]
The response*: свет (light)*

At the first step, 25 items were constructed by Repeykova et al. [26] using this model.

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[1] Note that in English translation a compound word may not be formed for some of the cue-words (like *fear of light* that is definitely a collocation but not a compound word).

For the current study, only 23 items were selected as the most appropriate. Then 3 of them were selected as training triads and 20 items as the test triads (Appendix 1).

The use of the words as stimuli or associated lexical representations needs taking into account the frequency of occurrence of the word because it is proved as one of the strongest predictors of word processing efficiency in a great number of studies. High-frequency words are known to a greater number of speakers and are processed (recognized, recalled, read etc.) faster than low-frequency words.

At the second step, all potential solutions we queried via the General Internet Corpus of Russian (http://www.webcorpora.ru/en/) by exploring word frequencies (instances per million) in a large corpus (19.801 billion words) as one of the most robust linguistic measures of word familiarity and word usage (less frequent words are typically used less often than more frequent ones).

To solve the RAT problem, participants should construct three compound words as potential solutions ("светоотражение" (0.005 ipm), "светобоязнь" (0.069 ipm) and "светорассеяние" (0.001 ipm[1)]) which have different word frequencies as well. Finally, participants come up with the solution ("свет"). The lower frequency of potential solutions may inhibit the compound RAT problem solving process until the necessary representation is retrieved from the participant's semantic memory.

In this study, the Zipf-scale (a standardized measure of word frequency) is used for estimating solution word frequency of solutions:

$$\text{Zipf-value} = \log10(\text{fpmw})+3 \text{ or } \log10(\text{fpmw}*1000)$$

This measure is typically used as a standardized measure of word frequency that is independent of the corpus size. Zipf-values allow comparing the results across different samples and languages. All measures (ipm and Zipf-values) are presented in Appendix 2.

Procedure

1. Firstly, the participants were asked to sign an informed consent, provide their demographic characteristics.

2. Secondly, participants were asked to perform the compound RAT, while their eye-movements were recorded with *SMI RED-500* eye-tracker (with the maximum sampling rate of 500 Hz, or 500 times per second) without head support. Only monocular eye movements were recorded. The system was set to record the eye movements of the right eye. The participants took part in the experiment individually. Before the procedure, the participants were asked to sit about 70 centimetres away from a 22-inch screen (with the resolution of 1680×1050 pixels) on which RAT items were displayed. Then a 4-point calibration test was

[1] *fpmw* (or ipm)– frequencies per million words. In this study ipm (instances per million) is retrieved for each solution-word from the General Internet-Corpus of Russian (http://www.webcorpora.ru/en/)

conducted. The participants were asked to fix their gaze at the red spots that appear at different positions on the grey screen to calculate the values of the point of regard (eye position). After the calibration, the validation test was performed using the same procedure to check the consistency with the previous calibration test (the deviation of fixations positions on y and x axis ≤1° of visual angle was accepted).

The study design is presented in Figure 2:

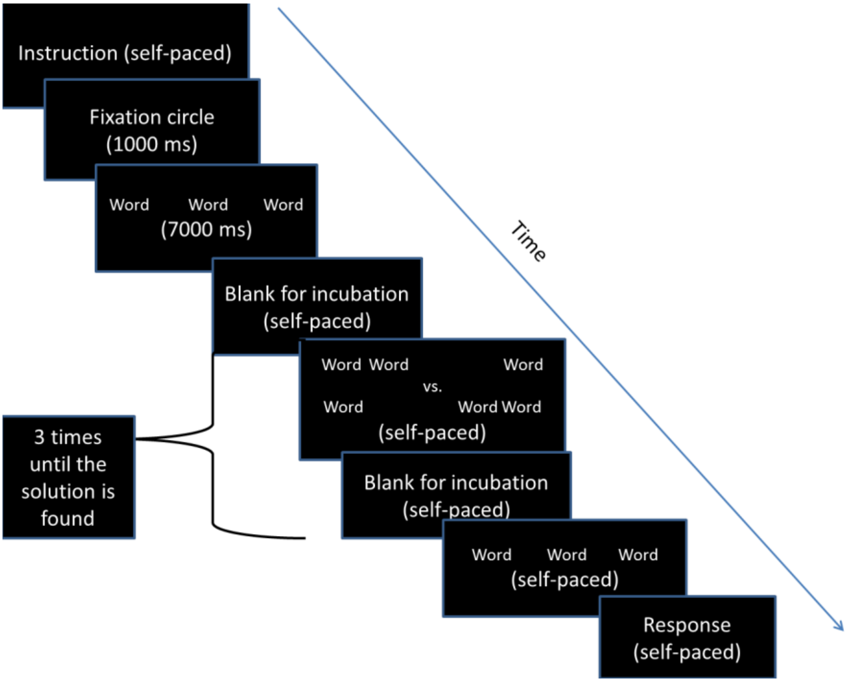

Fig. 2. The eye-tracking study design (after calibration and validation)

