NeuroImage 206 (2020) 116294

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Inferior frontal gyrus involvement during search and solution in verbal creative problem solving: A parametric fMRI study

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ARTICLE INFO

Keywords:
Cosine distance
CRA
Inferior frontal gyrus
Priming
Semantic control

ABSTRACT

In verbal creative problems like compound remote associates (CRAs), the solution is semantically distant and there is no predefined path to the solution. Therefore, people first search through the space of possible solutions before retrieving the correct semantic content by extending their search space. We assume that search and solution are both part of a semantic control process which involves the inferior frontal gyrus (IFG). Furthermore, we expect the degree of relevant semantic control areas like the IFG to depend on how much the search space needs to be extended, i.e. how semantically distant the solution is.

To demonstrate this, we created a modified CRA paradigm which systematically modulates the semantic distance from the first target word to the solution via priming. We show that brain areas (left IFG and middle temporal gyrus) associated with semantic control are already recruited during search. In addition, BOLD response in the left angular gyrus linearly correlates with search space extension. Hence, there is evidence that this process already takes place during search. Furthermore, bilateral IFG (pars orbitalis and triangularis) also correlates with search space extension but during solution. We discuss the role of the IFG in accessing semantically distant information during verbal creative problem solving.

1. Introduction

Restructuring is of one of the key concepts in creative problem solving and refers to the ability of re-representing a problem in a different way such that a solution can be found (Ohlsson, 1992). The goal of this study is to provide a mechanistic description for restructuring (or *search space extension* as we call it in this context) in the verbal domain.

The ability to flexibly retrieve specific conceptual knowledge from semantic memory is important to use language productively, solve problems and think creatively (Binder et al., 2009). Mednick defined creativity as "the forming of associative elements into new combinations, which either meet specified requirements or are in some way useful" (Mednick, 1962, p. 221). In verbal creative problems such as compound remote associates (CRA) which are an extended version of the classic Remote Associate Task originally developed by Mednick (1962), participants need to correctly retrieve specific semantic knowledge by forming word associations to find a non-obvious solution without knowing the solution path. The latter refers to a set of problem-relevant rules that guide the solver to the solution, e.g. the rules of how to solve a simple math equation. In a CRA paradigm, three target words (*pine, pie, sauce*) are presented and the task of the problem solver is to find the one compound word (*apple* because *pineapple*, *apple pie* and *applesauce*) that complements each of these three words to a meaningful compound word (Bowden and Jung-Beeman, 2003, 2007). In the case of CRAs, a solution path would for example refer to a rule of how the three target words need to be associatively combined so the solution can be derived. However, there is no such rule in these kinds of verbal creative problems and many possible word combinations and associative compounds to each target word exist. How are these problems solved when there is no clearly defined solution path?

Every word is associated with a large set of other concepts and upon presentation the target words together with their semantically related and frequent associates are automatically activated in a widely distributed network (Bowers et al., 1990; Patterson et al., 2007). The dominant or more frequent associations are activated first (Zempleni et al., 2007; Simpson and Burgess, 1985). If the solution word would be a dominant

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https://doi.org/10.1016/j.neuroimage.2019.116294
Received 29 January 2019; Received in revised form 16 September 2019; Accepted 16 October 2019
Available online 19 October 2019

associate of all three target words, it would be multiply co-activated and therefore be more easily retrievable for the solver than competing and non-dominant associates (Bowers et al., 1990, p. 80). However, dominant but solution-irrelevant associations (*pine →pine tree*) are often activated first in CRAs which is why the solution word (*apple*) seems remote and non-obvious to the solver (Bowden et al., 2005; Goel et al., 2014).

According to the representational change theory (RCT), participants try to solve problems without a predefined solution path (like CRAs or matchsticks problems) by first searching dynamically through a constrained search space (Ohlsson, 1992; Öllinger et al., 2014). The search space refers to all preactivated or retrievable knowledge elements that are related to the presented problem. However, the search space is constrained due to solution-*irrelevant* activated prior knowledge. In the case of a CRA, this corresponds to the attempt of retrieving semantic associations that fit to the dominant and most frequent meaning of each of the target words (*pine* as in *pine tree*) when actually the non-dominant meaning (*pine* as *in pine apple*) of at least one of the target words is solution-relevant (Bowden et al., 2005). For example, participants try to recall all possible compound words of one of the target words according to its dominant meaning (*pine forest, pine tree, pine oil* etc.). However, if the attempt to retrieve the correct semantic content continuously fails, participants either give up or may find the solution by changing the way they represent the problem (Öllinger et al., 2014). Note, changing the problem representation is not the only strategy that can lead to insightful problem solving (for a more thorough discussion on this matter, (see Ash et al., 2009). According to RCT, one way to change the problem representation is relaxing self-imposed knowledge constraints (Ohlsson, 1992; Knoblich et al., 1999; Öllinger et al., 2014). In the case of CRAs, this constraint relaxation refers to an extension of the search space which includes (a) inhibiting the preactivated dominant but solution-irrelevant meaning of the target word and its associations and (b) retrieving the remote and non-dominant but solution-relevant meaning of a target word and its respective associations) (Becker et al., 2018; Bowden et al., 2005; Dow and Mayer, 2004). For conceptual clarity, we will from now on refer to this process of inhibition and remote retrieval as *extension of the search space*. The ability to change the problem presentation or restructure (by means of constraint relaxation or search space extension as we call it in the case of CRAs) is a key concept in insight problem solving and creative cognition (Knoblich et al., 1999; Öllinger et al., 2014; Ohlsson, 1984, 1990; 1992; DiBernardi Luft, 2018). More creative individuals have been found to successfully avoid the most obvious but false candidate solutions (Gupta et al., 2012). However, the neural mechanism of search and search space extension in creative problem solving is still vastly uncharacterized (e.g. Di Bernardi Luft et al., 2018).

We assume that this process of search space extension involves enhanced semantic control. We define semantic control as executive control directing the activation of semantic knowledge in a task appropriate manner (Harvey et al., 2013). Evidence from studies using lexical decision tasks demonstrate that semantic control is relevant in situations when retrieval or selection of semantic knowledge is difficult. Retrieval of semantic knowledge can be difficult for example when task-relevant information is only weakly activated (e.g. weak cue-target associative strength in a lexical decision task) (Badre et al., 2005). Selection of semantic knowledge can be difficult when a subset of task-relevant semantic knowledge must be selected over a competing subset of irrelevant knowledge (Badre et al., 2005; Bedny et al., 2008; Noonan et al., 2010, 2013; Whitney et al., 2010b; Rodd et al., 2011; Thompson-Schill et al., 1997). For example when subjects need to judge the similarity between stimuli along a specific semantic dimension (e.g. form) despite other task-irrelevant semantic features of the stimuli (e.g. color). Retrieval and selection of semantic knowledge is also difficult in CRAs because the remote compound is only weakly activated and task-irrelevant (dominant) associations of the target words are often activated first. Therefore, we assume that finding the solution involves enhanced semantic control.

To demonstrate this assumed relationship in a verbal creative problem solving context, we recently experimentally manipulated semantic control in CRAs by parametrically modulating the extent of the search space necessary to find a solution (Becker et al., 2018). This is achieved via semantic priming: A prime (*back, dew*) is additionally presented next to the three target words (*drop, coat, proof*) changing the meaning of the first target word (*backdrop* or *dewdrop*). We quantified this change in meaning parametrically by measuring the semantic distance between the prime compound (*backdrop*, *dewdrop*) and the solution compound (*raindrop*). We assumed that the higher the semantic distance between the target words and the solution word, the more remote the solution and the more semantic control is necessary to retrieve the correct semantic content.

We have previously shown behaviorally that solution time linearly increases and accuracy decreases with the degree of how much the search space had to be extended (measured as semantic distance between the prime and solution compound, see Methods section) (Becker et al., 2018). Hence, there is behavioral evidence for enhanced semantic control with increasing search space extension during verbal creative problem solving. However, this behavioral evidence does not elucidate yet two relevant questions: First, which brain areas are associated with this process of search and search space extension? Are those brain areas the same that are also associated with semantic control? Second, at what point do participants try to extend their search space to retrieve the correct semantic content? Is it already during search or only during solution?

