

Quantifying insightful problem solving: A modified compound remote associates paradigm using lexical priming to parametrically modulate different sources of task difficulty

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Abstract

Insight problem solving has been conceptualized as a dynamic search through a constrained search space where a non-obvious solution needs to be found. Multiple sources of task difficulty have been defined that can keep the problem solver from finding the right solution such as an overly large search space or knowledge constraints requiring a change of the problem representation. Up to now, there are very few accounts that focus on different aspects of difficulty within an insight problem-solving context and how they affect task performance as well as the probability of finding a solution that is accompanied by an Aha! experience. In addition, we are not aware of any approaches investigating how knowledge constraints parametrically modulate task performance and the Aha! experience in compound remote associates (CRA) when controlling for other sources of task difficulty. Therefore, we first developed, tested and externally validated a modified CRA paradigm in combination with lexical priming that is more likely to elicit representational change than the classical CRA tasks. Second, we parametrically estimated the effect of the knowledge constraint together with other sources of difficulty (size of the problem and search space, word length and frequency) using General Linear Mixed Models. The knowledge constraint (and the size of the search space) was operationalized as lexical distance (measured as cosine distances) between different word pairs within this task. Our results indicate that the experimentally induced knowledge constraint still affects task performance and is negatively related to the Aha! experience when controlling for various other types of task difficulties. Finally, we will present the complete stimulus set in German language together with their statistical (i.e. item difficulty and mean solution time) and lexical properties.

Keywords

insight, problem-solving, restructuring, compound remote associates, lexical priming, General Linear Mixed Models,

Introduction

Although insight problems represent a heterogeneous class of problems (Bowden et al. 2005; Chronicle et al., 2004), one task that has been widely used to study insight are compound remote associates (CRA) (Bowden & Jung-Beeman, 2007; Kounios & Beeman, 2014; Jung-Beeman et al., 2004). In a *CRA paradigm*, three target words are presented and the task is to find the compound associate to these three words. For example, when the target words *drop*, *coat* and *proof* are presented, the solution would be *rain* because this word can be meaningfully combined to each of the target words (*raindrop*, *raincoat*, *rainproof*) (Bowden & Jung-Beeman, 2003, 2007). One characteristic of CRA tasks is that they have no clearly defined goal state (Bowden et al., 2005; Reed, 2016). In general, problems can be represented by a problem space - a theoretical construct - which consists of initial (intermediate) and goal states that are connected by legal moves (Simon, 1973). For CRA tasks, the goal state (finding the solution compound word) lies in a part of the problem space that is remotely connected (or unconnected) to the initial state (the three target words) and therefore not easily recognized by the problem solver (Goel, 2014). A consequence of these kinds of insight problems is that a solution is less likely to be approximated linearly via a step-by-step procedure, because the goal state is undefined. Therefore, a search for a solution that appears to be making no progress is sometimes followed by an insight – an unpredictable moment of full (or partial) comprehension of a solution – when the solution is found (Sternberg & Davidson, 1995; Reed, 2016).

There are different definitions of *insight*: While the definition of insight tasks refers more to the defining characteristics (undefined goal state) of tasks that (are assumed to) elicit insight solutions, one can also regard the defining characteristics of an insight solution itself and how it differs from a non-insight solution: Insight solutions are often experienced by the solver as sudden (the *Aha!* moment), obviously correct and progress towards a solution seems non-linear and is often not reportable (Metcalf & Wiebe, 1987). To avoid confusion of the different definitions of insight, we will refer to the term of an *insight solution* as the *Aha! experience* (it needs to be noted that what we refer to as *Aha!* experience is less the emotional state associated with an insight solution but more the impression of suddenness and correctness of the solution).

It has been argued that there is no set of indispensable criteria determining whether a person has solved a task with an *Aha!* experience and that especially CRA tasks can be solved with or without *Aha!* experience (for example via trial-and-error) (Bowden et al., 2005; Webb, Little & Cropper, 2016, 2017; Danek et al., 2016; Kounios & Beeman, 2014). For this reason,

participants are prompted to report whether the solution was solved with or without Aha! experience instead of simply assuming that insight had occurred (Kounios & Beeman, 2014).

But why are some items solved with an accompanied Aha! experience and others are not, when CRA items seem structurally identical? What are task inherent obstacles that make it more likely that a remote association (solution) between the three target words can be found? We will argue that despite the structural identity of the three target words, there are different task and language related sources of difficulty in CRAs that together affect task performance and the Aha! experience. To our knowledge, task difficulty has not yet been systematically controlled in CRAs.

Sources of task difficulty – process, perceptual and knowledge factors

It has been proposed that when solving an insight problem, participants need to overcome multiple sources of difficulty in a single thinking step (Kershaw & Ohlsson, 2004; Wu, Knoblich & Luo, 2013; Öllinger et al., 2014, Knoblich et al., 1999). Different factors have been identified to be causing task difficulty in a problem solving context: *process, perceptual* or *knowledge* factors (Kershaw & Ohlsson, 2004, Knoblich et al., 1999).

Process factors of task difficulty include for example the length of a solution or size of the problem space, i.e. the amount of potential solutions (Bowden et al., 2005). Using the example of CRA, we propose that the size of the problem space relates to the sum of meaningful compound words that can be appended to each of the three target words. Increasing the number of available moves in the problem space is known to increase reaction time (MacGregor, Ormerod & Chronicle, 2001; Ash & Wiley, 2006). There is further evidence suggesting that the size of the problem space like the amount of possible word compounds in simple lexical memory problems influences task performance (Ben-Zur, 1989). The perceptual and knowledge factor of task difficulty have been of particular interest when investigating insight problem solving and the concept of representational change (or restructuring of a problem) (Knoblich et al., 1999; Kershaw & Ohlsson, 2001, Weisberg & Alba, 1981). According to the representational change theory, the insight problem solving process has been characterized as a dynamic search through a constrained search space (Ash & Wiley, 2006; Ohlsson, 1992; Öllinger et al., 2014). Especially perceptual and knowledge sources of task difficulty influence the way a problem is represented to the solver when she first encodes the problem, which subsequently determines the search space (Ohlsson, 1992; Öllinger et al., 2014). In contrast to the problem space, the search space represents the legal

and illegal moves, which the solver *evaluates* into what does and does not count as a solution (Reed, 2016).

Perceptual factors of task difficulty refer to Gestalt laws like figural-ground relationships (Kershaw & Ohlsson, 2004) or a process referred to as chunking (combining components or features to meaningful perceptual patterns) which subsequently influence problem perception (Knoblich et al., 1999). Task difficulty in this context is defined by how difficult it is for the solver to decompose a specific chunk into its constituent features in order to derive a solution. Perceptual difficulty factors have been successfully identified in non-verbal problems like the nine-dot task (Chronicle et al., 2001; MacGregor et al., 2001) or in verbal problems using Chinese characters (Wu et al., 2009). However, perceptual factors do not directly relate to CRAs because its solution does not depend on perceptually dechunking letters or words.

Knowledge factors refer to prior knowledge being activated in a problem situation. That is to say, when presented with a specific problem, knowledge elements (for example ideas, word concepts or rules) that originate from former experiences with similar problems get automatically activated from long-term memory, but can be insufficient to solve the problem (Knoblich et al., 1999; Chi, Feltovich, & Glaser 1981). Difficulty in this context refers to the probability of a knowledge element (constraining the search space and keeping the solver from finding a solution) to be relaxed. The latter is inversely proportional to the scope of a constraint, meaning how much a problem representation is affected if that constraint was relaxed (Knoblich, et al., 1999, p. 1535). In the case of the CRA problem, the constrained search space due to activated prior knowledge would be searching for a compound solution word that fits to the most likely and frequent meaning of each of the target words. However, if one or more of the target words are ambiguous and a compound is required for the less dominant meaning of the target word then the participant would need to restructure the search space by also searching for more distant compounds words that fit to the less dominant word meaning of the target words (Bowden et al., 2005; Dow & Mayer, 2004).

It is possible that participants need to change their problem representation when solving a CRA problem, because they initially adopted an inadequate word meaning of (one of) the target words, which makes it difficult to find the remote association to the solution word. Evidence supporting this assumption comes from Bowers and colleagues (1990). However, task difficulty due to knowledge factors constraining the search space has not yet been systematically investigated in classical CRA tasks, but only inferred post hoc (Bowers et al., 1990). Furthermore, other simultaneous effects of task difficulty like the size of the problem

or search space as well as language related difficulty factors like word length and frequency have not been controlled for. Therefore, it is not evident what the exact influence of a constrained search space due to knowledge factors on task performance and the probability for an Aha! experience in CRA tasks is. For this reason, we have developed a modified CRA paradigm using lexical priming that systematically changes the scope of a knowledge constraint (i.e. how much the problem representation is affected if that knowledge constraint was relaxed) while keeping the size of the problem space constant. Furthermore, by determining the lexical relationship between different word pairs within a modified CRA item, this task design also allows for a parametric investigation of the influence of the knowledge constraint and other task difficulties.

In the following, we are going to outline the concept of lexical priming, the modified CRA paradigm and how priming can be used to manipulate the representation of the problem space resulting in a constrained search space. Finally, we will describe how the lexical relationship between two word compounds in a modified CRA item can be used to represent the scope of a knowledge constraint.

Priming and insight problems

Priming describes a situation when a second (target) word is processed more efficiently when it is preceded by a related first (prime) word (Jones et al., 2015). In lexical priming, the magnitude of efficient processing depends on the semantic or associative similarity between the prime and the target (Hoey, 2005). For example, when *nurse* is preceded by *doctor* it is processed more efficiently than when preceded by *bread* (Meyer & Schvaneveld, 1971). However, it is still a matter of debate whether lexical priming is due to semantic overlap or simply due to learned associational strength between the prime and the target (McNamara, 2005). Both prime-target pairs are more efficiently processed irrespective of whether the relationship between both words is semantic or associative (Jones, et al., 2006). Because both relationships evoke a priming effect, we did not strictly differentiate between associative and semantic relationships when constructing the primes for the modified CRA paradigm. In the remainder of this text, we will therefore call word pairs lexically related when they are semantically and/or associatively similar. The lexical relationship between words can either be derived via ratings of participants who rate the lexical similarity between two word pairs or it can be derived computationally through statistical co-occurrence (that is how frequently both words appear in similar contexts) across a large text corpus (see Method section). We chose to assess the lexical relationship computationally because of the large amount of

possible word pairs in our data set (~400 word pairs). Computational co-occurrence models have been successfully used to determine lexical similarity between word pairs in various languages and to investigate priming (Köhn, 2015; Jones, Kintsch & Mehworth, 2006).

We are not aware of studies using lexical priming in classical CRA items to increase the likelihood for representational change. However, there is evidence that presenting a prime can affect task performance and the likelihood of an Aha! experience in problems that can sometimes be solved insightfully: For example, Bowden investigated the effect of reportable and non-reportable priming on anagrams (Bowden, 1997). He found that participants showed better anagram task performance when they were presented with a reportable as well as unreportable lexically related prime compared to no prime. Participants also produced more solutions with self-reported Aha! experience for the lexically related compared to unrelated prime (Bowden, 1997). However, participants only showed performance costs when the anagram was preceded by a reportable (not by an unreportable) lexically unrelated prime.