After confirming that the eye-tracker could accurately record the participants' eye movements, the instruction and practical phase were started. The objective of the practical phase was to familiarize a participant with the compound RAT problems. After reading the instruction, the participants were allowed to take up to five trials: the 1st one was presented for 7 sec., the next three trials were self-paced, and the last trial was allowed for the verification of RAT problem solving. No time limit will be given for responses. Confirming that the participants had no problem with the procedure, the main RAT was started.

In the main RAT, the words in each triad were presented in different combinations to avoid the effect of sequence of RAT items: bilateral horizontal presentation of pairs of words in the left or right visual field vs. distributed equal presentation. There are at least 20 characters between words presented separately and 5 characters between words presented together. The distance between words is measured according to Rayner's [70] measures for parafoveal perceptual span in reading (when a participant can read the following or previous words while not fixating these words on one's fovea).

In this study, the participants were not presented solution words or any other cues. The design was in line with the four stages of creative acts [38], including: (1) preparation (when the participant familiarizes oneself with the triad for 7000 ms); (2) incubation (when the problem is analyzed unconsciously during blank exposure); (3) illumination (when the participant's ideas come together to give a possible solution and this process can emerge at any subsequent trials); (4) verification (when the participant checks one's assumption and comes up with the final solution).

In our study, every trial was coded as 0 (incubation stage) and 1 (non-incubation stage when visual stimuli are presented on the screen). For the non-incubation stage, the words were presented on the black screen and typed with white colour script (Arial 26 pt centered). During the incubation stage, only black screen was demonstrated.

Thus, 20 RAT items were presented on the screen on by one in fixed order. The participants were asked to press the spacebar at any time to change the stimulus. They were allowed to verbalize their response at any time, once they came up with the answer. If a participant was able to answer before the last trial ended, then they might skip all the rest trials for this solved RAT item. The experimenter fixated the trial on which the participant gave the answer and then consequent trials were not included in the analysis. Also, the experimenter was not judging the correctness of the participants' responses. If a participant had no answer, they would proceed to the next problem. In this study, the participants had no chance to return to the previous RAT item and to try to solve it again. The maximum allowable time for solving RAT problems was not fixed (except the 1st trial presented at 7 sec.). The whole RAT test took around 50 minutes. No money was paid for the participation.

After the experimental session, the recorded data were pre-processed with SMI software (Experiment Center and BeGaze) including a large set of eye movement parameters: fixation count, fixation frequency (count/s.), fixation duration (total, ms), blink count, blink frequency (count/s.), blink duration total (ms) etc. According to the literature review, fixation frequency and blink frequency were analyed as predictors of individual performance of the RAT along with one linguistic predictor (the average Zipf-value of the compound solutions of the item) that were discussed in the previous sections.

Hypotheses

1. Average Zipf-value of the compound solutions of the item (average solution frequency) will be positively correlated with the RAT item performance.

2. Number of eye blinks will increase when the participant is engaged in divergent thinking to solve RAT problem successfully. Positive correlation of eye blink frequency with the individual performance of the compound RAT will be

plausible because several researchers assume divergent process along with convergent thinking are involved in RAT problem solving. The hypothesis is compatible with Ueda et al.'s [41] suggestion that spontaneous eye blinks are actively involved in attentional disengagement from the external world allowing more divergent thinking to occur when participants search for the links between remote associates.

3. Individual RAT performance will be positively correlated with fixation count per second because RAT as convergence thinking test requires attention and focus on the task and if so the fixation frequency is one of the plausible predictors of RAT.

Results

After automatic data pre-processing with BeGaze software, 3960 observations were obtained for further analysis. One observation was deleted due to technical problem. Each of the rest 3959 observations represented recorded data on trial per participant and thus we had obtained a large dataset with individual eye movement parameters during RAT problem solving.