Concerning the first question, we assume that the inferior frontal gyrus (IFG) is associated with the amount of search space extension because this brain region has been repeatedly identified as a key semantic control region in lexical decision tasks (Badre et al., 2005, 2007; Whitney et al., 2010a; Hampshire et al., 2010). Moreover, although previous studies investigating verbal creative problem solving often report a distributed network of activated brain areas during solution, the IFG seems to be consistently co-activated during solution (Wu et al., 2013; Zhao et al., 2013; Luo, Niki and Phillips, 2004a, 2004b; Tang et al., 2015). Hence, there is evidence for increased semantic control during problem solution executed via the IFG, but it is still unknown whether this brain area is *specific* for search space extension. In addition, the above named studies only report results during solution not during search. It is therefore unknown whether semantic control is already applied during search in a verbal creative problem solving context. Because participants retrieve task-relevant semantic content from lexical memory already during search, we assume that search also requires semantic control. The difference between search and solution is rather that during search the retrieved semantic content does not yet suffice all task constraints (i.e. the possible solution builds a reasonable compound with one or two of the target words but not with three) and is therefore *incorrect* compared to the solution. Hence, semantic control areas like the IFG should already be active during the search phase.

Concerning the second question, two scenarios are possible: First, participants do not realize that their search space is constrained and keep searching within this constrained space. For example, they try to find a solution compound to *rain* in the sense of *pine tree* instead of *pineapple*. Subsequently, only before solution they extend their search space by also considering non-dominant associations of the target words (*pine apple*) which increases the chance that the correct solution word is activated and therefore becomes part of the current (extended) search space. In this case, activation in semantic control areas like the IFG should linearly correlate with the degree of search space extension only during solution and not during search. The second scenario would be that participants already extend their search space during search by activating non-dominant but solution-irrelevant associations of the target words (like *pine nut*) but still fail to find the correct solution word. In this case, semantic control areas should already correlate linearly with the degree of necessary search space extension during search.

In order to investigate these hypotheses, we conducted a fMRI-study using the aforementioned modified CRA paradigm that parametrically modulates the extent the search space.

2. Materials and methods

2.1. Participants

We included 30 healthy right-handed participants recruited via an online student platform in Hamburg (age [in years]: range = 18–31, 23 females: $M = 23.5$; 7 males: $M = 25.1$). All 30 participants had normal or corrected-to-normal vision, were German native speakers and received a financial compensation for their participation. The ethics committee of the German society for psychology approved of this study. Informed consent was obtained from all individual participants included in the study. Participants were selected based on their performance (at least 40% accuracy) in an online pretest. In this online test, subjects were asked to solve 16 compound remote associates. 14 participants were rejected prior to invitation due to too low performance in the pretest (the final sample included 30 participants). This procedure ensured that the invited subjects were expected to produce a sufficient number of events in the MRI for later analyses.

However, we have reason to believe that performance of the included participants is comparable to that of a wider population. First, the selected participants ($M = 7.17$, $SD = 2.01$) performed similar in terms of a short version of the Raven's Advanced Progressive Matrices -an approximate measure for general problem solving ability - compared to the excluded participants ($M = 7.0$, $SD = 2.49$) (Arthur and Day, 1994). Second, accuracy and solution time of the modified CRAs were comparable between the preselected participants in this study (accuracy: $M = 69\%$, $SD = 47\%$; solution time $M = 11$sec; $SD = 13$sec) and a previous online study (n = 40; accuracy: $M = 73\%$, $SD = 43\%$; solution time: $M = 12$sec; $SD = 12$sec) (see, Becker et al., 2018). In the previous online study, we did not preselect participants based on their performance while using the same set of modified CRAs.

2.2. Experimental design and procedure

The experimental paradigm was a modified compound remote associates task as described in detail in Becker et al. (2018). We designed this task utilizing semantic priming to constrain the search space experimentally and more systematically than the classic CRAs as described in Bowden and Jung-Beeman (2003).

Three target words (*drop, coat, proof*) were presented and the goal was to find a solution word (*rain*) that can be appended in front or in the back of every one of the target words building a meaningful compound respectively (*raindrop, raincoat, rainproof*). Additionally, a prime word (*dew* or *back*) was presented building a compound word with the first target word (see Fig. 1, panel 1): As compound with a semantically related prime, the meaning of the first target word remains the same (*dewdrop*) compared to when building a compound with the solution word (*raindrop*). In case of the demonstrated example, both compounds (*dewdrop*, *raindrop*) refer to small quantities of liquid. Whereas in combination with a semantically unrelated prime (*backdrop*), the first target word changes its meaning compared to the solution compound (*raindrop*). We specifically chose the first target word to build a compound with the prime so that the prime compound reads as a complete word (*backdrop*). We assumed that the presentation of the prime compound as a coherent visual chunk should increase the effect of the induced solution-ir/relevant associations.

To ensure that participants understood all task requirements, they had to complete four test examples outside of the scanner and were additionally instructed orally. They were told that the solution word could be put in front or in the back of every target word and the solution would only be a common noun word which exists in the German dictionary. In addition, they were told that the prime word can but does not have to be semantically related to the problem solution. In the MRI, the participants received a button press device with five buttons for their right hand. They were asked to press button 1 as soon as they came up with a solution. To also get an estimate of their search behavior,

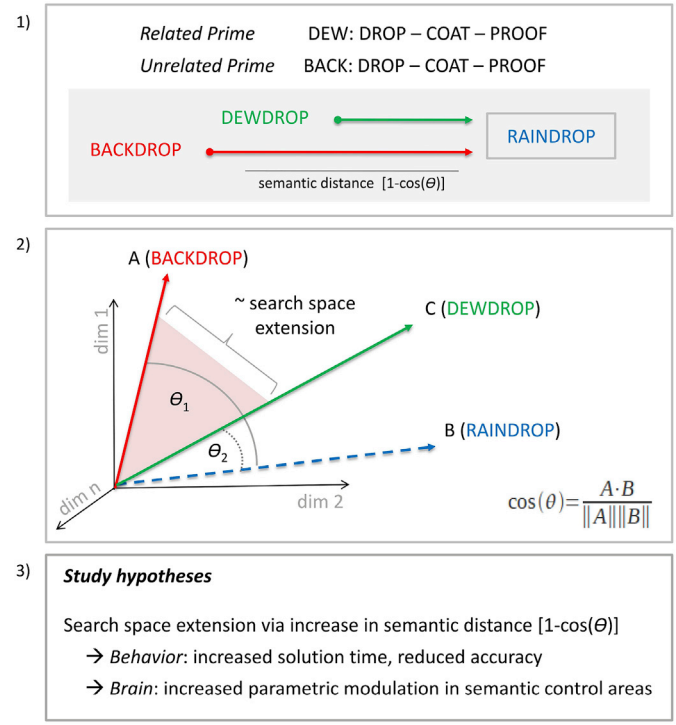

Fig. 1. Example of a modified CRA item, estimation of extent of the search space via cosine distance 1-cos(Θ) and study hypotheses.
Note. **Panel 1**: Example of a modified CRA item with a semantically more (*dew*) and less related prime (*back*), illustration with gray background depicts the measure of interest (*Search extension* variable) – the semantic distance between the respective prime and solution compound. **Panel 2** is a simplified representation of how to quantify change in meaning of the first target word due to the semantically more and less related prime via cosine similarity cos(Θ). The concepts (backdrop, dewdrop and raindrop) are represented as vectors (A, B, C) in an n-dimensional space and the cosine similarity cos(Θ) is calculated between every word pair by using the dot product and magnitude as depicted in the formula in the right corner. The more the meaning changes as a function of prime, the smaller is the cosine similarity (and the bigger the cosine distance) between the solution compound (raindrop) and the respective prime compound (backdrop or dewdrop). dim = dimension. **Panel 3.** Hypotheses regarding changes in meaning as represented by the *Search extension* variable: With increasing semantic distance between the prime and solution compound, solution time is expected to increase and accuracy is expected to decrease. On the brain level, semantic control areas like the IFG are expected to be parametrically modulated by the amount of Search space extension (*Search extension* variable).

participants were instructed to press button 2 (=search button) whenever they thought of a potential solution word but which was not their final solution (for a visual representation of search and solution button presses over all presented items in a selection of participants, see Fig. 7, supplementary material). During the test trials outside of the scanner, participants were specifically instructed to press the search button whenever they had a potential solution and they did not enter the scanner before we were not convinced that they were able to follow these task instructions. We specifically chose a button press for search instead of verbalization of potential solutions due to evidence that verbalization harms performance in insight-problem solving (Schooler et al., 1993; Kiyokawa and Nakazawa, 2006).

Participants completed a set of max. 66 items ($M = 61$, $SD = 6$) in 3 consecutive sessions (22 items per session) of max. 15 min scanning time each. All utilized items were in German, validated and are listed in Becker et al. (2018) with their respective lexical and statistical properties. The items do not statistically differ in word length of the primes, average frequency of the three target words and the solution word, or mean amount of possible compounds for all three target words per item

(Becker et al., 2018).