Modified CRA paradigm

The modified CRA item is structurally identical to the classical CRA item in the sense that three target words (*drop*, *coat*, *proof*) are presented and the participants are asked to find the correct compound word (solution: *rain*). However, in the modified CRA version, a lexical prime (*air* or *tear*) is additionally presented together with the target words (all items are listed in the appendix B). Both prime options also present another compound with the first of the three target words (*airdrop*, *teardrop*) (see fig. 1). These compound words are either lexically related or (rather) unrelated to the compound of the solution with the first target word (*raindrop*). Finally, the first target word changes meaning depending on the combination with the respective prime (*drop* in *airdrop* vs. *teardrop*). In the condition of the lexically unrelated prime compound, the meaning of the first target word (*drop* in *airdrop*) is different than in combination with the solution word (*drop* in *teardrop*). In contrast, the condition in which the prime compound is related to the solution compound, the first target word keeps the same meaning relevant for solution. That is to say, the meaning of *drop* in the context of *teardrop* does not need to be reinterpreted whereas *drop* in the context of *airdrop* necessarily needs to be reinterpreted to build a reasonable compound with *rain*. Hence, the ground assumption here is the following: From the view point of the representational change theory, the problem solver needs to revise her constrained search space by retrieving inactive, but solution relevant knowledge elements (reinterpret the primed target word) to find the remotely associated solution. Because the target words do not change depending on the condition, the

problem space (the amount of possible compound words per target word) remains the same. Solely the search space (i.e. what is regarded as meaningful compounds per target word) changes depending on the condition. This way, the effect of the knowledge factor constraining the search space via lexical priming is better experimentally disentangled from the size of the problem space (process factor) than in previous attempts (Bowers et al., 1990). To further quantify the scope of the knowledge constraint (that is deriving a parametric instead of dichotomous measure of how much the problem representation is constrained due to the prime), we determined the lexical relationship between the prime compound (*teardrop* or *airdrop*) and the solution compound (*raindrop*). As already mentioned further above, this lexical relationship best represents the scope of the knowledge constraint as it reflects how much the meaning of the first target word (drop) changes as a function of the prime condition. In other words, we operationalize the amount of representational change necessary to solve the problem by equating it to the amount of semantic or associative distance between the prime compound and the solution compound. The semantic/associative distance is computationally derived through statistical co-occurrence quantifying how frequently both word pairs appear in similar contexts (see Methods section). Finally, it can be expected that the lexical similarity between the target words (*drop*, *coat*, *proof*) and the solution word (*rain*) as well as the similarity between a respective prime word (*air* or *tear*) and the solution word introduce additional task difficulties in the context of CRAs affecting task performance and the likelihood of an Aha! experience by modulating the size of the search space. In addition, word frequency (i.e. how commonly a word is used in daily speech) has been reported to modulate task performance in a verbal problem solving context and might therefore be an additional source of task difficulty (Oltețeanu & Falomir, 2015).



Figure 1. Example of modified CRA item for both conditions: a) lexically related and b) unrelated prime condition. Note that *teardrop* is semantically/lexically more closely related to *raindrop* than *airdrop* to *raindrop*. Consequently, the meaning of *drop* in *teardrop* is more closely related to *drop* in *raindrop* (each referring to a small quantity of liquid) than the meaning of *drop* in *airdrop* to *raindrop*.

Hypotheses

PCRA Paradigm. We hypothesize that if the modified CRA paradigm (in the following referred to as PCRA) is more likely to elicit representational change in the lexically unrelated

prime condition as theoretically described in the previous section, then this condition should be more difficult to solve and this should be reflected in quantitative measures such as: 1) relatively longer response times until a solution is reached (as measured in solution time), 2) a decreased probability to solve these problems (as measured in percentage correct [accuracy]) and 3) a higher active search for potential solutions through the constrained search space (as measured by the amount of potential solution words until the final solution is reached). Given the evidence provided by Bowden (1997) with anagrams and lexically un/related primes as reported further above, we might assume 4) a smaller amount of problems solved with self-reported Aha! experience in the lexically unrelated prime condition.

To externally validate this PCRA paradigm, we compared the PCRA problems to classical insight problems that are assumed to entail representational change (like the eight-coin problem) (Ormerod, MacGregor & Chronicle, 2002). We hypothesized that accuracy in the lexically unrelated prime condition as well as the difference values between both conditions (reflecting the specific performance impact due to the knowledge constraint) should correlate with accuracy in classical insight problems.

Parametric analysis of task difficulty. We assume that different sources of task difficulty affect performance, amount of search for potential solutions and self-reported Aha! experience. However, we hypothesize that the scope of the knowledge constraint (here operationalized as the lexical relationship between the prime compound [*airdrop*, *teardrop*] and the solution compound [*raindrop*]) linearly affects the above named dependent measures when controlling for other sources of task difficulty. These other sources are the size of the problem space (amount of potential solution compounds), the size of the search space (lexical similarity between prime [*air*, *tear*] and solution [*rain*] as well as the target words [*drop*, *coat*, *proof*] to the solution) that do not represent a necessity for representational change but rather an extent of the search space and other language related sources of difficulty (word length and frequency).

Methods

Participants

The first sample which the items were tested on (with and without prime condition) consisted of 258 university students (age [in years]: range= 18-35; 183 females: $M=25.7$; 75 males: $M=24.4$). 123 participants received no prime condition and 133 participants did. The second sample consisted of 42 university students (age [in years]: range= 18-35; 24 females: $M=24.5$;

18 males: $M=25.7$) on which we validated the final stimulus list (only with prime condition). The same participants from the second sample ($n= 42$) also completed a separate online experiment solving classical insight tasks. All participants were German native speakers and were recruited via an online student platform in Hamburg and via an existing participant pool. The ethics committee of the German society for psychology approved of this study.

Materials

Prime Compound Remote Associates (PCRA). We initially constructed 100 CRA problems in German language and evaluated those according to their item difficulty and solution time. Although it is not the main focus of this paper, it needs to be mentioned that for task construction and evaluation, we tried to ensure that this paradigm could also be used within a neurophysiological task setting (fMRI, EEG). Time resolution is slow in the MRI and a preferably high amount of solved items are necessary for an acceptable signal to noise ratio: For this reason, we expected at least 45% accuracy (this includes both failure to solve the problem as well as incorrect solution responses) and a solution time of at least 5 seconds and we selected 68 problems accordingly from this original pool of 100 items. Subsequently, we evaluated their lexically related and unrelated prime (according to the same cut off criteria). In the appendix B, the full list of the 68 CRA problems with their respective primes is presented. Six out of 68 items did not fulfill these requirements, which is why we marked those 6 items with a star in the appendix B. We reevaluated the 68 items on an independent sample of 42 participants (we refer to this as *second sample*).

The problems were constructed as described further above: the solution word (*rain*) is associated with all three target words of the triad (DROP – COAT – PROOF) through a formation of a compound word (*raindrop*, *raincoat*, *rainproof*). The prime (AIR or TEAR) always forms an additional compound with the first target word (*airdrop* or *teardrop*) (see, fig. 1). In the lexically related prime condition, the meaning of the first target word remains the same, as when building a compound with the solution word. Whereas in the lexically unrelated prime condition, the first target word has a different meaning. In order to prevent unintentional priming effects, no word occurred twice, i.e. the whole set list consists of unique words except for one lexically unrelated prime word (“Zahn”, see appendix B). Furthermore, we constructed all problems in such a way that the prime as well as the solution word would always be appended prior to the first target word (*air-drop* never *drop-air*) when building a compound to prevent position effects. Moreover, we tried to avoid word combinations where the compound word is additionally inflected (for example - solution: “Meer” [sea], 1st target word: “Rauschen” [rush] → compound: “Meeresrauschen” [sound of the sea]). It seems that

item difficulty rises when participants have to perform an extra cognitive step of inflecting words while searching for the correct compound.

Classical Insight Tasks. In order to have a broad scope of insight problems, we selected 13 verbal and 11 non-verbal problems (see Dow & Mayer, 2004). The verbal insight problems contained a phrase or word that needed to be reinterpreted in an unobvious way to derive a solution (Dow & Mayer, 2004, p. 391). Non-verbal problems were classified as either visual-spatial (containing a visual component that constrained the search space) or matchstick problems. All of the verbal and 6 of the non-verbal problems were directly adapted from Dow & Mayer (2004) and translated into German (for the verbal problems, see Dow & Mayer's examples in the appendix A number 1, 14, 22, 25, 26, 32, 33, 34, 38, 42, 45, 50, 52, 60 and for the non-verbal problems, see number: 4, 9, 11, 16, 51, 64). Additionally, we used three different types of matchstick problems as described in (Knoblich, Rhenius & Ohlsson, 1999, p. 1542), the eight-coin problem (adapted from Öllinger et al., 2013) and the pond problem (adapted from Sloane & MacHale, 1994) as non-verbal insight problems. All classical insight problems are shown in the appendix A.

Procedure

The participants were tested individually online using the research software Inquisit 4.0 (Draine, 1998). During continuous item evaluation the number of items presented for every participant belonging to the first sample varied between 50 and 70 problems per online test. The second sample (n=42) received the final item set of 60 problems (see appendix B, all items without star). The participants received 6.5 – 8 € compensation depending on the duration of the test. The problems as well as the primes were presented in Arial font, black on a white background, occupying 3% of the respective screen height.

In the instructions, the participants were told that they would see three target words and their task was to generate a fourth word, which results in a common compound word when combined with each of the three target words. They were additionally told that the solution word could either be put in front or in the back of the respective target word. To further limit the participant's search space for words, they were told that the solution word would only be either an adjective or a singular noun and it is a common word that exists in the German dictionary. Those participants who received the prime condition were additionally told that the compound between the prime in combination with the first target word is lexically related to the compound between the solution and the first target word. For this reason, they were

instructed to attend to the prime and make use of it to find the solution. No information was given that the prime compound could also be lexically unrelated to the solution compound. Additionally, participants were asked to press the space bar whenever they thought of a new possible solution word irrespective of whether that word was the final solution, to get an estimate of the amount of space searched for possible solutions. Finally, participants were instructed to indicate whether they found the solution with or without *Aha! experience*. The difference between both solution styles was explained to them (in German) in the following way:

“The defining characteristic of a solution with an Aha! experience is how sudden and obviously correct the solution appears to you. This can also be the case when you have already searched for the solution for quite some time. In contrast, the solution without Aha! appears to you more in a stepwise manner. For example, through active search you feel like you increasingly approached the solution.”

The participants were given two practice problems prior to the experiment itself. In the case of the prime condition, they always received a lexically related prime. All problems were presented in random order. Each trial began with the presentation of a fixation cross appearing in the center of the screen for 600 ms. The target words were then presented simultaneously in normal horizontal orientation in the middle of the screen for max. 60 seconds. In the case of the prime condition, the respective prime word was presented 7° vertically above from the center of the screen for the first two seconds. While the prime word remained at the same position, the three target words were additionally presented in the center of the screen for max. 60 seconds (hence, the prime was maximally presented for a total of 62 seconds). The reason why we decided to present the prime continuously is to ensure that the participants actively represent the solution relevant or irrelevant meaning of the first target word as a function of the respective condition. The participants were instructed to press the “v” button in case they found the final solution before the end of the 60 seconds. Solution time was calculated from the moment of the presentation of the target words (with prime) until the time of the “v” button press. They were then presented with five response options (four gap words which entailed one correct answer like r _ _ n for *rain* and one to indicate an alternative solution) for eight seconds. If participants chose the alternative solution (“5 ?”), they were then asked to write down their solution in a text field. This option was given, since it is always possible that participants produce a correct solution, which is not the one that we provided. When evaluating the items, we rejected those that produced too many alternative solutions (more than ~15 %), since it is difficult to give participants the option to write

something down in neurophysiological experiments. Furthermore, an alternative solution would introduce ambiguity (i.e. the trial could not be distinctly classifiable as correct or wrong and would therefore have to be discarded from later analyses). For the second sample that received the evaluated items, in 4.29% ($SD = 3.62\%$) of all responses, participants reported to have found an alternative solution. However, only 14.73% ($SD = 25.23\%$) of all reported alternative solutions turned out to be correct alternatives. If participants did not choose one of the five response alternatives within eight seconds, the trial was counted as incorrectly answered because we have to assume that the participants did not find the correct solution word prior to the “v” button press. Subsequently, the question concerning their solution style (whether they solved the problem more with or without Aha! experience) was presented.