Next, data processing was implemented in R-studio. After reading a data frame, the trials, which were skipped by the participants due to the fact they had already solved a particular RAT item during the previous trial, were coded as 2 (or irrelevant trials) and then deleted from the analysis (2310 observations were taken for further analysis as relevant trials):

```
df <- read.csv2("data.csv", dec = ".")
library("lme4")
library("lmerTest")
df <- df[df$Correct_resp < 2,]
```

Next, the generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod'] was computed for the dependent dichotomous variable "Correct_resp", where correct response (1) and incorrect response (0) refer to individual response for every relevant trial (the trial on which the response was given and all trials before the response for each RAT item). The model referred to the logistic regression (for predicting dichotomous dependent variable – see Figure 3 for an evaluation of the model's assumptions) through fixed and random effects. We used correct response variable as dependent one. The fixed effects included: average solution frequency (that represents average Zipf-value of three compound solutions), Blink Frequency count/s (the number of blinks per second for each analyzed trial), Fixation Frequency count/s (the number of fixations per second for each analyzed trial), and a factor of trial (0 – incubation, 1 – non-incubation trial). Participant ID was used as a random effect in the model.

The formula of the model was the following:

Correct_resp ~ Aver_Solution_Freq + Blink.Frequency..count.s. +
+Fixation.Frequency..count.s. + as.factor(Type_0_incub) + (1 | Participant_ID)

The script for R was the following:

```
model <- glmer(Correct_resp ~
```

```
Aver_Solution_Freq +
Blink.Frequency..count.s. +
 + Fixation.Frequency..count.s.+
 as.factor(Type_0_incub)+
(1|Participant_ID), data = df, family = binomial(link = "logit"))
```

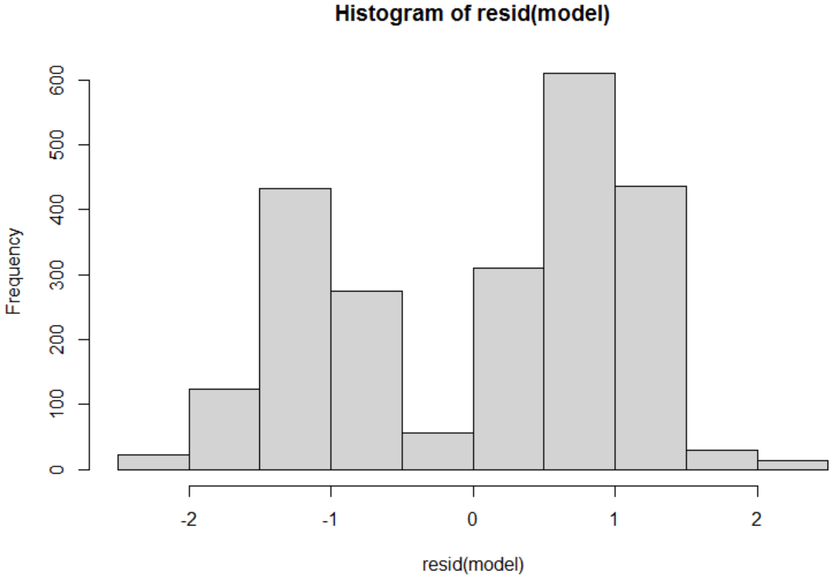

Fig. 3. The generalized linear mixed model of standardized residuals distribution (for logistic regression dichotomous variable was converted to the probability distribution). The histogram of residuals represents normal distribution of residuals for both incorrect and correct responses

We found that two fixed effects (average solution frequency and blink frequency count/s) were significant predictors of the probability of correct/incorrect individual response to the RAT items (see Table 1).

Table 1

The estimation of fixed effects in generalized linear mixed model for correct response (binary dependent variable)[1]

Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-0.37	0.40	-0.93	0.35362
Aver_Solution_Freq	**0.47**	**0.11**	**4.38**	**0.00001**
Blink.Frequency..count.s.	**0.32**	**0.09**	**3.76**	**0.00017**
Fixation.Frequency..count.s.	-0.02	0.04	-0.56	0.57447
as.factor(Type_0_incub)1	-0.05	0.10	-0.46	0.64290

[1] Significant fixed effects are bolded.

Next, we estimated the random effect of participant and found that intercept of each participant can be interpreted as participant's ability to solve RAT problems.