Every problem was presented for max. 60 s in random order in each session. The session order and the prime conditions were counter balanced between participants. The items were presented on a screen in the MR scanner (see Fig. 2): The prime word appeared for 2 s and subsequently the three target words appeared next to the prime for max. 60 s. If participants did not press button 1 (solution) then they would be asked how much effort they invested in finding the solution (on a scale from 1 to 5) and subsequently the next trial would start. We inserted the last question to control for differences in effort on task performance. If they did press button 1 for the solution, they would see five response options for 8 s: four gap words with one correct answer like R _ _ N (see Fig. 2) and one question mark indicating an alternative solution. In 8% of all cases, participants responded to have found an alternative solution, however because we cannot verify whether this solution was correct, we discarded those answers for the calculation of accuracy and all behavioral as well as fMRI analyses. The response options were only presented for 8 s to prevent participants from reevaluating their solution using the gap words. If participants did not respond within those 8 s the trial was counted as incorrectly solved. Subsequently, participants were asked about their solution experience, i.e. whether they had an Aha! experience upon solving the problem or not. Note, we do not report and discuss results concerning the solution experience here, as it is a matter on its own and it is discussed elsewhere (Becker et al., 2019).

2.3. Quantification of change in meaning via cosine distances

In order to quantify this change in meaning, we calculated the semantic distance between the prime compound (*dewdrop*, *backdrop*) and solution compound (*raindrop*) via the cosine similarity (see further below, Fig. 1, panel 2). As already mentioned further above, participants retrieve semantic associations based on the most likely (primed) meaning of the target words that build the basis for searching for an associative compound word fitting to all three target words. We assume that the more semantically distant the primed target word will be from the solution compound, the more semantically remote is the solution and the more solution-irrelevant associations are preactivated. Hence, we assume that the semantic distance between the target and solution compound is proportional to the amount that the search space would have to be extended in order to find the correct solution. Note that it is not the semantic distance of the prime to the solution that is of interest here because this distance does not represent the (changed) meaning of the first target word and its solution-irrelevant associations. However, the semantic distance between the prime word (*dew*, *back*) and the solution (*rain*) as well as the mean distance between the target words (*drop, coat, proof*) and the solution could be possible confounds. That is to say, they could represent other aspects of task difficulty (for example the amount of accessible compound words or solution-ir/relevant associations only due to the prime, for a discussion on this matter see, Becker et al., 2018). Therefore, we additionally used the semantic distance of both measures (i.e., first, mean semantic distance between target words and solution [in the following referred to as *Target words* variable] and second, semantic distance between prime and solution [in the following referred to as *Prime* variable]) as covariates of no interest in all further analyses.

Semantic distances between the respective word pairs were derived from statistical co-occurrences in text data via word embeddings. The method of extracting semantic distances via word embeddings has been described in detail in Becker et al., (2018). For reasons of brevity we will not go into detail on this here. The text database to compute the semantic distances between the respective word pairs was the Leipzig Corpora

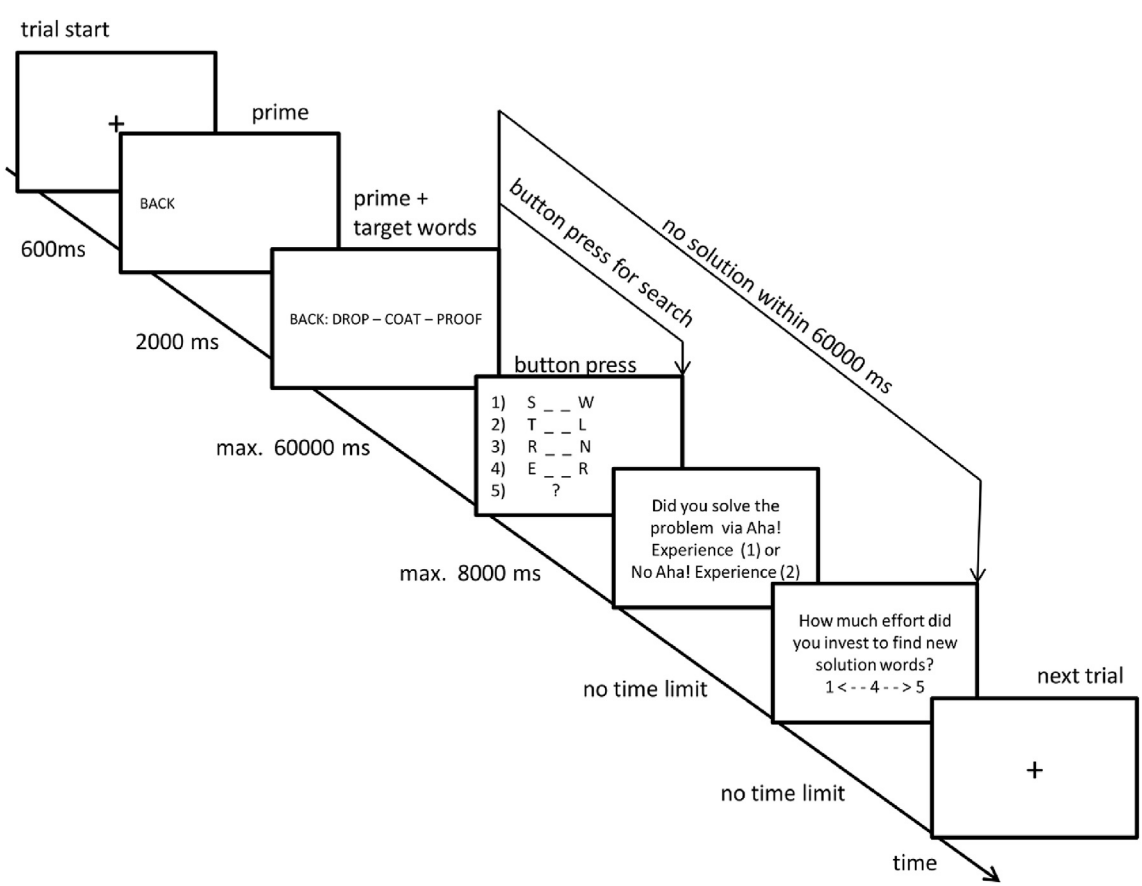

Fig. 2. Time flow of *modified CRA* – paradigm.
Note. The participants were instructed to press the button 2 every time they thought of a potential solution and button 1 for their final solution. Upon button press 1, they had eights to choose between four response options (1–4) or choose option 5 for their alternative solution.

Table 1a
List of GLMMs: the influence of the *Search extension* variable onto solution time, accuracy & search.

Baseline model: RT/accuracy/search ~ Target words + Prime + (1|subjects) + (1|items) + ε
Full model: RT/accuracy/search ~ Search extension + Target words + Prime + (1|subjects) + (1|items) + ε
Full model + RT: search ~ RT + Search extension + Target words + Prime + (1|subjects) + (1|items) + ε
Exploratory model: RT ~ Search extension*Raven + Target words + Prime + (1|subjects) + (1|items) + ε

Note. RT = solution time. ε = an error term. We modeled solution time, accuracy and search (for potential solutions) separately but with the same fixed and random effects. For search, we added solution time (RT) as an additional predictor to control for more search due to longer solution time. *Target words* = mean semantic distance between target words and solution, *Prime* = semantic distance between prime and solution, *Search extension* = semantic distance between prime compound and solution compound. Raven = mean solution time for 12 items of Raven's advanced matrices weighted by amount of correctly solved items.

Collection sampled from news websites in German language (Biemann et al., 2007) as well as 1.4 million sentences from web texts. Specifically, the first 200 hits on the Google search engine for each word from the CRA item list were automatically crawled and the sentences contained in the text paragraph tags on these pages were extracted (Becker et al., 2018). Dependency-based word embeddings with a neural network architecture as introduced by Levy and Goldberg (2014) were computed. In summary, this network learns to put words which occur in similar contexts in word documents in proximate regions of the vector space (see Fig. 1, panel 2: the respective words [*dewdrop, raindrop & backdrop*] are represented as vectors [A, B, C]). We determined the semantic relationship between two concepts (i.e., *backdrop, raindrop*) by computing the cosine similarity between two word vectors (A, B) as depicted in the lower right formula in Fig. 1, panel 2).

That is to say, a high cosine similarity (value close to $\cos(0^\circ) = 1$) signifies that both word vectors point into a similar direction which is interpreted as a high semantic similarity. Low cosine similarity (value close to $\cos(90^\circ) = 0$) means that both vectors are almost orthogonal. We inverted those values to cosine distance (1 – cosine similarity) so that a value close to 1 can be interpreted as high semantic distance and a value close to 0 as low semantic distance. Finally, despite the bimodal design (two primes for one CRA item), the derived cosine distances are normally distributed across all items and primes (see, Fig. 6, supplementary material). This is due to the fact that CRA items differ between each other in terms of their semantic distance between the related and unrelated prime compound to the solution compound. The average cosine distance between the semantically related prime compound (*dewdrop*) and solution compound (*raindrop*) was $M = 0.41$ ($SD = 0.09$) and between the unrelated prime compound (*backdrop*) and solution compound was $M = 0.59$ ($SD = 0.09$). The difference in cosine distance between the un/related prime compound to the solution compound (*backdrop* to *raindrop and dewdrop* to *raindrop*) was significant ($t(65) = -11.57$, $p < .001$). In addition, the cosine distance between the semantically related prime and the solution and the semantically unrelated prime and solution also differs significantly ($t(65) = -8.54$, $p < .001$). Therefore, as mentioned further above, we added the semantic distance between prime and solution word into all behavioral and fMRI analyses as covariates.