Hereupon, they were asked to estimate their extent of effort to find a solution: “How much effort did you invest into finding new solution words on a scale from 1 - 7?”. We originally introduced this extra question to control effects of differences in effort on task performance. However, we discarded the answers for the later analyses because participants answered consistently high.

Finally, after answering this question the next trial started again with a fixation cross. If participants did not find a solution (by pressing the “v” button) within 60 seconds of the remaining trial, they were also subsequently asked about their extent of effort to solve the respective problem (see, fig. 2). After completing the PCRA task, participants were asked to respond to demographic questions concerning their age, gender, education and native language.

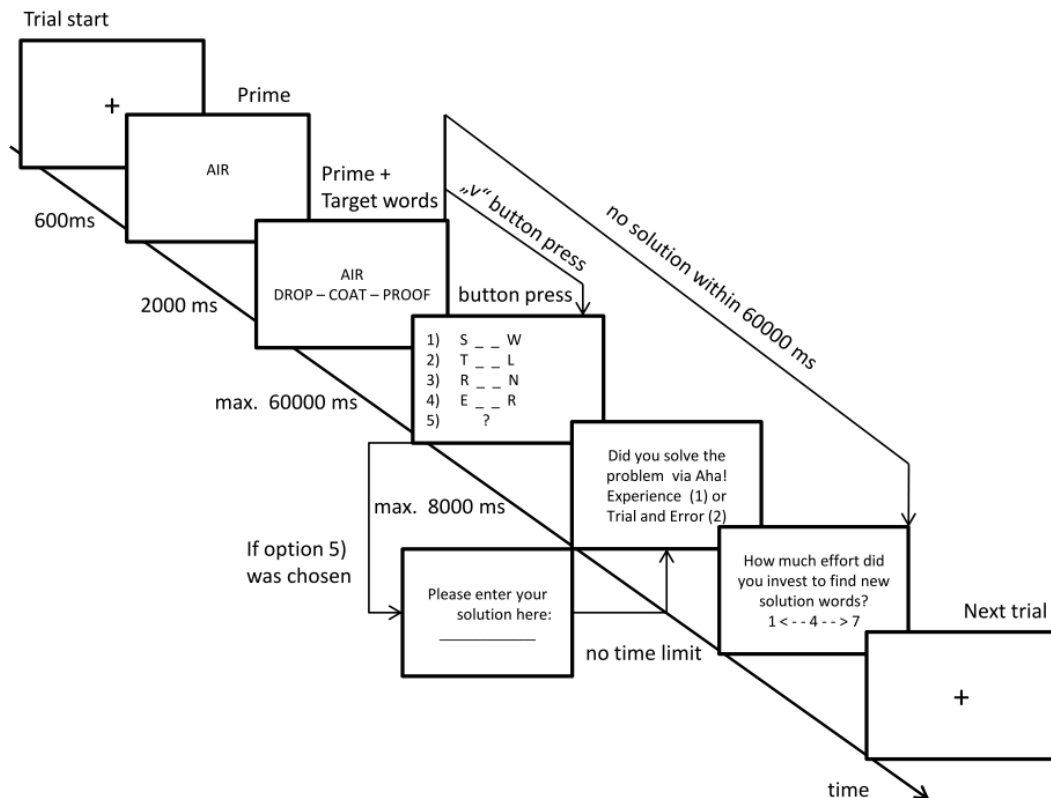


Figure 2. Time flow of *Prime CRA (PCRA)* – paradigm. The participants were instructed to press the spacebar every time they thought of a potential solution and the “v” button for their final solution. Upon “v” button press, they had eight seconds to choose between four response options (1 – 4) or choose option 5 to write down their alternative solution.

Concerning the classical insight tasks, the 24 items were tested individually online in a separate experiment using the research software Inquisit 4.0 (Draine, 1998). All items were presented in a randomized order for maximally 5 minutes. Participants were instructed to press the Enter button when having solved the problem and write down their answer into a textbox. In order to prevent participants from continuing to solve the problem while already having pressed the Enter button, the time for writing down the answer was restricted to a period of 30 seconds to 5 minutes (depending on the complexity of the answer). Subsequently, they were asked whether they already knew the respective problem (yes/no answer). If they did not indicate to have solved the problem within 5 minutes, the next problem would be automatically presented.

Data Analysis

Validation of PCRA paradigm – influence of prime – Because of non-independencies of the data (every subject completed a series of items) and to account for the random effects that are

due to the subjects and different items, we modeled the data using (Generalized) Linear Mixed Models ((G)LMMs) (for a discussion of the advantages using this (G)LMM approach especially when dealing with language, see Barr, Scheepers & Tilly, 2013; Baayen, Davidson & Bates, 2008, Cummings, 2012, Kliegl et al., 2010). We used one LMM to investigate the relationship between *solution time* (reaction time to solution per item – continuous variable) and prime condition (lexically unrelated vs. related prime – binary variable) and three GLMMs to separately investigate the relationship between a) *accuracy* (items were correctly or incorrectly solved per trial – binary variable) and prime condition, b) *Aha! experience* (item was solved with or without Aha! experience – binary variable) and prime condition and c) *search for potential solutions* (amount of search for potential solutions per item indicated by space-bar button presses before solution – count variable) and prime condition (see table 1). For the analyses, we used R (R Core Team, 2012) and the lme4 package (Bates, Maechler & Bolker, 2012). Solution time was square root-transformed in order to reach normality and we assumed a Gaussian error distribution with the default identity link function (Baayen et al., 2008). Accuracy and Aha! experience were modeled assuming a binomial error distribution with the default logit link function (Giustolisi et al, 2017; Bates et al., 2012). The amount of search for potential solutions was modeled as count data assuming a Poisson error distribution with the default log link function (Gardner et al., 1995).

[please insert table 1 here]

To assess the influence of the prime condition (lexically related vs. unrelated prime) onto solution time, accuracy, Aha! experience and search for potential solutions, we performed likelihood ratio tests of the full model with the prime effect against the baseline model without the prime effect. The baseline model included only random intercepts for subjects and items (random effects) (see, table 1). The full model was identical to the baseline model with the exception of the additional variable *prime condition* (as fixed effect). The P-values were obtained from the likelihood ratio tests and for model comparison we report the Chi-square (all values for model comparison can be seen in table 2 and 3). Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality for all analyses of the LMM. To demonstrate that the effect of the prime is a robust result, we performed all described models on two independent samples as described further above in the participants section (the *first* and *second* sample).

We excluded all trials from individuals for all analyses if they solved 0% of all trials correctly. Because the study was carried out online we cannot exclude the fact that participants with this score either did not understand the task instructions or did not seriously engage in the task. For the first sample, we had to exclude 12 participants, while there were no participants rejected from the second sample. For accuracy analyses, we included all trials from the remaining participants. Finally, for solution time analyses, trials were further discarded if they were not solved within the 60 seconds time window.

Validation of PCRA paradigm – external criterion. Concerning the classical insight problems, we only took those answers into account where the participant indicated to not have already known the problem (however, the results were not affected by this). An independent rater assessed the accuracy of the individual answers and categorized them as correct or false. The verbal and non-verbal scale was separately summed and we used accuracy (percent correct) as our target measure for both task types. Assumptions of normality were not met for classical verbal nor non-verbal insight problems. For this reason, we used the robust Spearman correlation between the latter two variables and accuracy in the lexically related and unrelated prime condition as well as for the difference values between both prime conditions (we assume that the difference values most purely represent the scope of the knowledge constraint because these values contain the remaining unique variance of the lexically unrelated prime condition, removing the shared variance between both conditions). Because we had a directed hypothesis, we used a one-tailed test of significance with $p=.05$.

Computation of lexical relationship – The lexical relationship was computed from statistical co-occurrences in text data via so-called word embeddings. The latter refers to a representation of words as dense numerical vectors, derived using training methods inspired from neural-network language modeling with huge text corpora (Levy & Goldberg, 2014a). We selected 72 million well-formed sentences from the Leipzig Corpora Collection sampled from news websites in German language (Biemann et al., 2007). A well-formed sentence is defined as a minimum length of three words, beginning with a capital letter and ending with an end-of-sentence character. To ensure that also rare words used for the PCRA items are available in sufficient numbers in our text corpus, we furthermore collected an additional 1.4 million sentences from web texts. That is to say, the first 200 hits on the Google search engine for each word from our item list were automatically crawled, and the sentences contained in text paragraph tags on these pages were extracted. Recurring phrases on web pages were

excluded. The sentences from the Leipzig Corpora Collections and the web texts were finally merged in random order.

For the actual embedding model, we computed dependency-based word embeddings with a neural network architecture as introduced by Levy & Goldberg (2014a). Initially, Mikolov and colleagues introduced word2vec as a shallow neural network to infer word representations in vector space (Mikolov et al., 2013). From the task to predict surrounding n context words for a given word in samples of empiric language data (skip-gram model), the network learns to place words which occur in similar contexts in near-by regions of the vector space. The word vectors inferred in this way encode the lexical relationships of words in the sense that lexically similar words have a high proximity to each other in vector space. Levy and Goldberg slightly extended this model by additionally incorporating syntactic information such as subject/object-verb relations from the input sentences which increases proximity of similar terms of the same syntactic type (Levy & Goldberg, 2014b).

We calculated an embedding model with 300 embedding dimensions and negative sampling with 10 negative examples running 10 iterations (epochs) over the entire dataset. To reduce noise in the data, we removed words from the vocabulary which occurred less than 50 times beforehand and also used downsampling of highly frequent words (Mikolov et al., 2013). As output, we received a 300-dimensional vector for each of the 455,050 different words in the remaining vocabulary of the model. The procedure ensured that all the words from our item list are also contained in the model vocabulary. Lexical relationship between words was computed based on the cosine distance of their corresponding vectors. Measuring vector similarity regardless of their length is useful for word embedding vectors because different vector length can be a result from high unevenly distributed word frequencies in natural language texts. The cosine similarity ($\cos \theta$) between two non-zero vectors (A and B) is calculated as follows:

$$\text{similarity} = \cos(\theta) = \frac{A \cdot B}{\|A\| \|B\|} = \frac{\sum_{i=1}^n A_i \times B_i}{\sqrt{\sum_{i=1}^n (A_i)^2} \times \sqrt{\sum_{i=1}^n (B_i)^2}}$$

A high cosine similarity (value close to $\cos(0^\circ) = 1$) means that the vectors share a very similar direction. Low similarity values (close to $\cos(90^\circ) = 0$) represent almost orthogonal vectors. The corresponding cosine distance values ($1 - \text{cosine similarity}$) can be interpreted as a high (smaller distance values), respectively low (larger distance values) lexical relationship (Levy & Goldberg, 2014b).

Parametric analysis of task difficulty – We performed (G)LMM analyses with the same dependent variables and the same assumed error distributions as described further above for the models investigating the prime condition. We chose to only do the analyses on the *second sample* because this sample received the same evaluated 68 items (see appendix B). We quantified the different sources of task difficulty as follows:

- *Knowledge constraint variable* – Cosine distance between prime compound & solution compound (**KnowConstraint**): This value describes the cosine distance (see last section) between the respective prime compound (*airdrop* or *teardrop*) and the solution compound (*raindrop*). It best represents what we refer to as a knowledge constraint requiring representational change, as it gives an estimate about how much the meaning of the first target word (*drop*) changes as a function of the prime condition.
- *Size of search space 1 variable* - Cosine distance between target words & solution (**Size_SearchSpace1**): This value describes the mean cosine distances between each target word and their respective solution word. This variable also serves as general measure for item difficulty. The reason for this is because we assume that the bigger the value of the average cosine distance between the target words and the solution word the less related the target words are to the solution word and the more difficult it should be to find the solution.
- *Size of search space 2 control variable* - Cosine distance between prime and solution (**Size_SearchSpace2**): This value describes the cosine distance between the respective prime (*air*, *tear*) and the solution (*rain*). This measure serves mainly as control variable to exclude the possibility that the observed behavioral effects are merely due to systematic differences between the lexically un/related prime and the solution (but not due to differences between the prime *compound* and solution *compound*).
- *Size of problem space variable (#Compounds)*: This variable contains an estimate of the amount of possible compound words per target word and therefore represents an estimate of the problem space (see process factor of task difficulty as described further above). Hence, this variable is not represented by cosine distances. Instead, we used the online platform www.dict.cc to count the total number of suggested meaningful compound words per target word and averaged this number over all three target words per item.