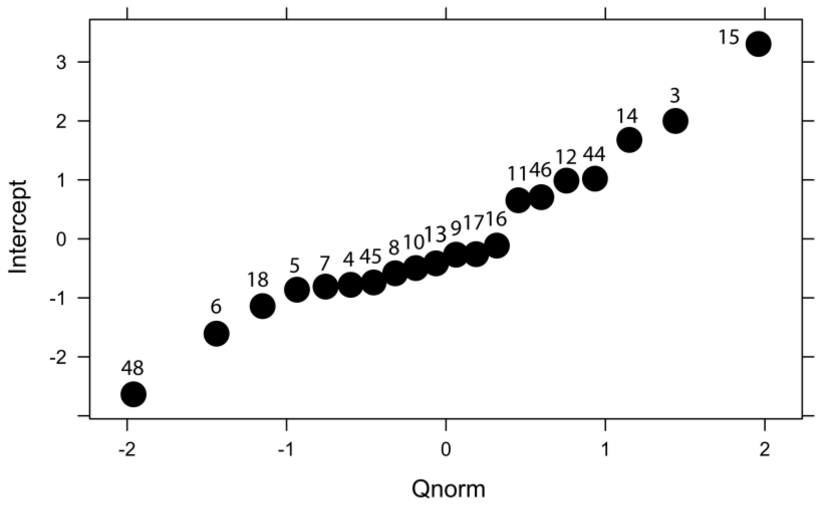

Fig. 4. The random effect of participants (*Intercept*) on the probability plot
(*Qnorm* on the horizontal axis correspond to the quantiles of standard normal distribution)

Thus, Figure 4 demonstrates how successful a particular participant was in solving RAT problems. For example, on the *Qnorm* axis, the score around -2 means that participant had 2 SD lower RAT performance across all items on average than participant with mean RAT performance (0). On the *Intercept* axis, the score around -2.5 means that participant had 2.5 SD more chance to solve RAT problems incorrectly across all items on average than those participants who have 0 intercept score (which means an equal probability to solve RAT problems correctly and incorrectly).

Table 2

Frequency of predicted and observed RAT individual responses
(correct model predictions are bolded)

Fitted / Observed RAT responses	incorrect	correct
incorrect	**511**	261
correct	398	**1140**

The model predicted 1651 individual responses (both as correct and incorrect to the RAT key – see Table 2) out of 2310 relevant trials (71.47% of trials were predicted correctly). To sum up, this pretty high percentage of predicting correct and incorrect responses on RAT items led us to the conclusion that using predictors from different domains (registered psychophysiological, linguistic fixed effects and individual random effects) may shed light on the underlined individual strategies of compound RAT problem solving.

Discussion

The original RAT proposed by Medinck in 1962 and different types of currently developing RATs have certain advantages compared to other techniques for measuring creativity. Linguistic versions of RAT can be implemented in a short period of time, in online or offline format. In the nearest future, it will be easier to develop such tests for languages with large corpora and lexical databases because a lot of computational techniques are currently developed. Some studies proposed computational models of human-like RAT performance, and that could help in further RAT development [71, 72].

For compound RATs, one of the prospective directions in test construction for different languages is using more consistent protocols for defining grammatical and semantic features of stimuli and compound words as mediating links with the responses. There is an inconsistency in defining the compound word in different languages, and thus some RAT compound solutions may occasionally include both compound words and collocations which represent different language units. As objective measures of stimuli remoteness, word frequency can be used for compound words (including Zipf-value), and word co-occurrence can be used for collocations and phrases.

There is one more general question regarding the processes involved in RAT problem solving. Specifically, whether the Russian compound RAT requires more convergent thinking processes (or only this process) more likely than divergent thinking. We tried to answer this question and found that one of the plausible psychophysiological measures of divergent thinking process is eye blinks rate. Blinking frequency (count/s) was one of the strongest predictors: if this measure increases by 1 SD, taking into account the individual characteristics of the solution, the probability of correct response on the RAT item will be .32, p=0.00017.

According to Mednick's original idea, the RAT requires the participant to "form associative elements into new combinations by providing mediating connective links" [1]. On the one hand, this idea may be interpreted in the end analytical thinking process (step-by-step problem solving). On the other hand, during solving RAT problems people misdirect (or fail to direct) retrieval processes and thus reach an impasse. On solving RAT problems, people often have the "Aha!" experience [3] but they often cannot describe the processing that has led them to the solution. The compound RAT problem solving seems to involve both analytical thinking (when solvers form compound words in their mind) and insight experience (when solvers reach an impasse and can't find any analytical path for solving the RAT problem, or maybe someone tends to use only insight experience without any analytical thinking).