2.4. Behavioral data analysis

To investigate the influence of the search space extension on behavior, we modeled the behavioral responses from the fMRI experiment using Generalized Linear Mixed Models (GLMMs). Specifically, solution time (time between the presentation of the target words of the modified CRA problem and the respective solution button press – continuous variable), accuracy (correctly vs. incorrectly or not solved items per trial – binary variable) and amount of search (amount of search button presses per trial – count variable) served as dependent variables. These variables quantify to what degree task performance linearly depends on the amount of how much participants need to extend their search space. Hence, the main independent variable of interest was the *Search extension* variable that was operationalized as the semantic distance between the prime compound (*backdrop*) and solution compound (*raindrop*). We assumed that the more the search space needs to be extended the longer participants search for a solution and the less accurate they will be. If participants already extend their search space during the search phase, then this may reflect in a higher amount of search button presses.

To control for possible confounds of task difficulty between the presented CRA words as mentioned further above, we additionally included the *Prime* variable (the semantic distance between prime [*dew*] and solution [*rain*]) and the *Target words* variable (the mean semantic distance between the target words [*drop, coat, proof*] and the solution [*rain*]) as independent variables into all GLMMs (see Table 1a, Becker et al., 2018). Thus, the latter two variables were only modeled as covariates of no interest. Furthermore, we modeled all subjects and items as random intercept effects to control for possible differences between subjects and between CRA items. The analyses were carried out using R (R Core Team, 2014) and the lme4 package (Bates et al., 2012). In order to reach normally distributed error terms when modeling solution time, we assumed a Gamma error distribution with the default inverse link function (Verhelst et al., 1997). Accuracy was modeled assuming a binomial error distribution with the default logit link function (Bates et al., 2012). The amount of search was modeled assuming a Poisson error distribution with the default log link function (Gardner et al., 1995).

Table 1b
List of GLMs for fMRI analysis.

Model	Onset regressors	Parametric modulator	Time (in sec)
1	all Search	(1) Prime, (2) Target words, (3) Search extension	0
	Solution	(1) Prime, (2) Target words, (3) Search extension	0
2	cor Search	(1) Prime, (2) Target words, (3) Search extension	0
	Solution	(1) Prime, (2) Target words, (3) Search extension	0
3	all Search	(1) Prime, (2) Target words, (3) Search extension	last 2
	Solution	(1) Prime, (2) Target words, (3) Search extension	last 2

Note. Time refers to the time in seconds **before** pressing the search or solution button – onset regressor and parametric modulator are modeled according to the same time, *Prime* = semantic distance between the prime and the solution word, *Target words* = mean semantic distance between the target words and the solution, *Search extension* = semantic distance between the prime compound and solution compound. *All Search* = all search button presses from all (solved and unsolved) trials, *cor Search* = search button presses from trials that were later solved correctly. Model 3 was set up only for exploratory purposes.

Table 2
Likelihood ratio tests to test the influence of the *Search extension* variable onto solution time/accuracy/search.

	df	AIC	BIC	logLik	deviance	χ^2	χ^2(df)	*p*-value of χ^2
Acc:Base	5	2170.6	2198.1	−1080.3	2160.6			
Acc:Full	6	2124.3	2157.3	−1056.1	2112.3	48.28	1	<.001
Search: Base	5	3952.1	3978.6	−1971.0	3942.1			
Search: Full	6	3924.2	3956.1	−1956.1	3912.2	29.84	1	<.001
Search: Full + RT	7	3295.8	3333.0	−1640.9	3281.8	630.41	1	<.001
RT:Base	6	11028	11160	−5558.1	11116			
RT:Full	7	11095	11132	−5540.5	11081	35.12	1	<.001
RT:Exploratory	9	11092	11139	−5536.8	11074	7.47	2	<.05

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, Search = search for potential solutions, Base = Baseline model, Full = Baseline model + *Search extension* variable, Full + RT = Full model with solution time as additional predictor; Exploratory = Exploratory model with interaction term including a measure for general problem solving ability. For specification of Baseline, Full, Full + RT and Exploratory model, see Table 1a.

Table 3
GLMM results of full model – Influence of *Search extension* variable and other sources of task difficulty on solution time, accuracy and search.

Random effects:	Solution time		Accuracy		Search	
	variance (SD)		variance (SD)		variance (SD)	
Item (Intercept)	.0001 (.008)		0.501 (.71)		.00 (.00)	
Subject (Intercept)	.0001 (.011)		0.277 (.53)		.66 (.81)	
Fixed effects:	ß (SE)	t-value	ß (SE)	z-value	ß (SE)	z-value
Intercept	.072 (.02)	4.40**	2.04 (1.11)	1.83	-.98 (.29)	−3.32**
Search extension	-.057 (.01)	−5.88**	−4.55 (0.70)	−6.49**	.34 (.22)	1.55
Target words	.053 (.03)	2.14*	2.77 (1.71)	1.62	-.41 (.38)	−1.09
Prime	-.026 (.01)	−2.82*	−0.99 (0.62)	−1.58	.06 (.21)	0.26
RT					.04 (.00)	26.75**

Note. Significance codes: 0.001 '**', 0.05 '*', ß = standardized mean estimates; standard errors (SE) or standard deviation (SD) is given in parenthesis. Prime = cosine distance between prime (*dew*) and solution (*rain*); Target words = mean cosine distance between all three target words per item (*drop, coat, proof*) and solution; *Search extension* = cosine distance between prime compound (*dewdrop*) & solution compound (*raindrop*). Random and fixed effects for solution time and accuracy are depicted for the full model. For search these effects are depicted for the full model + RT, see Table 1a. Note, because solution time was modeled via a Gamma function with an inverse link function, the signs of the respective fixed effects are inverted.

The influence of the parametric *Search extension* variable onto the dependent variables was assessed with likelihood ratio tests of the respective full model against the baseline model without the *Search extension* variable (see Table 2). The full model included the *Search extension*, *Prime* and *Target words* variables as fixed effects and random intercepts for subjects and items as random effects (see, Table 1a). To analyze the influence of the *Search extension* variable on search, we additionally added solution time as covariate of no interest. The reason for this is to investigate whether participants searched for more possible solutions due to a constrained search space over and beyond longer solution times. The P-values for the single predictors as reported in Table 3 were obtained via the lmerTest-toolbox. Furthermore, visual inspection of residual plots did not reveal obvious deviations from homoscedasticity and normality for the analyses of solution time and amount of search.

There have been various accounts linking insight problem solving and restructuring to measures of executive control and the general ability to solve problems as measured by Raven matrices (Raven et al., 1983; Paulewicz et al., 2007; Gilhooly and Firatou, 2009; Ash and Wiley, 2006). Given this evidence and to additionally validate our paradigm, we performed an exploratory analysis assuming that the ability to extend the search space (which we assume to be restructuring in the context of this modified CRA paradigm) should be mediated by a general problem solving ability. Specifically, we set up another GLMM investigating the interaction between the *Search extension* variable and general problem solving ability on solution time while controlling for the *Prime* and *Target words* variable (see *Exploratory model*, Table 1a). General problem solving ability was measured by the average time in minutes to solve 12 items of the Raven's advanced progressive matrices weighted by the amount of correctly solved items (Arthur and Day, 1994).

Finally, we also measured the effort in finding a solution. We assumed that the more the search space needed to be extended, the more effort participants had to put into finding the solution. Because this variable turned out to be uniformly distributed, we could not model search effort as the other variables but calculated Spearman correlations.

2.5. MRI data acquisition, preprocessing and general linear analysis

Brain images were collected with a 3 T S Magnetom Skyra MRI scanner system (Siemens Medical Systems, Erlangen, Germany) using a 20-channel radiofrequency head coil. The structural images were collected using a three-dimensional T1-weighted magnetization prepared gradient-echo sequence (MPRAGE) (repetition time (TR) = 2500 m s; echo time (TE) = 2.12 m s; TI = 1100 m s, acquisition matrix = 256 × 256 × 192, flip angle = 9°; FOV = 240 mm, voxel size = 0.8 mm × 0.8 mm × 0.9 mm). Functional images were obtained using a T2*-weighted echo planar imaging (EPI) sequence sensitive to blood oxygen level dependent (BOLD) contrast (TR = 2400 m s, TE = 30 m s, image matrix = 64 × 64, FOV = 216 mm, flip angle = 80°, voxel size = 3 mm × 3 mm × 3.0 mm, 36 axial slices).