- *Frequency* – (**Frequency**): This variable represents the average frequency of the three target words and the solution word per CRA item. The frequency of every single word was derived using the Google Ngram Viewer (<https://books.google.com/ngrams>) based on the year 2008.
- *Word length control variable* (**Word_length**): This variable represents the amount of letters per prime word: Similarly to *Size_SearchSpace2*, this variable merely serves as control variable to exclude the possibility that observed behavioral effects are due to differences in the prime's word length.

To assess the influence of the knowledge constraint onto solution time, accuracy, Aha! experience and search for potential solutions, we performed a likelihood ratio test of the full model including the knowledge constraint variable (KnowConstraint) against the baseline model without this variable. The baseline model included the size of the problem space (#Compounds), the size of the search space (Size_SearchSpace1, Size_SearchSpace2) and both language related control variables (Word_length and Frequency) as fixed effects as well as random intercepts for subjects and items as random effects (see, table 5). The full model was identical to the baseline model with the exception of the additional variable KnowConstraint as fixed effect. The P-values were also obtained from the likelihood ratio tests and for model comparison we report the Chi-square (all values for model comparison can be seen in table 6). P-values for the single predictors as reported in table 7 and 8 were obtained via the lmerTest-toolbox (<https://cran.r-project.org/web/packages/lmerTest/index.html>). Furthermore, visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity and normality for all analyses of the LMM.

[please insert table 5 here]

Results

Validation of PCRA-paradigm – item properties. An overview of all items of the final selection of the 68 PCRA problems with their summary statistics (accuracy, solution time) and respective case number is given in the appendix B. The descriptive values depicted there are the combined values of the first and second sample. As most of the items were part of an ongoing evaluation, the amount of case numbers differs between items (and conditions). The solution time for all items without the prime condition ranges between 7.33 and 22.69 seconds. The solution time for all items with lexically related prime ranges between 6.41 and 17.75 seconds whereas for the lexically unrelated prime condition, solution time was between

9.88 and 25.95 seconds. Concerning accuracy, 73% ($SD = 12\%$) of all participants solved the PCRA problems without the prime condition. When given a lexically related prime, 76% ($SD = 12\%$) of the participants solved the problem, but when given a lexically unrelated prime, accuracy dropped to 55% ($SD = 15\%$). We further controlled for differences in word frequency and word length between the lexically related and unrelated prime. A paired T-test showed no statistical difference in word frequency ($t(67) = .029, p = .978$) and no difference in word length ($t(67) = .982, p = .330$) between both conditions.

Validation of PCRA paradigm – influence of prime: first sample. Participants solved the PCRA problems on average in 12.38 sec ($SD = 12.09$) when a lexically related prime was presented. They needed 17.89 sec ($SD = 14.29$) on average for the same problems when being presented with a lexically unrelated prime. The LMM analyses revealed a significant main effect for the prime condition ($\chi^2(1) = 409.03, p < .001$, see table 2) suggesting that solution time is increased by the unrelated prime by about $6.11 \text{ sec} \pm 0.33 \text{ sec}$.

Similar effects could be seen when investigating accuracy: On average, participants solved the CRA problems with a probability of 70% ($SD = 46\%$) when presented with a lexically related prime. However, when presented with a lexically unrelated prime, they solved the same problems with a lower probability of 52% ($SD = 50\%$). In the GLMM, this difference in accuracy was significant ($\chi^2(1) = 337.95, p < .001$, see table 2).

Participants reported to have found 0.842 (median) potential (but wrong) solutions (spacebar) in the lexically related prime condition before reaching the final solution whereas they reported to have found 1.04 (median) solutions in the lexically unrelated condition. This difference was also statistically significant ($\chi^2(1) = 188.71, p < .001$, see table 2).

Finally, 77.3% ($SD = 42\%$) of all PCRA items in the lexically related prime condition were solved with a self-reported Aha! experience, whereas only 68.7% ($SD = 46\%$) were solved with Aha! experience when a lexically unrelated prime was presented. This difference was also significant ($\chi^2(1) = 75.30, p < .001$, see table 2).

A summary of all likelihood ratio tests for the full model against the baseline model is shown in table 2.

[please insert table 2 here]

Validation of PCRA paradigm – influence of prime: second sample. When presented with a lexically related prime, participants solved the CRA problems in 11.53 sec ($SD = 11.52$) on average. They solved the same problems in 17.07 seconds ($SD = 14.16$) on average when they received a lexically unrelated prime beforehand. The prime condition was statistically

significant ($\chi^2(1)=177.25, p<.001$, see table 3) suggesting that participants from this sample needed 6.05 sec \pm 0.49 longer to solve the same CRA problem when presented with a lexically unrelated compared to a related prime.

Concerning accuracy, participants solved 73% ($SD = 43\%$) of the PCRA problems correctly on average when they were presented with a lexically related prime. They solved 53% ($SD = 50\%$) of the same problems correctly when these were presented with a lexically unrelated prime. The prime condition was statistically significant ($\chi^2(1) = 130.98, p<.001$, see table 3).

Participants reported to have found 0.52 apparent solutions (median) in the lexically related prime condition before having reached the final solution whereas they reported to have found 0.81 solutions (median) in the lexically unrelated condition. The GLMM revealed a significant effect of the prime condition onto the amount of reported search for potential solutions ($\chi^2(1) = 63.33, p<.001$, see table 3).

Finally, 78.7% ($SD = 41\%$) of all PCRA items in the lexically related condition were solved with a self-reported Aha! experience. In contrast, only 63.9% ($SD = 48\%$) of the same PCRA items presented with a lexically unrelated prime were solved with a self-reported Aha! experience. This difference was also statistically different ($\chi^2(1) = 58.70, p<.001$, see table 3). A summary of all likelihood ratio tests for the full model against the baseline model in respect to solution time, accuracy, search for potential solutions and Aha! experience is shown in table 3.

[please insert table 3 here]

Validation of PCRA paradigm – external criterion. Participants from the second sample solved about half of the verbal problems correctly ($M=48.09\%$, $SD=20.01\%$) while they solved only one third of all non-verbal problems correctly ($M=33.83\%$, $SD=16.56\%$). Accuracy in the lexically unrelated prime condition correlated significantly with classical verbal ($r=.315, p=.020$, 1-tailed) as well as with non-verbal ($r=.413, p=.003$, 1-tailed) insight problems. Accuracy in the semantically related prime condition also positively correlated with classical verbal ($r=.471, p=.001$, 1-tailed) and non-verbal ($r=.325, p=.017$, 1-tailed) insight problems. Finally, the difference values between the lexically related and unrelated prime condition only revealed a significant negative correlation with classical non-verbal insight problems ($r=-.288, p=.031$, 1-tailed) while the correlation with the classical verbal problems did not reach significance ($p>.38$) (for an overview of all correlation coefficients, see table 4).

[please insert table 4 here]

Parametric analysis of task difficulty – second sample. As expected, the cosine distance between the prime compound and solution compound in the lexically related prime (*teardrop – raindrop*) condition ($M=0.42$, $SD=0.10$) and the unrelated prime (*airdrop – raindrop*) condition ($M=0.59$, $SD=0.09$) differs and this difference is significant ($t(67)=-11.57$, $p<.001$). Furthermore, also the cosine distance between the prime and the solution in the lexically related prime (*tear - rain*) condition ($M = 0.56$, $SD = 0.14$) and unrelated (*air – rain*) prime condition ($M=0.72$, $SD = 0.07$) differs significantly ($t(67)=-8.69$, $p <.001$).

Finally, when modeling the influence of the cosine distance between the prime compound and the solution compound (*KnowConstraint*) as depicted in table 6, this variable turns out to be a significant predictor for solution time ($\chi^2(1) = 33.01$, $p<.001$, see table 6). The relationship is positive, that is to say, that solution time increases with increasing cosine distance of *KnowConstraint* when keeping other task difficulties or possible confounds (*Size_SearchSpace1*, *Size_SearchSpace2*, *Compounds*, *Frequency* and *Word_length*) constant. The cosine distance between the prime and solution (*Size_SearchSpace2*) also showed a positive significant relationship ($t(560.8.4) = 2.64$, $p = .008$) while all other predictors remained non significant ($p>.104$) (see, table 7).

The knowledge constraint variable (*KnowConstraint*) serves as significant single predictor for accuracy ($\chi^2(1)=25.42$, $p<.001$, see table 6). The significant relationship between accuracy and *KnowConstraint* is negative, stating that with increasing cosine distance the likelihood to solve the problem correctly decreases when keeping the other predictors constant. Furthermore, the cosine distance between the prime and solution (*Size_SearchSpace2*) also serves as significant predictor ($p = .002$) while the other variables remain non significant ($p>.117$).

[please insert table 6 here]

Moreover, there is a positive relationship between *KnowConstraint* and the amount of search for potential solutions and this relationship is significant ($\chi^2(1) = 12.96$, $p<.001$, see table 8). Hence, the less the prime compound is related to the solution compound, the more participants keep searching for the solution word and come up with solution ideas. The cosine distance between the prime and the solution (*Size_SearchSpace2*) functions as significant predictor for search for potential solutions ($p = .047$). Furthermore, the average frequency between the target words and the solution word (*Frequency*) is a negatively related to the search for possible solutions ($p = .041$). This suggests that the less frequent the targets and the solution word is the more often participants actively search for a solution. All other variables remain non-significant ($p>.116$).

Finally, *KnowConstraint* also serves as significant additional predictor for self-reported Aha! experience ($\chi^2(1) = 15.64, p < .001$, see table 8). The likelihood to report an Aha! experience decreases with increasing cosine distance between the prime compound and solution compound when keeping all other predictors constant. While the cosine distance between the prime and the solution (*Size_SearchSpace2*) and self-reported Aha! experience is also significantly negative ($p = .034$), the average cosine distance between the target words and the solution word is positively related to the likelihood of reporting an Aha! experience ($p = .037$). That is to say, the less the target words are lexically related to the solution word on average the more likely participants will report to have found the respective solution via Aha! experience.

[please insert table 7 here]

[please insert table 8 here]

Discussion

In this paper, we presented different sources of task difficulty (i.e., process and knowledge and language related factors) that may explain why verbal insight tasks like CRAs, which seem structurally identical, differ in their probability and time to be solved and are sometimes solved with and without an Aha! experience. Especially the influence of knowledge factors constraining the search space and requiring representational change has not yet been systematically investigated in these tasks. Therefore, our goal was to first construct a modified CRA (PCRA) task using lexical priming which is able to elicit representational change more systematically compared to the classical CRA tasks. Subsequently, we investigated its parametric influence on task performance and Aha! experience while keeping other task difficulties constant.

PCRA paradigm. In line with our hypotheses, the prime condition has an impact on performance, search for potential solutions and self-reported Aha! experience. In the lexically unrelated prime condition, solution time was increased as well as the search for potential solutions through the problem space (as indicated by “space bar” button presses until the final solution was found), accuracy and the likelihood of an Aha! experience was reduced. The prime induced effects of task difficulty seem to be robust as they could be replicated within a second independent sample with the previously evaluated items. In addition, we found first evidence that the performance in the unrelated prime condition was positively related to classical non-verbal and verbal insight tasks. Moreover, we found a negative relationship between classical non-verbal tasks and the performance difference between the lexically

related vs. unrelated prime condition specifically representing restructuring of a problem. That is to say, the higher the performance drop in the lexically unrelated prime condition, the lower was the performance in the non-verbal insight tasks.