Another limitation of the original RAT revealed by Worthen and Clark [24] is that the "RAT measured sensitivity to language rather than creative potential". Hence, the researchers should take into account language development processes (e.g., new associates could emerge in everyday language environment and the old ones fade away). Logically, the more interactive language environment a native speaker has, the more new associates could emerge in one's mental lexicon. This leads to the use of objective measures, e.g., word frequency for the triad of compound solutions as the mediating link between stimulus and final response. More and less creative people who share a common environment and who make many common experiences hence establish common associative hierarchies. It means that objective measures of word frequency reflect individual's familiarity with the words used in solving RAT problems. In our eye-tracking study, average solution frequency (average Zipf-value of all compound words in the triad) was one of the strongest predictors: if this measure increases by 1 SD, taking into account the individual characteristics of the solution, the probability of correct response on the RAT item will be .47, p = 0.00001.

Limitations:

1. The sample in the eye-tracking study is biased towards females and linguists.

2. In designing RAT triads we did not take into account stimuli word frequency. The lower word frequency of any of stimulus-words can evoke attentional bias to this word. For example, in solving the problem of the Russian triad "отражать, бояться, рассеивать", all three words represent different word frequency (1.411 ipm, 41.153 ipm, 0.124 ipm, respectively) with the most frequent one ("бояться"). Two other words are less frequent and typically evoke attentional bias in reading. Most likely, participants will firstly compare these two less frequent words ("отражать", "рассеивать"), come up with the potential solution, and then assess the similarity of the third one. Less frequent words in the triad may evoke less lexical representations and consequently fewer candidates for forming a compound solution. This may lead to the priming effect or attentional bias to these less frequent words and their potential derivates.

3. One possible extraneous variable can be potential boredom or lack of task motivation in participants. This can be controlled by the description of the potential uses of the experimental findings during special games or any other interactive activity with the participants.

The further validation studies of the Russian compound RAT may include the comparison of the divergent thinking test performance and RAT performance as well as the study of relationship between metalinguistic awareness and RAT performance.

The use of the objective neurocognitive measures during RAT performance may help researchers to understand the underlying mechanisms of RAT problem solving, e.g., whether it requires more convergent or divergent thinking via the analysis of blinking rate and how we can predict the RAT performance from other eye-movement parameters.

Appendix 1

Russian language compound Remote Associates Test (Rus-Com-RAT)
Тест отдаленных ассоциаций «Сложные слова»
(авторы: В.А. Репейкова, М.С. Власов)

Придумайте Ваш ID. Запомните и используйте его для дальнейших тестов и опросов.
Ваш пол (муж., жен.)_______
Возраст_________
Укажите вашу сферу деятельности (например, учитель русского языка, менеджер). Если вы являетесь студентом, пожалуйста, укажите вашу специальность_______________________________________

Вам будет предложено решить 20 заданий. Каждое задание состоит из трех глаголов. Например: *отражать – бояться – рассеивать*. Ваша задача - подобрать такое существительное-ответ, которое бы образовало сложное слово* с КАЖДЫМ из представленных глаголов. Например, к глаголам *отражать*, *бояться*, *рассеивать* существительным-ответом является слово СВЕТ, потому что с каждым глаголом можно образовать сложное слово: СВЕТоОТРАЖЕНИЕ, СВЕТоБОЯЗНЬ, СВЕТоРАССЕЯНИЕ. Для слов ПЕЧАТАТЬ – ВЫСТАВЛЯТЬ – ИЗОБРАЖАТЬ ответом будет слово ФОТО (ФОТОПЕЧАТЬ, ФОТОВЫСТАВКА, ФОТОИЗОБРАЖЕНИЕ). Для слов ЧИСТИТЬ – РАЗВОДИТЬ – ЛОВИТЬ ответом будет слово РЫБА (РЫБОЧИСТКА, РЫБОВОДСТВО, РЫБОЛОВ). Как видите, в процессе образования сложного слова может меняться часть речи, появляться суффиксы и т.д. Для ответа на каждое задание, необходимо дать существительное-ответ в именительном падеже («Кто?», «Что?»), единственном числе, как только Вы поймете, что это за слово. Справочно: сложное слово – это слово, имеющее в своём составе два (и более) корня. Например, слово «снегоход» – это сложное слово, так как состоит из образующих «снег» и «ход», а также соединительной гласной «о». Сложное слово может получиться как путем собственного сложения (при помощи гласных «о» или «е», например, снегоход), так и несобственного сложения (без соединительной гласной, например, Царьград). Важно: в данном тесте не будет составных сложных слов, которые пишутся через дефис (например, плащ-палатка). На выполнение всех заданий у вас будет неограниченное количество времени. Если вы не знаете ответ на какое-либо из заданий, то переходите к решению следующего.