Image Processing. All fMRI data analyses were performed in SPM12 (Welcome Department of Cognitive Neurology, London, UK). The imaging series was slice-time corrected, realigned and coregistered to the individual structural image. Structural images were segmented into gray and white matter as well as cerebral fluid. Subsequently, structural scans were normalized to Montreal Neurological Institute (MNI) space and functional images were smoothed with an 8-mm FWHM-Gaussian filter. The preprocessing was performed using the default SPM12 default parameter choices.

Statistical analysis. First and second level analyses were conducted in the framework of general linear models as implemented in SPM (for a list of all three models, see Table 1b).

For the first model (*Model 1*) we created two separate regressors including the exact onset of all the button presses for search (button press 2) and solution (button press 1) and a third onset regressor of no interest including all other button presses by convolving the onset regressors with the canonical HRF. Button presses included in the third onset regressor of no interest were for example incorrectly solved solutions or button presses regarding one of the five response options. We excluded all search button presses from the analysis (13.8%) that were executed up to 3 s before the solution button press because it is possible that these search events may already have been the final solution. Additionally, we parametrically modulated the search and solution onset regressors by 1st the *Prime*, 2nd the *Target words* and 3rd the *Search extension* variable as described above. Similar to the behavioral analysis, we included the *Prime* and *Target words* variables as parametric modulators of no interest to exclude potential confounding effects. All parametric modulators were orthogonalized according to their sequential order and all values were mean centered and normalized (range: 1 till 1). That is to say, for every search and solution event of every subject a respective mean centered and normalized semantic distance value according to the respective variable was additionally modeled. All resulting vectors were convolved with a canonical hemodynamic response function (HRF) and its first temporal derivative to form the main regressors in the design matrix. Finally, we included three regressors representing the mean for each of the 3 runs and 6 motions parameters. A high-pass filter with a 128 s cutoff period was applied. Contrast images for each individual were calculated to compare the relevant parameter estimates for the regressors containing the canonical HRF.

As an additional analysis, we set up an identical GLM (*Model 2*) to the one described above but instead of using all search button presses, we included only search button presses from trials that were correctly solved. The reasoning here is that if search space extension takes place already during search then this is more likely to happen during trials that end up being solved correctly.

The rationale for the specific contrasts of both GLMs is described in the results section.

At the group level, we analyzed the contrast images of interest for all participants using a random effects general linear model (for *Model 1* and *Model 2* separately). A one-sample *t*-test was performed of the respective contrast images. To avoid confounding interindividual effects due to age, sex and differences in verbal fluency, we added those variables as covariates of no interest into the second level analyses. We assessed verbal fluency outside of the scanner and this measure consisted of the sum of all correctly named animals and plants that the participant could produce within 60 s, respectively. The resulting statistical values from the whole-brain analysis were thresholded at a voxel level of $p < .001$ ($z > 3.09$, uncorrected). To correct for multiple comparisons, we adopted a cluster-level FWE error correction at $p < .05$ for all fMRI analyses. The resulting statistical maps were superimposed on the averaged normalized structural image of all participants. Anatomical areas were determined using the AAL atlas (Tzourio-Mazoyer et al., 2002) based on the peak voxels from the random effects analysis and the reported coordinates correspond to the MNI coordinate system.

We used rfxplot to visualize the unique parametric effect of the *Search extension* variable (in the contrast *Search extension* > *Prime*) in percent signal change for two peak voxels during solution (Gläscher, 2009). The parametric modulator (*Search extension* variable) was split into four bins based on the 25th, 50th, 75th and 100th percentile. Percent signal change was computed as indicated in Gläscher (2009) for the time point of the solution button press. This measure represents how much the evoked BOLD response at this time point deviates from its voxel-wise baseline (Gläscher, 2009).

For exploratory purposes, we tested the hypothesis whether the observed parametric effect in the contrast *Search extension* > *Prime* variable during solution can already be observed before the actual solution button press. We assumed that the search space needs to be extended at some point *before* the final solution can be found. Former research investigating restructuring (what we refer to as search space extension) with EEG found prefrontal decrease in alpha power up to 1.5 s before the solution (Sandkühler & Bhattacharya, 2008). Because the BOLD response does not have a high temporal resolution and we cannot estimate the exact temporal onset, we set up an additional GLM (*Model 3*, see Table 1b) where we modeled the averaged last 2 s before the solution button press (see Jung-Beeman et al., 2004). We kept the design matrix identical to the one described further above with the difference that we excluded the onset regressor of the *search* button presses with its respective three parametric modulators (1st *Prime*, 2nd *Target words*, 3rd *Search extension* variable). All events other than the solution button presses (also including the search button presses) were captured with an onset regressor of no interest. This GLM was also analyzed on a whole-brain level thresholded at a voxel level of $p < .001$ ($z > 3.09$, uncorrected) and corrected for multiple comparison adopting a cluster-level FWE correction at $p < .05$.

3. Results

3.1. Behavioral results

On average, participants solved 68.45% ($SD = 46.5\%$, max = 90.2%, min = 45.3%) of all presented modified CRA problems correctly. The likelihood of solving the problems reduced significantly through the influence of the *Search extension* variable ($\chi^2(1) = 48.23$, $p < .001$) while the other variables did not significantly influence accuracy ($p > .105$) (see, Tables 2 and 3).

Furthermore, participants produced one other possible solution ($SD = 1.94$) on average (median) when trying to solve the modified CRA problem. Although the *Search extension* variable significantly increased the likelihood for another search button press by the factor of 3.85 (CI: 2.35–6.31; $\chi^2(1) = 28.84$, $p < .001$) when controlling for the other semantic distances in the full model, this influence disappeared when also controlling for solution time ($p > .12$) (see, Tables 2 and 3).

On average, participants needed 12.17 s (CI: 10.9 s–19.2 s) to solve the modified CRA problems. When modeling the influence of the *Search extension* variable while controlling for other confounding effects (*Prime* and *Target words* variable), this variable turns out be the a significant linear predictor for solution time ($\chi^2(1) = 35.12$, $p < .001$, see Table 2). When the semantic distance between the prime compound (backdrop) and solution compound (raindrop) was 0.4 (range 0–1) participants needed 15.1 s (CI: 13.7 s–16.9 s) to solve the problem. In contrast, when the semantic distance was 0.8 participants needed on average 23.0 s (CI: 19.2sec–28.7sec) to solve the problem. Both covariates of no interest also influence solution time. Participants also took longer to solve the modified CRAs with increasing semantic distance between prime and solution ($t = -2.82$, $p < .05$) and with decreasing mean distance between the target words and the solution ($t = 2.14$, $p < .05$). Note, solution time was modeled via a Gamma function with an inverse link function (to ensure normally distributed error terms). Therefore the signs of the reported t-values and estimates are inverted (see also Table 3).

When additionally modeling the interaction term between the Search extension variable and performance on the Raven's advances progressive matrices, it turns out to be a significant predictor for solution time ($\chi^2(2) = 7.47$, $p < .05$; see, Table 2 and Fig. 3).

Finally, the effort to search for a solution moderately but significantly correlated with the *Search extension* ($r_s = 0.12$, $p < .001$) as well as with the *Prime* variable ($r_s = 0.08$, $p < .001$) but not with the *Target words* variable ($p > .14$).

3.2. Brain imaging results

Model 1. Our research question focused on the brain areas associated

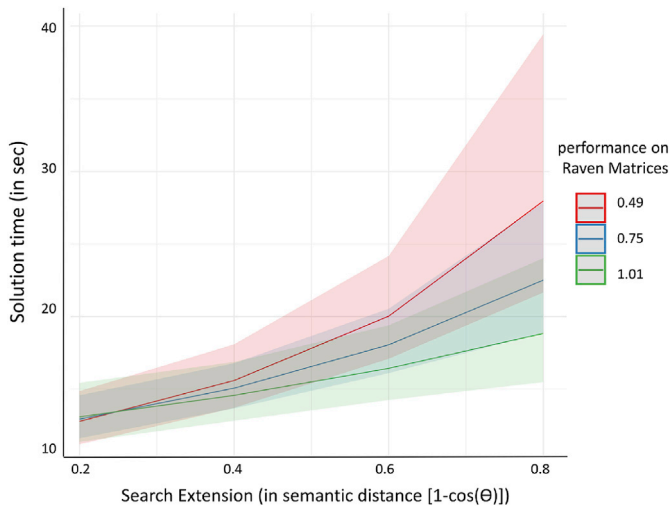

Fig. 3. Predicted values for solution time of modified CRA problems as a function of the *Search extension* variable mediated by performance on Raven's advanced progressive matrices.
Note. The regression lines stem from a GLMM termed *Exploratory model* (see, Table 1a). The shaded areas represent 95% confidence intervals of the respective regression lines. Performance on Raven's advanced progressive matrices was measured in mean solution time of all twelve presented items weighted by the amount of correctly solved items (a bigger value represents a higher general problem solving ability). The continuous measure of this performance was split into three bins for demonstration purposes. Time to solve the modified CRAs increases with an increasing need to extend the search space (i.e. an increasing semantic distance between the prime compound [backdrop] and solution compound [teardrop]). An exploratory analysis revealed that this relationship is mediated by the general problem solving ability (measured via the Raven's matrices).

with the process of search and search space extension.