Parametric analysis of task difficulty. We found evidence that the scope of the knowledge factor operationalized as lexical distance between the prime compound and the solution compound linearly affects the above mentioned dependent measures. This lexical relationship represents a parametric measure of what we refer to as representational change, because it quantifies how much the first target word changes in meaning when building a compound with a prime in comparison to when building a compound with a solution word. As hypothesized, the knowledge factor still remained a significant predictor for the dependent measures when controlling for other sources of task difficulty (or confounds) like the size of the search and problem space as well as word length and frequency.

However, it is important to mention that there are also other sources of task difficulty simultaneously affecting the dependent measures. The size of the search space operationalized as the lexical relationship between the solution and the prime (*Size_SearchSpace2*) also affects all reported dependent measures. This source of task difficulty is not directly related to representational change as it does not systematically change the search space (that is changing the solution relevant meaning of the target word). However, this source of task difficulty rather extends the existing search space by misleading the solver to associate an unrelated prime with a solution word. For future research it would be interesting to try to further disentangle both sources of task difficulty (*Size_SearchSpace2* and *KnowConstraint*). That is to say, it would be worthwhile to expand the existing data set and create primes that show either a lexical relationship between the prime and the solution (extending the search space) or a lexical relationship between the prime compound and the solution compound (changing the search space) but not both.

Interestingly, the average amount of possible compound words (*#Compounds*) – the size of the problem space – did not seem to have an impact on the reported dependent measures when taking the other predictors (*KnowConstraint*, *Size_SearchSpace1* & *Size_SearchSpace2*, *Frequency* and *Word_length*) into account. This could indicate that participants already search very selectively through the net of possible solution words and therefore the total amount of possible solutions is irrelevant.

One potential criticism could be that the priming induced knowledge constraint only extends the search space involving more search through the semantic network for potential compound

words but does not involve a change of the search space (i.e. representational change). However, there are reasons to believe that restructuring is at least made more likely in the lexically unrelated prime condition:

First, the tasks are constructed to such extent that the first compound word needs to be reinterpreted in the unrelated prime condition in order to find a solution. Of course, it is possible to solve the problems without paying attention to the prime by only trying to find a solution to the second or third target word. However, because the prime is present during the entire duration of the problem presentation, it is hard to entirely ignore it as the robust behavioral results of the prime condition indicate.

Second, the difference values in accuracy between both PCRA conditions – possibly representing the extra restructuring effort – negatively correlated with classical non-verbal insight tasks. However, this correlation provides only indirect evidence because it is possible that the observed relationship between the unrelated prime condition and the classical verbal as well as non-verbal insight problems is merely the consequence of a general ability to solve problems or working memory capacity. There have been various accounts linking fluid intelligence (that is the general ability to solve problems) as measured by the Raven matrices (Raven, Court & Raven, 1983; Paulewicz, Chuderski & Nęcka 2007; Gilhooly & Fioratou, 2009; Nęcka, Zak & Gruska, 2016) and working memory capacity (Ash & Wiley, 2006; Chein & Weisberg 2014, De Dreu et al., 2012) to insight problem solving and representational change. Moreover, we would have expected to also find a relationship between accuracy in classical verbal insight tasks and those difference values between both PCRA conditions because both tasks are language-based. One reason for the absence of effects could be the selection of classical insight problems. In contrast to the verbal insight problems, the non-verbal insight problems that we used here (like the eight-coin or two-string problem) are the ones usually referred to as standard tasks for representational change in the literature (Webb, Little & Cropper, 2016; Gilhooly & Murphy, 2005). Therefore, classical non-verbal problems might represent a more direct measure for representational change than the verbal ones. Finally, future research demands a more specific comparison between this PCRA paradigm and other verbal classical insight tasks (for example riddles as presented by Luo & Niki, 2003) while controlling for fluid intelligence and working memory to further validate the paradigm.

Our results are in line with previous research, where participants were shown to produce more solutions with self-reported Aha! experience for the lexically related compared to unrelated

prime in anagram problems (Bowden, 1997). However, our results seem counterintuitive if it is assumed that the Aha! experience is necessarily related to representational change (Kounios & Beeman, 2014) and we argue that representational change is induced in the lexically unrelated prime condition. Thus, one would expect more self-reported Aha! experience for solved problems in the lexically unrelated prime condition. However, recent research demonstrates that classical insight problems like the eight-coin or matchstick arithmetic problems that assume to involve representational change can also occur without an Aha! experience (Danek et al., 2016). This raises the question how the Aha! experience and representational change are related in insight problems. Danek and colleagues propose that the amount of self-reported Aha! experiences varies with the necessary degree for representational change (Danek et al., 2016). According to these authors, the more steps participants need to make to achieve a representational change and solve the problem, the more one feature – the suddenness of the solution – is lacking (Danek et al., 2016). In our paradigm, this would correspond with an increased search for more distantly related word compounds of the primed target word to find the solution. Indeed, participants increase their search for the solution by producing more potential (but wrong) solutions in the lexically unrelated prime condition when solving a PCRA problem. This could explain why participants report fewer solutions with Aha! experience in the unrelated prime condition: a) they searched for *more* (distant) compound words as possible solutions and therefore indicated to have found the solution more incrementally without Aha! experience and b) they might have experienced the correct solution as less sudden due to the fact that they have already produced a relatively high number of potential (but wrong) solutions. Lastly, the decreased rate of Aha! experience in the unrelated prime condition could also be explained by a lack of coherence. That is to say, the fact that participants may try to find a solution that integrates all the given information (including the misleading unrelated prime) into a coherent solution. Because this goal is not achieved due to the unrelated prime, their solution may not appear to them as obviously correct which is one necessary criterion for a solution with Aha! experience.

Hence, because representational change seems to be closely related to an extended search for lexically more distant compound words in this paradigm, the suddenness of the Aha! experience might not be the best indicator for representational change in this particular task setting. Although speculative but the self-reported Aha! experience in this context might indicate how surprising the unobvious solution of the PCRA problem in general was and less whether a target word needed to be reinterpreted. This speculation is in line with our results

stating a positive relationship between the likelihood of an Aha! experience and the average cosine distance between the target words and the solution word. Hence, the less the solution word was lexically related to the target words the more likely participants reported an Aha! experience.

Therefore, a different approach to indicate whether representational change is induced is to use eye tracking as established by Knoblich, Ohlsson and Raney (2001). This continuous measure allows to precisely track which word on the screen (be it the prime or one of the target words) is paid overt attention to during the problem solution. This could reveal relevant information about the dynamics of the solution process. For example, whether the first target word is more often fixated shortly before the final solution could be indicative of an attempt to reinterpret the first target word. An alternative approach to measure representational change would be to have participants continuously verbalize their search for the correct solutions (Gilhooly, Fioratou & Henretty, 2010; Fleck & Weisberg, 2004). That is to say, participants are prompted to speak out loud each possible solution word they come up with. This procedure would offer more qualitative information than just the amount of search for potential solutions. For example, the moment when the participant starts producing compound solutions of the less dominant meaning of the target word.

Finally, the main goal of this study was to present an idea of how to parametrically investigate the influence of knowledge constraints requiring representational change while controlling for other sources of task difficulty in verbal insight tasks. The paradigm is specifically well suited for a neurophysiological test setting because the items are short, structurally identical and can be solved within a short amount of time (Kounios & Beeman, 2014; Luo & Knoblich, 2007). Of course, we do not claim that the presented list of items is exhaustive. However, we hope that researchers interested in measuring different aspects of task difficulty with insight tasks can benefit from these considerations and use the already existing set of verbal problems or develop new items in their respective language.

Compliance with Ethical Standards

The ethics committee of the German society for psychology approved of this study and the procedures performed in it were in accordance with the 1964 Helsinki declaration and its later amendments.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Conflict of interest

MB was funded by the German Science Foundation (SFB 936/C7). The authors declare no conflict of interest.

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Supplementary Material

Table 1.

List of (G)LMMs: the influence of the prime condition onto solution time / accuracy / search / Aha! experience

Baseline: $\text{sqrt}(\text{RT}) / \text{accuracy} / \text{search} / \text{Aha! experience} \sim (1 | \text{subjects}) + (1 | \text{items}) + \epsilon$

Full model: $\text{sqrt}(\text{RT}) / \text{accuracy} / \text{search} / \text{Aha! experience} \sim \text{prime} + (1 | \text{subjects}) + (1 | \text{items}) + \epsilon$

Note. $\text{Sqrt}(\text{RT})$ = square root transformed solution time. ϵ = an error term. We modeled solution time, accuracy, search (for potential solutions) and Aha! experience separately but with the same fixed and random effects.

Table 2.

Results from *first sample for prime condition*: Likelihood ratio tests of full against baseline model

| | df | AIC | BIC | logLik | deviance | χ^2 | $\chi^2(\text{df})$ | p-value of χ^2 |
|--------------|----|--------|--------|---------|----------|----------|---------------------|---------------------|
| RT:Base | 4 | 22911 | 22938 | -11452 | 22494 | | | |
| RT: Full | 5 | 22504 | 22504 | -22538 | 11247 | 409.03 | 1 | < .000 |
| Acc: Base | 3 | 8852.3 | 8873.2 | -4423.2 | 8846.3 | | | |
| Acc: Full | 4 | 8516.4 | 8544.2 | -4254.2 | 8508.4 | 337.95 | 1 | < .000 |
| Search: Base | 3 | 19273 | 19294 | -9633.4 | 19267 | | | |
| Search: Full | 4 | 19086 | 19114 | -9539.0 | 19078 | 188.71 | 1 | < .000 |
| Aha: Base | 3 | 5225.5 | 5245.3 | -2609.8 | 5219.5 | | | |
| Aha: Full | 4 | 5152.2 | 5178.6 | -2572.1 | 5144.2 | 75.304 | 1 | < .000 |

Note. df = degrees of freedom (of respective model), AIC = Akaike information criterion, BIC = Bayesian information criterion, logLik = log-likelihood, χ^2 = Chi-square, RT = solution time, Acc = Accuracy, Aha = Aha! experience, Search = search for potential solutions, Base = Baseline model, Full = Full model, for specification of Baseline and Full model, see table 1.

Table 3.

Results from *second sample for prime condition*: Likelihood ratio tests of full against baseline model

| | df | AIC | BIC | logLik | deviance | χ^2 | $\chi^2(\text{df})$ | p-value of χ^2 |
|--------------|----|--------|--------|---------|----------|----------|---------------------|---------------------|
| RT: Base | 4 | 8659.3 | 8682.4 | -4325.7 | 8651.3 | | | |
| RT: Full | 5 | 8484.1 | 8513.0 | -4237.0 | 8474.1 | 177.25 | 1 | < .000 |
| Acc: Base | 3 | 3378.3 | 3396.1 | -1686.2 | 3372.3 | | | |
| Acc: Full | 4 | 3249.4 | 3273.1 | -1620.7 | 3241.4 | 130.98 | 1 | < .000 |
| Search: Base | 3 | 6044.7 | 6062.5 | -3019.4 | 6038.7 | | | |
| Search: Full | 4 | 5983.4 | 6007.1 | -2987.7 | 5975.4 | 63.33 | 1 | < .000 |
| Aha: Base | 3 | 1906.4 | 1923.2 | -950.22 | 1900.4 | | | |
| Aha: Full | 4 | 1849.8 | 1872.1 | -920.87 | 1841.8 | 58.70 | 1 | < .000 |

Note. df = degrees of freedom (of respective model), AIC = Akaike information criterion, BIC = Bayesian information criterion, logLik = log-likelihood, χ^2 = Chi-square, RT = solution time, Acc = Accuracy, Aha = Aha! experience, Search = search for potential solutions, Base = Baseline model, Full = Full model, for specification of Baseline and Full model, see table 1.