Russian language Compound Remote Associates Test (Rus-Com-RAT) keys

Stimuli	Solution	Compound 1	Compound 2	Compound 3
1. падать лазить проводить	вода	водопад	водолаз	водопровод
2. генерировать возить увлажнять	пар	парогенератор	паровоз	пароувлажнитель
3. хранить любить издавать	книга	книгохранилище	книголюб	книгоиздание
4. рубить возить пилить	лес	лесоруб	лесовоз	лесопилка
5. метать тушить стоять	огонь	огнемет	огнетушитель	огнестойкость

Stimuli	Solution	Compound 1	Compound 2	Compound 3
6. летать падать считать	звезда	звездолет	звездопад	звездочет
7. печь стоять лечить	солнце	солнцепек	солнцестояние	солнцелечение
8. складывать сочетать употреблять	слово	словосложение	словосочетание	словоупотреб-ление
9. записывать регистрировать наблюдать	видео	видеозапись	видеорегистра-тор	видеонаблюде-ние
10. резать ломать кружить	голова	головорез	головоломка	головокружение
11. режиссировать изолировать усиливать	звук	звукорежиссер	звукоизоляция	звукоусилитель
12. писать пожимать мыть	рука	рукопись	рукопожатие	рукомойник
13. сидеть строить управлять	дом	домосед	домострой	домоуправление
14. трясти рыть делать	земля	землетрясение	землеройка	земледелие
15. хранить греть двигать	тело	телохранитель	телогрейка	телодвижения
16. пить варить молоть	кофе	кофепитие	кофеварка	кофемолка
17. падать тесать дробить	камень	камнепад	каменотес	камнедробилка
18. хулить являться служить	бог	богохульство	богоявление	богослужение
19. колоть резать ходить	лед	ледокол	ледорез	ледоход
20. течь харкать изливать	кровь	кровотечение	кровохарканье	кровоизлияние

Appendix 2

Zipf-values and average solution frequencies (average Zipf-values) for the Russian language RAT solutions

1. Ipm values for compound words were retrieved from the General Internet-Corpus of Russian: http://www.webcorpora.ru/en/
2. Zipf-values (calculation): http://crr.ugent.be/archives/1352

Zipf-values are easy to calculate from fpmw (ipm) values. Simply take log10(fpmw)+3 or log10(fpmw*1000): Zipf, G. (1949), Human Behaviour and the Principle of Least Effort. Reading MA: Addison-Wesley

Stimuli	Average Solution Frequency (Average Zipf-value)	Compound 1 Zipf-value	Compound 2 Zipf-value	Compound 3 Zipf-value
1. падать лазить проводить	2.848	3.389	2.276	2.880
2. генерировать возить увлажнять	1.748	1.863	3.382	0
3. хранить любить издавать	1.764	1.851	1.851	1.591
4. рубить возить пилить	1.886	2.033	1.820	1.806
5. метать тушить стоять	2.278	2.305	2.751	1.778
6. летать падать считать	2.224	2.068	2.799	1.806
7. печь стоять лечить	1.407	1.724	2.496	0
8. складывать сочетать употреблять	1.902	0.699	3.476	1.531
9. записывать регистрировать наблюдать	2.989	3.299	2.838	2.829
10. резать ломать кружить	1.793	2.676	2.859	2.990
11. режиссировать изолировать усиливать	2.842	2.612	2.164	0.602
12. писать пожимать мыть	2.664	3.219	2.573	2.199
13. сидеть строить управлять	2.066	2.155	2.238	1.806
14. трясти рыть делать	2.494	3.673	1.362	2.447
15. хранить греть двигать	2.357	2.747	1.653	2.671
16. пить варить молоть	2.037	1.462	2.427	2.223
17. падать тесать дробить	1.419	2.107	1.672	0.477
18. хулить являться служить	2.587	2.484	2.161	3.115
19. колоть резать ходить	1.946	2.980	0.477	2.382
20. течь харкать изливать	2.309	3.028	1.380	2.591

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