(semantic distance between prime compound and solution compound). Therefore, we first investigated which brain areas are associated with the search phase. Second, we were interested in whether there are brain areas that linearly depend on the extension of the search space during (a) search and/or (b) during solution. We specifically looked at both events (search and solution) because we did not know at which moment participants tried to extend their search space, i.e. inhibit solution irrelevant associations or retrieve remote associations, respectively.

To address the first point, we contrasted all button presses during search (button 2) with all correct button presses during solution (button 1). The random-effects analysis of the contrast search > solution revealed significant activation in the left IFG, pars triangularis [peak voxel x; y;z(MNI) = −50; 28; 6; $t = 6.18$], left MTG [peak voxel x; y;z(MNI) = −52; -42; 2; $t = 5.96$] and right posterior insula [peak voxel x; y;z(MNI) = 33; -16; 22; $t = 6.64$] (see, Table 4; Fig. 4, panel 1). The inverted contrast (solution > search) revealed a wide-spread activation of various brain areas peaking in the left middle occipital gyrus [peak voxel x; y;z(MNI) = −34; -80; 24; $t = 6.18$].

To address the second point, we assessed which brain areas' BOLD response is linearly affected (on a trial-by-trial basis) by the *Search extension* variable during search and solution (we will refer to this as simple contrast).

During search (considering all search button presses), there was no significant BOLD response correlating with this variable. Also a more liberal voxel based threshold of $t = 1.71$ ($p < .05$) revealed no significant clusters. In addition, there were no significant clusters negatively correlating with the *Search extension* variable (given the same liberal voxel based threshold of $t = 1.71$).

However, because search space extension is more likely to take place when the problem was solved correctly, we correlated the *Search extension* variable for only search button presses that lead to a correct solution (*Model 2*). A cluster in the left angular gyrus [peak voxel x; y;z(MNI) = −42; -74; 40; $t = 6.13$] significantly correlated with the Search extension variable. No clusters negatively correlated with the reverse contrast.

During solution, we found a predominately bilateral fronto-temporal network of brain areas positively correlated with the *Search extension* variable: left and right IFG (including pars opercularis, triangularis and anterior insula): [peak voxel x; y;z(MNI) = −28,24,0; $t = 5.63$/36,16,0; $t = 7.25$], left superior frontal gyrus [peak voxel x; y;z(MNI) = −22; 38; 32; $t = 4.79$], anterior and middle cingulum extending to supplementary motor area [peak voxel x; y;z(MNI) = 4; 34; 34; $t = 6.25$] and right MTG [peak voxels x; y;z(MNI) = 66, −32, −6; $t = 4.45$] (see Table 4; Fig. 4, panel 2). Furthermore, the right angular gyrus [peak voxel x;

Table 4
Whole brain analysis of the brain activation related to verbal creative problems solving during search and solution with different contrasts.

	Side	Peak voxel MNI coordinates (mm)			Cluster size	Peak t
		x	y	z	(voxel)	score
Model 1- fMRI results during search phase (search > solution)						
IFG, pars triangularis	L	−50	28	6	224	6.18
Middle Temporal Gyrus	L	−52	−42	2	203	5.96
Posterior Insula	R	38	−16	22	171	5.03
Model 1 - fMRI results during solution: Brain areas correlating with parametric modulator Search extension variable (positive trial-by-trial relation with higher semantic distance)						
Anterior Insula extending into IFG, pars triangularis and opercularis	L/R	−28	24	0	1357	8.00
		36	16	0	796	7.25
Mid-cingulate Cortex extending into left Anterior-cingulate Cortex and Supplementary Motor Area	R	4	34	34	1269	6.25
Thalamus	L	−12	−14	2	248	6.08
IFG, pars opercularis	R	58	16	26	329	4.85
Superior Frontal Cortex	L	−22	38	32	87	4.79
Precentral Cortex	L	−48	10	48	51	4.67
Angular Gyrus	R	34	−56	38	89	4.47
Middle Temporal Gyrus	R	66	−32	−6	70	4.45
Model 1 - fMRI results during solution: Brain areas correlating with contrast Search extension > Prime variable (positive trial-by-trial relation with higher semantic distance)						
IFG, pars triangularis extending into pars orbitalis and opercularis	L	−46	18	4	95	4.41
IFG, pars orbitalis extending into Anterior Insula	R	34	24	−8	83	4.52
Intersection between Angular Gyrus and Supramarginal Gyrus	R	52	−46	36	62	4.67
Model 2 - fMRI results during search: Brain areas correlating with parametric modulator Search extension						
Angular Gyrus	L	−42	−74	40	80	6.13
Model 3 - fMRI results during last 2 s before solution: Brain areas correlating with contrast Search extension > Prime variable (positive trial-by-trial relation with higher semantic distance)						
IFG, pars orbitalis	L/R	−50	18	−6	66	4.74
		44	28	−6	121	5.50
Anterior Insula	L	−34	24	−4	84	5.29
Middle Temporal Gyrus	L/R	−66	−22	−4	86	5.43
		54	−70	18	861	5.89
Nucleus Caudatus	R	10	2	12	71	6.00
Fusiform Gyrus	R	40	−58	−20	203	6.80
Middle Occipital Gyrus	L	−44	−78	−2	135	6.58
Calcarine Gyrus	L	−12	−66	14	419	6.31

Note. Clusters are whole-brain FWE corrected for multiple comparisons at $p < .05$, L = left; R = right; size (voxel) = cluster size, peak t score = maximum t value of significantly activated clusters.

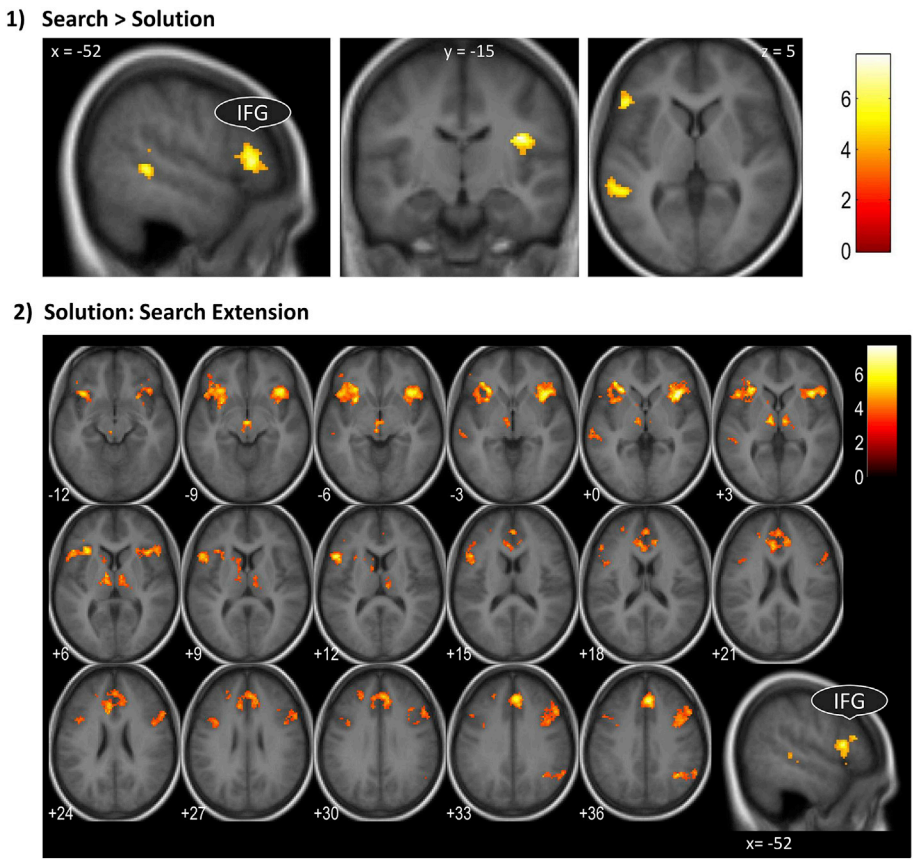

Fig. 4. fMRI results during search and solution while solving modified CRA problems.
Note. **Panel (1) Search > Solution**: Relative brain activity for the contrast Search > Solution. **Panel (2) Solution: Search extension**: Relative brain activity at the time of solution parametrically correlated with the semantic distance between the prime and solution compound (*Search extension* variable). The last slice in sagittal view refers to the same contrast. The significant height threshold for every depicted contrast is $t = 3.44$, $p < .001$, clusterwise FWE-corrected ($p < .05$).