Table 4.

External validation – Correlations coefficients of accuracy between prime conditions in the PCRA paradigm and classical insight tasks

| | related prime | unrelated prime | difference values | classical non verbal IS |
|-------------------------|---------------|-----------------|-------------------|-------------------------|
| unrelated prime | .615** | | | |
| difference values | .173 | -.599** | | |
| classical non verbal IS | .325* | .413* | -.288* | |
| classical verbal IS | .471** | .315* | -.047 | .518** |

Note. Signif. codes: 0.01 ‘***’ (1-tailed) 0.05 ‘**’ (1-tailed); IS = insight tasks. Difference values refer to the accuracy difference between the related vs. unrelated prime condition in the PCRA paradigm.

Table 5.

List of nested (G)LMMs – the influence of different sources of task difficulty onto solution time / accuracy / search and Aha! experience

Baseline model: $\text{sqrt}(\text{RT}) / \text{accuracy} / \text{search} / \text{Aha! experience} \sim \text{Word_length} + \text{Frequency} + \text{Size_SearchSpace1} + \text{Size_SearchSpace2} + \# \text{Compounds} + (1 | \text{subjects}) + (1 | \text{items}) + \varepsilon$

Full model: $\text{sqrt}(\text{RT}) / \text{accuracy} / \text{search} / \text{Aha! experience} \sim \text{Word_length} + \text{Frequency} + \text{Size_SearchSpace1} + \text{Size_SearchSpace2} + \# \text{Compounds} + \text{KnowConstraint} + (1 | \text{subjects}) + (1 | \text{items}) + \varepsilon$

Note. $\text{Sqrt}(\text{RT})$ = square root transformed solution time. ε = an error term. We modeled solution time, accuracy, search (for potential solutions) and Aha! experience separately but with the same fixed and random effects. The different predictors are: *Word_length* = Word length of respective prime word; *Frequency* = average frequency of target CRA words and respective solution per item; *Size_SearchSpace2* = cosine distance between prime & solution per item; *Size_SearchSpace1* = mean cosine distance between target words and solution per item; *#Compounds* = mean amount of possible compounds for all three target words per item; *KnowConstraint* = cosine distance between prime compound & solution compound per item.

Table 6.

Likelihood ratio tests from *second sample* to test the influence of the knowledge constraint variable onto solution time / accuracy / search and Aha! experience

| | df | AIC | BIC | logLik | deviance | χ^2 | $\chi^2(\text{df})$ | p-value of χ^2 |
|-------------|----|--------|--------|---------|----------|----------|---------------------|---------------------|
| RT:Base | 9 | 7124.2 | 7174.6 | -3553.1 | 7106.2 | | | |
| RT:Full | 10 | 7093.2 | 7149.2 | -3536.6 | 7073.2 | 33.01 | 1 | < .001 |
| Acc:Base | 8 | 2747.2 | 2793.1 | -1365.6 | 2731.2 | | | |
| Acc:Full | 9 | 2723.7 | 2775.4 | -1352.9 | 2705.7 | 25.42 | 1 | < .001 |
| Search:Base | 8 | 5020.1 | 5066.1 | -2502.1 | 5004.1 | | | |
| Search:Full | 9 | 5009.2 | 5060.8 | -2495.6 | 4991.2 | 12.96 | 1 | < .001 |
| Aha: Base | 8 | 1806.4 | 1849.9 | -895.20 | 1790.4 | | | |
| Aha: Full | 9 | 1792.8 | 1841.7 | -887.38 | 1774.8 | 15.64 | 1 | < .001 |

Note. df = degrees of freedom (of respective model), AIC = Akaike information criterion, BIC = Bayesian information criterion, logLik = log-likelihood, χ^2 = Chi-square, RT = solution time, Acc = Accuracy, Aha = Aha! experience, Search = search for potential solutions, Base = Baseline model, Full = Full model, for specification of Baseline and Full model, see table 5.

Table 7.

(G)LMM results of Full model from second sample – Parametric modulation of different sources of task difficulty and its influence on solution time and accuracy

| Solution time | | | | Accuracy | | |
|---------------------|---------------|--------------|---------|---------------|---------|---------|
| Random effects: | Variance (SD) | | | Variance (SD) | | |
| Item (Intercept) | 0.225 (0.47) | | | 0.351 (0.59) | | |
| Subject (Intercept) | 0.523 (0.72) | | | 0.448 (0.67) | | |
| Fixed effects: | β (SE) | t-value (df) | p-value | β (SE) | z-value | p-value |
| (Intercept) | 3.438 (0.13) | 25.98 (62.3) | < .001 | 0.713 (0.14) | 5.11 | < .001 |
| Word_length | -0.075 (0.05) | -1.63 (706) | .104 | 0.109 (0.07) | 1.57 | .117 |
| Frequency | -0.027 (0.06) | -0.42 (50) | .676 | 0.124 (0.08) | 1.48 | .140 |
| Size_SearchSpace1 | -0.104 (0.08) | -1.36 (51.5) | .179 | 0.148 (0.10) | 1.47 | .142 |
| Size_SearchSpace2 | 0.141 (0.05) | 2.64 (560.8) | .008 | -0.246 (0.08) | -3.05 | .002 |
| #Compounds | 0.068 (0.08) | 0.90 (49.7) | .373 | -0.07 (0.10) | -0.73 | .467 |
| KnowConstraint | 0.289 (0.05) | 5.78 (761) | <.001 | -0.383 (0.07) | -4.90 | <.001 |

Note. β = standardized mean estimates; standard errors (SE) or standard deviation (SD) is given in parenthesis. Word_length = number of letters of respective prime; Frequency = average frequency of three target words and solution per item; Size_SearchSpace2 = cosine distance between prime & solution; Size_SearchSpace1 = mean cosine distance between target words and solution; #Compounds = mean amount of possible compounds for all three target words per item; KnowConstraint = cosine distance between prime compound & solution compound.

Table 8.

GLMM results of Full model from second sample – Parametric modulation of different sources of task difficulty and its influence on search and Aha! Experience

| Search | | | | Aha! Experience | | |
|---------------------|---------------|---------|---------|-----------------|---------|---------|
| Random effects: | Variance (SD) | | | Variance (SD) | | |
| Item (Intercept) | 0.063 (0.25) | | | 0.289 (0.54) | | |
| Subject (Intercept) | 3.549 (1.89) | | | 2.944 (1.72) | | |
| Fixed effects: | β (SE) | z-value | p-value | β (SE) | z-value | p-value |
| (Intercept) | -1.154 (0.30) | -3.83 | < .001 | -0.532 (0.28) | -1.87 | .061 |
| Word_length | -0.02 (0.03) | -0.71 | .481 | 0.140 (0.08) | 1.68 | .093 |
| Frequency | -0.074 (0.04) | -2.05 | .041 | 0.009 (0.08) | 0.11 | .914 |
| Size_SearchSpace1 | -0.069 (0.04) | -1.57 | .116 | 0.219 (0.10) | 2.09 | .037 |
| Size_SearchSpace2 | 0.074 (0.04) | 1.99 | .047 | -0.203 (0.09) | -2.12 | .034 |
| #Compounds | 0.041 (0.04) | 0.97 | .332 | -0.113 (0.10) | -1.11 | .266 |
| KnowConstraint | 0.126 (0.03) | 3.57 | < .000 | -0.367 (0.09) | -3.84 | < .001 |

Note. β = standardized mean estimates; standard errors (SE) or standard deviation (SD) is given in parenthesis. Word_length = number of letters of respective prime; Frequency = average frequency of three target words and solution per item; Size_SearchSpace2 = cosine distance between prime & solution; Size_SearchSpace1 = mean cosine distance between target words and solution; #Compounds = mean amount of possible compounds for all three target words per item; KnowConstraint = cosine distance between prime compound & solution compound.

APPENDIX A

List of classical insight tasks

Verbal insight tasks (adapted from Mayer & Dow, 2004)

- 1) **Prisoner:** A prisoner was attempting to escape from a tower. He found in this cell a rope, which was half long enough to permit him to reach the ground safely. He divided the rope in half and tied the two parts together and escaped. How could he have done this?
- 2) **Twins:** Marsha and Marjorie were born on the same day of the same month of the same year to the same mother and the same father – yet they are not twins. How is that possible?
- 3) **Sand piles:** A child playing on the beach has 6 sand piles in one area and 3 in another. If he put them all together, how many sand piles would he have?
- 4) **Archeologist:** One archeologist reported finding a Roman coin with Julius Caesar's image on it, dated 21 B.C. Another archeologist correctly asserted that the find was a fraud. Why?
- 5) **Widow:** Is it legal for a man to marry his widow's sister? Why or why not?
- 6) **Hole:** How many cubic centimeters of dirt are in a hole 6 meters long, 2 meters wide and one meter deep?
- 7) **Captain Scott:** Captain Scott was out for a walk when it started to rain. He did not have an umbrella and he wasn't wearing a hat. His clothes were soaked yet not a hair on his head got wet. How could this happen?
- 8) **Ancient invention:** there is an ancient invention still used in parts of the worlds today that allows people to see through walls. What is it?
- 9) **Earring in coffee:** One morning a woman's earring fell into a cup that was filled with coffee, yet her earring did not get wet. How could this be?
- 10) **Ping pong ball:** A magician claimed to be able to throw a ping pong ball so that it would go a short distance, come to a dead stop, and then reverse itself. He also added that he would not bounce the ball against any object or tie anything to it. How could he perform his feat?

- 11) **Fishing:** Two mothers and two daughters were fishing. They managed to catch on big fish, one small fish, and one fat fish. Since only three fish were caught how is it possible that each woman had her own fish?
- 12) **Window washer:** A window washer was cleaning the windows of a high rise building when he slipped and fell off a sixty-foot ladder onto the concrete sidewalk below. Incredibly he did not injure himself in any way. How was this possible?
- 13) **Boat ladder steps:** If a boat, at low tide, has 6 of its 12 ladder steps in the water. How many ladder steps will be in the water at high tide?
- 14) **28 days:** How many months have twenty-eight days in them?

Non verbal insight tasks (adapted from Mayer & Dow, 2004)

- 1) **Four dot:** Without lifting your pencil from the paper, show how u could join all 4 dots with 2 straight lines:



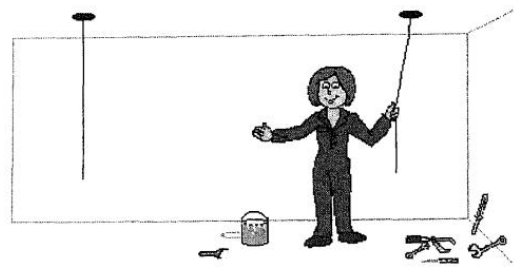
- 2) **Chain:** A woman has four pieces of a chain. Each piece is made up of three links. She wants to join the pieces into a single closed loop of chain. To open a link costs 2 cents and to close a link costs 3 cents. She only has 15 cents. How does she do it?
- 3) **Pens:** Describe how to put 27 animals in 4 pens in such a way that there is an even number of animals in each pen.
- 4) **6 Pencils:** How can you arrange 6 identical pencils in such a way as to form 4 identical triangles whose side areas are all equal, without modifying the pencils in any way?
- 5) **Put the Z:** Can you figure out where to put the letter Z, top or bottom line and Why?

A EF HI KLMN T VWXY

BCD G J OPQRS U

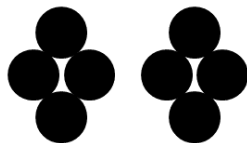
(source: Mayer & Dow, 2004)

- 6) **Two strings:** There are two strings hanging from the ceiling in the room below. The woman cannot reach both. How can she tie the two strings together?



(source: Mayer & Dow, 2004)

- 7) **Eight Coins:** Move two coins in such a way that each coin touches exactly three other coins. How can you do it?