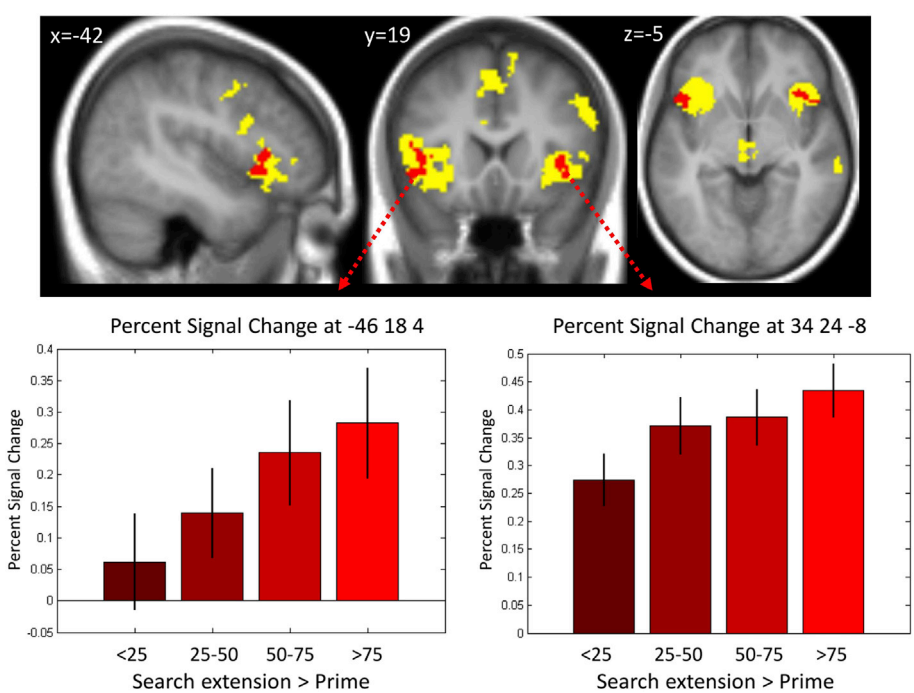

Fig. 5. Parametric modulation of BOLD response in left and right IFG as a function of the *Search extension* variable.
Note. **Upper panel**:Overlaid maps of relative brain activity at the time of solution parametrically correlated with the semantic distance between the prime [*backdrop*] and solution compound [*raindrop*] (*Search extension* variable) (yellow) and in the contrast *Search extension* > *Prime* variable (red). The significant height threshold for both depicted contrasts is $t = 3.44$, $p < .001$, clusterwise FWE-corrected ($p < .05$).
Lower panel: Mean percent signal change during solution for the parametric modulator representing the extent of the search space in the contrast *Search extension* > *Prime* in the left IFG, pars triangularis (x; y;z(MNI) = −46, 18, 4) and right IFG, pars orbitalis (x; y;z(MNI) = 34, 24, −8). The parametric modulator was split into four bins representing the 25th, 50th, 75th and 100th percentile. All error bars are standard error of the mean.

y;z(MNI) = 34; -56; 38; $t = 4.47$] and left thalamus activity [peak voxel x; y;z(MNI) = −12; -14; 2; $t = 6.08$] correlated with the *Search extension* variable during solution, while there was no significant negative correlation (voxel-based threshold $t = 3.44$, $p < .001$) (see Fig. 4, panel 2). Only for control purposes, we ran another GLM identical to *Model 1* but with the difference that the *Search extension* variable was orthogonalized first as parametric modulator (*Prime* was second, *Target words* variable was third). The results remain mostly the same (see Fig. 8, supplementary material).

The behavioral analyses showed that solution time was influenced by

the *Search extension* and the *Prime* variable. To isolate those brain areas that correlate more with the *Search extension* than the *Prime* variable during solution, we contrasted the first with the latter variable during solution (*Search extension* > *Prime*). This contrast revealed a significant effect in the left IFG (pars triangularis extending into pars orbitalis) [peak voxel x; y;z(MNI) = −46; 18; 4; $t = 5.45$] and right IFG (pars orbitalis) [peak voxel x; y;z(MNI) = 34; 24; -8; $t = 4.52$] (see, Fig. 5, upper panel, red) and on the intersection between the right angular gyrus and supramarginal gyrus [peak voxel x; y;z(MNI) = 52; -46; 36; $t = 4.67$] (for a visualization of the parametric modulation in this contrast see Fig. 5, lower panel). No brain areas correlated negatively with this contrast (*Search extension* > *Prime*) during solution.

Model 3. Finally and for exploratory purposes, we wanted to assess whether the parametric effect from the contrast *Search extension* > *Prime* during solution could already be observed before the actual solution button press. Therefore, we set up an additional GLM averaging the BOLD response of the last 2 s before the solution button press (as depicted in Table 1b). The following clusters significantly correlated with the contrast *Search extension* > *Prime* for this time window: right and left IFG (pars orbitalis) [peak voxel x; y;z(MNI) = 44, 28, -6; $t = 5.50$]; left anterior insula [peak voxel x; y;z(MNI) = -34,24, -4; $t = 5.29$]; right and left MTG [peak voxel x; y;z(MNI) = 54, -70,18; $t = 5.89$]; right caudate nucleus [peak voxel x; y;z(MNI) = 10, 2, 12; $t = 6.00$]; right fusiform gyrus [peak voxel x; y;z(MNI) = 40, -58, -20; $t = 6.80$]; left middle occipital gyrus [peak voxel x; y;z(MNI) = -44, -78,-2; $t = 6.58$] and left calcarine gyrus [peak voxel x; y;z(MNI) = -12, -66,14; $t = 6.31$] (see, Fig. 9, supplementary material).

The reverse contrast did not reveal any significant clusters.

4. Discussion

This is the first study that investigates the neural mechanism of search *and* search space extension (i.e. the ability to overcome solution-irrelevant associations and access solution-relevant but remote semantic information) during verbal creative problem solving. By using a semantic distance measure, we were able to parametrically quantify a specific sub-process that we refer to as search space extension (restructuring for the verbal domain) using fMRI.

Our goal was to elucidate the general question how correct conceptual information is accessed given that the solution is semantically remote and solution-irrelevant associations are automatically activated which keep the solver from finding the solution (constrained search space). In CRA problems, participants actively search for the solution and eventually extend their search space in order to retrieve the correct solution word. In this context, we proposed to regard search and solution as part of the same semantic control process of retrieving specific semantic content from lexical memory. Former studies investigating neural correlates of search space extension focused more on the time point of solution and less on the search itself. While semantic control areas have already been reported during solution, we provide evidence that some of these areas are also relatively more activated during search (Wu et al., 2013; Zhao et al., 2013; Luo, Niki and Phillips, 2004a; 2004b; Tang et al., 2015; Di Bernardi Luft et al., 2018). The left MTG and IFG activation could already be observed during search in the contrast search > solution. The left MTG has also been associated with semantic control and is often co-activated with the left IFG (Davey et al., 2015).

The reported results replicate behavioral findings from our previous paper showing that an increasingly constrained search space, as indicated by the *Search extension* variable, decreases the chances to solve the problem and leads to longer solution times when controlling for other sources of task difficulty (Becker et al., 2018). An exploratory analysis additionally revealed that the ability to extend the search space is mediated by a more general (language independent) problem solving ability. Specifically, for an increasingly constrained search space individuals need disproportionally more time to solve the modified CRAs the lower they perform on the Raven's advanced progressive matrices. Paulewicz and colleagues also found a significant positive correlation between performance on Raven's matrices and on solving remote associates as well as solving other insight problems (Paulewicz et al., 2007). Moreover, Ash & Wiley found evidence that increased cognitive control (attentional ability) might facilitate restructuring processes (Ash and Wiley, 2006). Our result is in line with these studies and further validates this parametric paradigm on modified CRAs.