- 8) **The pond problem:** How can the man reach the isle without touching the water. He has only 2 boards but both are 15 cm too short to directly put them onto the isle.



(source: Sloane & MacHale, 1994)

- 9) **Matchstick 1:** Which stick needs to be moved in such a way that the equation becomes true? $VI = VII + I$
- 10) **Matchstick 2:** Which stick needs to be moved in such a way that the equation becomes true? $I = II + II$
- 11) **Matchstick 3:** Which stick needs to be moved in such a way that the equation becomes true? $III = III + III$

APPENDIX B

| Solution | Remote Associates | Related prime | Unrelated prime | mean solution time in sec (SD) | | | % of participants correctly solving item accuracy (omission) | | | total number of participants | | | lexical relationship (cosine distance between prime compound & solution compound) | |
|----------|------------------------------|---------------|-----------------|--------------------------------|--------------------|----------------------|--|----------------|-----------------|------------------------------|---------------|-----------------|---|-----------------|
| | | | | no prime (SD) | related prime (SD) | unrelated prime (SD) | no prime | related prime | unrelated prime | no prime | related prime | unrelated prime | related prime | unrelated prime |
| ACHSEL | HÖHLE - SCHWEIß - ZUCKEN | KÖRPER | RÄUBER | 13,25 (13,73) | 11,03 (13,27) | 15,36 (11,68) | 0,74 (0,25) | 0,82 (0,03) | 0,57 (0,20) | 19 | 39 | 49 | 0,494 | 0,587 |
| AMEISE* | HAUFEN - SÄURE - BÄR | MAULWURF | KOMPOST | 20,71 (15,09) | 17,53 (11,58) | 21,91 (15,83) | 0,33 (0,35) | 0,38 (0,27) | 0,24 (0,51) | 48 | 55 | 55 | 0,516 | 0,460 |
| ANGST | STÖRUNG - HASE - SCHREI | PANIK | BETRIEB | 10,98 (10,47) | 8,98 (8,92) | 19,61 (14,88) | 0,72 (0,23) | 0,78 (0,06) | 0,39 (0,36) | 39 | 49 | 64 | 0,236 | 0,531 |
| APFEL | TASCHE - STRUDEL - BRATEN | FRUCHT | FEDER | 12,98 (10,01) | 9,90 (11,36) | 19,04 (14,83) | 0,79 (0,16) | 0,89 (0,04) | 0,64 (0,14) | 19 | 45 | 44 | 0,348 | 0,462 |
| ARM | REIF - DRÜCKEN - STÜTZE | FUSS | SPRUCH | 17,77 (11,48) | 15,41 (9,45) | 19,45 (15,32) | 0,73 (0,17) | 0,68 (0,23) | 0,46 (0,50) | 30 | 22 | 28 | 0,368 | 0,806 |
| ATOM | TEST - KERN - WAFFE | CHEMIKALIEN | AUFNAHME | 13,85 (13,29) | 10,39 (8,29) | 16,98 (14,72) | 0,73 (0,16) | 0,84 (0,04) | 0,55 (0,20) | 45 | 45 | 51 | 0,529 | 0,617 |
| AUGE | WINKEL - ZEUGE - SALBE | BLICK | DREH | 15,94 (12,89) | 12,10 (12,28) | 17,03 (13,08) | 0,54 (0,29) | 0,74 (0,16) | 0,47 (0,40) | 41 | 57 | 58 | 0,568 | 0,662 |
| AUTO | BATTERIE - DIEB - UNFALL | ANTRIEB | KÄFIG | 7,33 (6,97) | 14,74 (12,40) | 18,99 (14,20) | 0,93 (0,00) | 0,77 (0,14) | 0,60 (0,22) | 15 | 64 | 50 | 0,374 | 0,465 |
| BAHN | STATION - TARIF - SEIL | BUS | NOTFALL | 9,43 (7,12) | 11,61 (11,88) | 18,90 (14,34) | 0,77 (0,10) | 0,71 (0,04) | 0,45 (0,30) | 43 | 45 | 44 | 0,347 | 0,662 |
| BAND | LÄNGE - GUMMI - MAß | NAHT | SCHRITT | 17,46 (13,50) | 14,98 (11,73) | 18,81 (14,52) | 0,76 (0,14) | 0,65 (0,05) | 0,65 (0,08) | 37 | 40 | 49 | 0,230 | 0,378 |
| BANK* | AUSZUG - ZENTRAL - GEHEIMNIS | KONTO | WOHNUNG | 21,28 (15,37) | 13,33 (12,58) | 25,95 (16,85) | 0,71 (0,21) | 0,81 (0,13) | 0,17 (0,36) | 16 | 54 | 47 | 0,282 | 0,525 |
| BAUM | KRONE - STUMPF - CHRIST | WURZEL | ZAHN | 12,43 (12,50) | 12,59 (11,96) | 16,79 (13,61) | 0,82 (0,12) | 0,87 (0,04) | 0,62 (0,17) | 45 | 46 | 90 | 0,418 | 0,659 |
| BETT | DECKE - KANTE - HOCH | DAUNEN | BETON | 12,47 (9,49) | 14,00 (13,04) | 15,98 (12,09) | 0,71 (0,09) | 0,76 (0,07) | 0,50 (0,10) | 28 | 59 | 62 | 0,423 | 0,518 |
| BRIEF | WAHL - ÖFFNER - TAUBE | DIREKT | ZUCHT | 10,12 (13,82) | 9,43 (5,50) | 14,18 (13,69) | 0,77 (0,23) | 0,78 (0,13) | 0,76 (0,09) | 22 | 23 | 33 | 0,466 | 0,558 |
| BRILLE* | GLAS - HORN - GESTELL | KLAR | WEIN | 22,61 (19,61) | 17,48 (14,11) | 23,72 (16,11) | 0,44 (0,28) | 0,64 (0,10) | 0,37 (0,22) | 15 | 39 | 51 | 0,471 | 0,576 |
| BÜGEL* | FALTE - BRETT - KLEIDER | ROCK | SPECK | 13,62 (9,18) | 14,98 (12,85) | 17,27 (14,02) | 0,73 (0,20) | 0,65 (0,12) | 0,39 (0,30) | 45 | 57 | 46 | 0,502 | 0,485 |

| | | | | | | | | | | | | | | |
|----------|-----------------------------------|------------|-----------|------------------|------------------|------------------|----------------|----------------|----------------|----|----|----|-------|-------|
| DACH | BODEN - SCHRÄGE - BLECH | KACHEL | BECKEN | 13,70 (11,76) | 14,00 (12,45) | 17,99 (14,96) | 0,78 (0,09) | 0,67 (0,04) | 0,63 (0,07) | 46 | 46 | 43 | 0,490 | 0,612 |
| DARM | FLORA - INFEKTION - SPIEGELUNG | KEIM | ALPEN | 13,16 (14,19) | 10,09 (10,37) | 12,06 (8,96) | 0,74 (0,07) | 0,85 (0,05) | 0,57 (0,17) | 43 | 74 | 42 | 0,298 | 0,575 |
| EHE | BUND - KRACH - VERSPRECHEN | MÄNNER | STROH | 14,38 (11,22) | 9,68 (9,68) | 16,88 (14,88) | 0,70 (0,20) | 0,78 (0,11) | 0,45 (0,41) | 44 | 55 | 58 | 0,566 | 0,655 |
| FENSTER* | SCHEIBE - BRETT - LÄDEN | TÜR | BROT | 15,41 (15,07) | 10,03 (9,81) | 20,73 (16,07) | 0,75 (0,00) | 0,81 (0,04) | 0,35 (0,24) | 24 | 47 | 37 | 0,421 | 0,655 |
| FEUER | BALL - TEUFEL - ALARM | SCHNEE | GOLF | 14,78 (12,69) | 16,46 (14,79) | 23,34 (13,68) | 0,71 (0,21) | 0,69 (0,11) | 0,49 (0,31) | 38 | 45 | 49 | 0,483 | 0,608 |
| FINGER | RING - FERTIG - ABDRUCK | BAUCHNABEL | BOX | 12,05 (10,08) | 16,50 (13,56) | 20,43 (14,39) | 0,74 (0,18) | 0,71 (0,09) | 0,65 (0,19) | 39 | 45 | 48 | 0,460 | 0,691 |
| FISCH | BLASE - FILET - GOLD | WASSER | HARN | 8,86 (10,74) | 14,38 (13,39) | 22,61 (16,02) | 0,86 (0,07) | 0,62 (0,21) | 0,57 (0,22) | 29 | 63 | 67 | 0,444 | 0,512 |
| FLIEGE | FALLE - KLATSCH - STUBE | MOTTE | SCHULDEN | 9,66 (12,05) | 10,11 (11,42) | 11,63 (10,93) | 0,84 (0,11) | 0,82 (0,07) | 0,63 (0,04) | 19 | 71 | 57 | 0,281 | 0,729 |
| FUTTER | STELLE - NAPF - NEID | HERD | DIENST | 12,89 (13,90) | 11,06 (12,17) | 16,30 (15,36) | 0,75 (0,17) | 0,73 (0,03) | 0,52 (0,18) | 16 | 60 | 60 | 0,477 | 0,659 |
| GARTEN | LAUBE - ZAUN - HOF | HAUS | ROST | 12,45 (11,54) | 9,88 (8,54) | 17,28 (12,53) | 0,74 (0,18) | 0,82 (0,05) | 0,61 (0,11) | 39 | 60 | 56 | 0,399 | 0,413 |
| GESICHT | CREME - AUSDRUCK - PUPPE | SCHÖNHEIT | KOKOSNUSS | 14,32 (14,32) | 15,13 (12,72) | 25,58 (15,29) | 0,75 (0,14) | 0,69 (0,10) | 0,43 (0,27) | 51 | 49 | 60 | 0,401 | 0,421 |
| GLOCKE | TURM - KLANG - KUH | KIRCHE | EIFFEL | 10,61 (13,17) | 11,05 (12,51) | 16,68 (17,67) | 0,72 (0,26) | 0,81 (0,03) | 0,63 (0,22) | 43 | 67 | 63 | 0,337 | 0,524 |
| HERZ | SPENDER - KLOPFEN - Klappe | ORGAN | WÄSCHE | 15,46 (15,04) | 9,09 (7,99) | 24,24 (14,48) | 0,72 (0,26) | 0,77 (0,05) | 0,46 (0,33) | 43 | 56 | 54 | 0,413 | 0,571 |
| HOLZ | SCHUPPEN - WURM - DIELE | KOHLE | HAUT | 22,69 (15,41) | 12,59 (10,59) | 19,49 (13,83) | 0,83 (0,12) | 0,77 (0,14) | 0,56 (0,23) | 41 | 71 | 79 | 0,318 | 0,567 |
| HUND | BISS - SCHOß - STEUER | KATZE | GEWISSEN | 13,43 (12,18) | 12,42 (10,06) | 16,48 (15,38) | 0,72 (0,16) | 0,72 (0,16) | 0,63 (0,14) | 43 | 29 | 24 | 0,361 | 0,677 |
| KAFFEE | FILTER - FLECK - MALZ | TEE | RUß | 13,53 (13,48) | 12,51 (10,32) | 17,23 (14,21) | 0,78 (0,02) | 0,71 (0,07) | 0,48 (0,18) | 46 | 58 | 60 | 0,424 | 0,547 |
| KÄSE | PLATTE - SCHIMMEL - RAHM | WURST | SCHALL | 15,04 (12,28) | 9,09 (7,11) | 18,17 (13,32) | 0,64 (0,08) | 0,83 (0,04) | 0,44 (0,38) | 25 | 53 | 68 | 0,313 | 0,616 |
| KETTE | SÄGE - HALS - GOLD | KREIS | ZAHN | 15,93 (12,95) | 13,30 (10,39) | 16,79 (13,61) | 0,63 (0,13) | 0,64 (0,13) | 0,62 (0,17) | 24 | 45 | 90 | 0,360 | 0,678 |
| KOPF | SCHUSS - KISSEN - HÖRER | GENICK | START | 10,01 (11,79) | 9,75 (8,69) | 14,49 (13,05) | 0,77 (0,09) | 0,87 (0,13) | 0,47 (0,31) | 22 | 71 | 49 | 0,318 | 0,700 |
| LICHT | SCHALTER - NEBEL - BLITZ | HAUPT | ABFLUG | 16,78 (15,59) | 12,90 (12,70) | 20,33 (14,32) | 0,88 (0,08) | 0,90 (0,00) | 0,45 (0,33) | 24 | 41 | 51 | 0,400 | 0,473 |
| LIEBE | PAAR - ROMAN - LIED | BRAUT | REIM | 11,47 (11,03) | 9,65 (9,41) | 14,99 (11,72) | 0,85 (0,05) | 0,72 (0,02) | 0,67 (0,07) | 40 | 43 | 43 | 0,469 | 0,673 |
| LÖSUNG | WEG - MUSTER - VORSCHLAG | DENKE | FLUCHT | 17,98 | 13,02 | 15,67 | 0,65 | 0,59 | 0,56 | 23 | 44 | 45 | 0,493 | 0,450 |

| | | | | | | | | | | | | | | |
|--------|----------------------------|-------------|------------|---------|---------|---------|--------|--------|--------|----|----|----|-------|-------|
| | | | | (16,22) | (12,85) | (14,20) | (0,25) | (0,14) | (0,22) | | | | | |
| LUFT | STROM - BALLON - MATRATZE | ATEM | BESUCHER | 13,72 | 10,66 | 15,62 | 0,65 | 0,85 | 0,73 | 46 | 46 | 48 | 0,392 | 0,488 |
| | | | | (12,44) | (10,95) | (12,80) | (0,13) | (0,07) | (0,13) | | | | | |
| MEER | RAUSCHEN - JUNGFRAU - WELT | WELLE | BILD | 13,95 | 12,21 | 16,24 | 0,79 | 0,85 | 0,56 | 43 | 46 | 52 | 0,239 | 0,585 |
| | | | | (12,85) | (13,02) | (11,58) | (0,12) | (0,02) | (0,25) | | | | | |
| MODE | SCHAU - KATALOG - BEWUSST | KUNST | LEICHEN | 13,11 | 17,17 | 19,31 | 0,70 | 0,72 | 0,53 | 43 | 60 | 58 | 0,486 | 0,519 |
| | | | | (13,77) | (13,53) | (14,06) | (0,12) | (0,20) | (0,29) | | | | | |
| MORD | MOTIV - EHRE - VERDACHT | RACHE | LANDSCHAFT | 9,28 | 10,88 | 17,42 | 0,83 | 0,91 | 0,60 | 42 | 75 | 62 | 0,390 | 0,643 |
| | | | | (9,25) | (9,86) | (12,83) | (0,05) | (0,05) | (0,06) | | | | | |
| MÜLL | BERG - BEUTEL - ABFUHR | PAPIER | SCHULDEN | 10,63 | 6,41 | 11,63 | 0,86 | 0,89 | 0,63 | 36 | 72 | 57 | 0,471 | 0,443 |
| | | | | (12,75) | (5,57) | (10,93) | (0,14) | (0,06) | (0,04) | | | | | |
| MUTTER | SPRACHE - RABE - LEIB | BABY | AMT | 13,19 | 10,86 | 19,06 | 0,71 | 0,69 | 0,62 | 35 | 42 | 47 | 0,498 | 0,452 |
| | | | | (11,96) | (11,73) | (11,40) | (0,20) | (0,12) | (0,17) | | | | | |
| NAGEL | STUDIO - LACK - ZEH | KOSMETIK | FILM | 12,67 | 8,52 | 13,72 | 0,84 | 0,90 | 0,61 | 37 | 68 | 64 | 0,334 | 0,587 |
| | | | | (10,99) | (8,53) | (10,85) | (0,08) | (0,07) | (0,28) | | | | | |
| OHR | MUSCHEL - SCHMALZ - INNEN | HAND | PERLE | 10,44 | 8,41 | 13,40 | 0,80 | 0,86 | 0,84 | 46 | 42 | 43 | 0,333 | 0,630 |
| | | | | (11,30) | (8,93) | (13,82) | (0,00) | (0,07) | (0,07) | | | | | |
| ÖL | QUELLE - GEMÄLDE - OLIVE | SCHWEFEL | FEHLER | 13,35 | 11,16 | 14,35 | 0,83 | 0,84 | 0,66 | 23 | 64 | 58 | 0,502 | 0,605 |
| | | | | (12,98) | (9,48) | (13,16) | (0,17) | (0,05) | (0,10) | | | | | |
| PILZ | GIFT - FUß - HEFE | PFLANZEN | KASSEN | 12,25 | 11,65 | 16,07 | 0,79 | 0,83 | 0,69 | 38 | 42 | 51 | 0,318 | 0,561 |
| | | | | (13,94) | (11,84) | (12,32) | (0,21) | (0,07) | (0,20) | | | | | |
| POST | KASTEN - BOTE - ANSCHRIFT | SCHLÜSSEL | BESTECK | 7,63 | 10,20 | 13,16 | 0,79 | 0,81 | 0,75 | 24 | 63 | 60 | 0,560 | 0,568 |
| | | | | (4,57) | (9,98) | (10,90) | (0,11) | (0,03) | (0,05) | | | | | |
| PREIS* | WERT - SPRIT - SCHILD | ERTRAG | BEGEHREN | 16,66 | 8,05 | 18,47 | 0,50 | 0,50 | 0,10 | 11 | 10 | 10 | 0,745 | 0,564 |
| | | | | (6,96) | (3,98) | (17,96) | (0,45) | (0,30) | (0,75) | | | | | |
| RAD | KAPPE - PANNE - HAMSTER | VENTIL | NARREN | 12,98 | 10,16 | 12,90 | 0,91 | 0,85 | 0,81 | 22 | 60 | 59 | 0,364 | 0,610 |
| | | | | (14,43) | (7,01) | (10,94) | (0,00) | (0,07) | (0,07) | | | | | |
| RADIO | KANAL - FREQUENZ - WECKER | NACHRICHTEN | ÄRMEL | 9,87 | 10,14 | 18,69 | 0,64 | 0,74 | 0,50 | 22 | 54 | 62 | 0,367 | 0,750 |
| | | | | (7,60) | (9,10) | (13,36) | (0,14) | (0,02) | (0,19) | | | | | |
| REGEN | BOGEN - FRONT - RINNE | SONNE | ELLE | 9,52 | 7,68 | 16,31 | 0,71 | 0,70 | 0,64 | 41 | 40 | 44 | 0,540 | 0,724 |
| | | | | (11,40) | (7,22) | (13,78) | (0,03) | (0,03) | (0,07) | | | | | |
| REISE | LEITER - GEPÄCK - PASS | REGIONAL | STRICK | 16,42 | 12,36 | 14,39 | 0,68 | 0,74 | 0,64 | 37 | 46 | 47 | 0,582 | 0,720 |
| | | | | (12,94) | (11,37) | (10,66) | (0,08) | (0,04) | (0,13) | | | | | |
| SALAT | BLATT - SCHÜSSEL - SOBE | KOHL | DECK | 17,68 | 14,20 | 20,15 | 0,60 | 0,69 | 0,47 | 42 | 52 | 17 | 0,380 | 0,532 |
| | | | | (15,80) | (15,18) | (18,45) | (0,29) | (0,17) | (0,41) | | | | | |
| SALZ | STANGE - STREUER - KOCH | SELLERIE | STOß | 9,75 | 11,26 | 12,15 | 0,92 | 0,87 | 0,76 | 24 | 39 | 46 | 0,347 | 0,622 |
| | | | | (7,08) | (8,43) | (10,70) | (0,08) | (0,03) | (0,09) | | | | | |
| SAND | STURM - BURG - WÜSTE | STAUB | PROTEST | 12,30 | 9,04 | 21,58 | 0,79 | 0,83 | 0,61 | 39 | 54 | 66 | 0,311 | 0,604 |
| | | | | (10,01) | (8,47) | (14,74) | (0,21) | (0,06) | (0,18) | | | | | |
| SCHUH | RIEMEN - BÜRSTE - BALLETT | SCHNUR | KINN | 19,45 | 13,64 | 16,70 | 0,83 | 0,76 | 0,60 | 42 | 58 | 58 | 0,464 | 0,523 |
| | | | | (15,96) | (10,19) | (12,39) | (0,17) | (0,09) | (0,21) | | | | | |
| SPIEL | SUCHT - AUTOMAT - WÜRFEL | GEWINN | EIFER | 8,24 | 6,67 | 9,88 | 0,75 | 0,86 | 0,77 | 28 | 65 | 48 | 0,517 | 0,510 |
| | | | | (8,94) | (6,97) | (10,74) | (0,25) | (0,03) | (0,04) | | | | | |

| | | | | | | | | | | | | | | |
|--------|---------------------------|----------|--------|------------------|------------------|------------------|----------------|----------------|----------------|----|----|----|-------|-------|
| STADT | VIERTEL - PLAN - MAUER | HAFEN | DREI | 14,18 (12,87) | 15,00 (11,42) | 22,24 (19,00) | 0,63 (0,15) | 0,57 (0,19) | 0,50 (0,26) | 27 | 53 | 42 | 0,366 | 0,762 |
| STEIN | TAFEL - PFLASTER - GRAB | MARMOR | FEST | 13,22 (11,75) | 7,79 (6,90) | 16,17 (9,93) | 0,84 (0,08) | 0,89 (0,04) | 0,61 (0,11) | 38 | 56 | 38 | 0,292 | 0,605 |
| STUHL | BEIN - SCHAUKELE - LIEGE | TISCH | EIS | 16,58 (13,15) | 10,80 (10,23) | 23,13 (15,47) | 0,62 (0,13) | 0,70 (0,17) | 0,60 (0,18) | 45 | 46 | 45 | 0,483 | 0,576 |
| TAG | ZEIT - FEIER - GEBURT | ABEND | ELTERN | 14,28 (11,82) | 17,75 (11,46) | 19,50 (14,07) | 0,75 (0,20) | 0,77 (0,09) | 0,63 (0,13) | 20 | 53 | 60 | 0,470 | 0,701 |
| TIER | ART - VERSUCH - ALPHA | WAL | EIGEN | 8,45 (10,32) | 9,73 (9,31) | 11,52 (9,96) | 0,85 (0,06) | 0,91 (0,02) | 0,81 (0,05) | 34 | 65 | 59 | 0,293 | 0,626 |
| TOPF* | DECKEL - TON - LAPPEN | BEHÄLTER | BUCH | 14,43 (12,07) | 15,93 (18,05) | 19,40 (16,17) | 0,77 (0,13) | 0,29 (0,29) | 0,26 (0,43) | 31 | 16 | 23 | 0,354 | 0,625 |
| TOR | LINIE - LATTE - EIGEN | ABWEHR | FLUG | 15,03 (12,64) | 8,35 (5,78) | 19,59 (16,90) | 0,75 (0,13) | 0,80 (0,07) | 0,45 (0,25) | 40 | 56 | 51 | 0,522 | 0,766 |
| WALD* | RAND - SCHNEISE - SCHWARZ | WIESE | TELLER | 20,89 (14,98) | 16,20 (12,45) | 20,71 (15,74) | 0,57 (0,22) | 0,58 (0,16) | 0,43 (0,19) | 23 | 55 | 54 | 0,390 | 0,619 |
| ZUCKER | TÜTE - RÜBE - PUDER | WAFFEL | KNALL | 12,84 (13,57) | 10,28 (11,68) | 15,86 (13,08) | 0,83 (0,17) | 0,86 (0,07) | 0,69 (0,13) | 35 | 44 | 45 | 0,447 | 0,549 |