Because participants most likely need to extend their search space to find the correct solution, the question still remained whether this process already happens during search or is limited to the solution. The reported results replicate that a constrained search space leads to longer search times. Specifically, participants search *longer* as a function of the *Search extension* variable but do not produce *more* possible solutions relative to solution time. This behavioral evidence would suggest that participants may not search qualitatively differently due to a constrained search space. However, the BOLD response of the left angular gyrus linearly correlates with an increasingly constrained search space (*Search extension* variable). This fMRI evidence implies that participants already extend their search space during search. Note, this relationship, however, could only be observed when those search button presses were taken into account that lead to a correct solution. The angular gyrus is a highly integrative association cortex strongly related to semantic memory (Price et al., 2015) and it has often been implicated in semantic control (Binder et al., 2009; Davey et al., 2015; Noonan et al., 2013; Price, 2010). Crucially, the angular gyrus has been associated with complex information integration (Binder et al., 2009; Friederici et al., 2003) and combining of concepts ('pine' and 'tree) to form meaningful representations ('pine-tree') (Price et al., 2015). Hence, the correlation of the angular gyrus with the *Search extension* variable may reflect a search for distant, non-dominant and meaningful but solution-irrelevant compound associations of the target words (like *pine nut* instead of *pine tree*). Note, our design does not allow a differentiation between the search button presses. Future research may therefore consider the thinking-out-loud method to further investigate the exact time point when the participants start extending their search space during the search phase (see Search protocol analysis in Davelaar, 2015).

During solution, we found a bilateral fronto-temporal network also linearly correlating with the degree to which the search space needed to be extended (*Search extension* variable). This result is in line with Tang and colleagues (2015) who found a linear positive correlation of the left inferior frontal junction with increasing chunk tightness (i.e., some form of search space extension) during solution, among other reported brain areas. However, those reported networks might not be *specific* for the process of search space extension during solution and could similarly correlate with other sources of task difficulty. The behavioral results implied that also the *Prime* variable influenced solution time. Therefore, when investigating which brain areas correlated significantly more with the *Search extension* compared to the *Prime* variable, only bilateral IFG (including adjacent right anterior insular as well as right angular gyrus activation) remained from the above-mentioned fronto-temporal network during and within 2 s before the solution.

Our interpretation of this result during solution is the following: Specifically the IFG already being active during search may be critically involved in the extension of the search space that would lead to the correct solution. According to Badre and colleagues, the IFG is functionally divided among rostral regions concerning semantic control (Badre et al., 2005; Badre and Wagner, 2007). The IFG pars triangularis is involved in selection of concepts by resolving competition among active representations while the IFG pars orbitalis is involved in controlled retrieval of stored conceptual representations (Badre and Wagner, 2007). In line with Badre and colleagues, evidence from a meta-analysis suggests that activation in IFG, pars orbitalis increases with increasing difficulty to extract semantic content from a sentence (Price, 2010). According to the author, this probably reflects semantic retrieval at the single-word level (Price, 2010). Transferring this to the mechanism of search space extension in a verbal creative problem context, we assume the following.

The pars triangularis of the IFG might be involved in inhibiting solution irrelevant associations while the pars orbitalis could be involved in retrieving the remote semantic content. We already find a significant correlation with those regions specifically the IFG, pars orbitalis within the last 2 s before the actual solution. Therefore, especially retrieval of remote semantic content necessary to find the correct solution might already take place before the time of the solution button press. In line with this result is an electroencephalographic study using classical CRAs which reports increased alpha band (8–12 Hz) activity in right prefrontal brain regions 1.5 s *before* the solution button press (Sandkühler and Bhattacharya, 2008). Note, our fMRI design does not allow to locate the exact onset when the remote solution is retrieved from semantic memory. Therefore, further research involving other modalities like EEG/MEG is necessary to determine the exact onset of IFG activation before the solution.

Concerning inhibiting solution irrelevant associations, Di Bernardi Luft and colleagues provide robust evidence that right temporal alpha oscillations play a critical role in inhibiting obvious semantic word associations in CRAs (Di Bernardi Luft et al., 2018). While we also found BOLD signal in right MTG linearly correlating with the *Search extension* variable in the simple contrast during and before solution, this correlation ceased in the contrast Search extension > Prime. This is not unreasonable given that Di Bernardi Luft and colleagues used a different measure to study inhibition of solution irrelevant associations in CRAs. The authors did not experimentally manipulate the degree to which participants need to *reinterpret* the meaning of the first target word by means of a computationally derived semantic distance measure. Instead, they classified the CRA items post-hoc according to whether or not two target words from the triad shared a compound word that was not a compound of the third target word and therefore a potential but wrong solution (Di Bernardi Luft et al., 2018). Hence, the right MTG alpha oscillations most likely represent inhibition of shared but solution-irrelevant word associations of the target words in lexical memory. However, bilateral IFG in the specific contrast presented here may additionally represent updating of the solution-relevant first target word (i.e. inhibition of its solution-irrelevant word meaning [drop as in backdrop] and retrieval of the solution-relevant word meaning [drop as in raindrop]). This interpretation is in line with research investigating frontotemporal contributions to semantic ambiguity resolution. Rodd and colleagues found that it is specifically the (left) IFG responding to ambiguous words and selecting an appropriate word meaning rather than temporal regions (Rodd et al., 2011).

However, it must be assumed that a complex task such as solving modified CRAs involves an interplay of various brain regions performing different sub-processes of creative problem solving. In this regard, we also found a significant activation of right inferior parietal areas including the angular gyrus correlating with the Search extension variable and significantly more with the *Search extension* than with the *Prime* variable during solution. The contralateral side of the angular gyrus had already been associated with the *Search extension* variable in the simple contrast during search. Hence, the angular gyrus during solution may similarly reflect an additional contribution to the retrieval of a remote semantic association (only this time it is the solution). However, in contrast to the bilateral IFG, we do not find evidence for angular gyrus involvement within the last 2 s before solution (for *Search extension* > *Prime*).

Therefore, we believe that the bilateral rostral IFG, which correlated most strongly with the *Search extension* variable in the contrast *Search extension* > *Prime* during and before solution is most specific for extending the search space. However, we found bilateral anterior insula activation during solution correlating with the *Search extension* variable during solution and posterior insula activation during active search. This might not just reflect the insula's diverse role in language processing but could also be informative concerning the general verbal creative problem solution process (Ardila et al., 2014; Price, 2010):

A functional parcellation study indicates that the insula can be divided into three parts (Chang et al. 2012; Uddin, 2015). While the right posterior insula is most classically described in context of pain and processing somatosensory information, it has also been associated with auditory processing and automatic speech production due to its vicinity to the auditory cortex (Price, 2010; Ackermann and Riecker, 2010, Chang et al. 2012). It is furthermore co-activated in tasks requiring auditory working memory (O'Hare et al., 2008) and search processes during memory retrieval (Wheeler et al., 2005). We speculate that participants may access specific semantic information (via left MTG and IFG) during active search and hold this information in auditory working memory (supported by right posterior insula) by repeating it silently while evaluating whether the retrieved word is the correct solution.

The anterior insula is often co-activated with the IFG in general language related tasks (for a meta analysis, see Ardila et al., 2014). However, it has also been reported frequently in verbal creative tasks requiring inhibition of dominant but task-irrelevant associations (Wu et al., 2013; Tang et al., 2015; Luo et al., 2004b, Azih-Zadeh et al., 2009). According to the aforementioned functional parcellation study, the dorsal part of the anterior insula is functionally involved in cognitive processes such as task switching, inhibition, error processing and conflict (Chang et al. 2012; Uddin, 2015). Because there were also peak voxels correlating uniquely with the extent of the search space (in the contrast *Search extension* > *Prime*) during and before retrieval of the correct solution, we speculate that the dorsal anterior insula might be additionally involved in inhibiting solution irrelevant associations.

In general, we cannot entirely exclude that some of the brain signals measured during solution also refers to post-solution verification processes. For example, the wide-spread activation in the visual areas peaking in the left middle occipital gyrus in the contrast solution > search may represent the fact that participants verify the solution by visually comparing the solution to the target words. However, we found various clusters in visual cortex within the last 2 s before the solution button press correlating more strongly with the *Search extension* than with the *Prime* variable. Increased activity in occipital areas specifically changes in alpha power within 2 s before solving CRAs have been reported before in EEG studies (Sandkühler and Bhattacharya, 2008; Jung-Beeman et al., 2004). Here, increased alpha power has been interpreted as inhibition of visual information to reduce noise from distracting inputs to facilitate retrieval of weakly activated semantic concepts (Kounios & Beeman et al., 2014; Wu et al., 2009; Jung-Beeman et al., 2004).

What the reported results leave unanswered, however, is what neurocognitive mechanism leads to breaking the mental set, i.e. brain areas representing an "early warning system" that the activated solution-irrelevant associations are hindering the retrieval of the correct solution. ACC activation during solution in a creative problem solving context has been interpreted as mediator of breaking one's mental set to form novel task-related associations (Zhao et al., 2011; Luo et al., 2004b). In line with this, neuroimaging studies investigating general cognitive control associate the activation of the ACC with conflict monitoring (Botwinick et al., 2004; Kerns et al., 2004). Furthermore, evidence from single cell studies suggests that ACC encodes the discrepancy between previously held beliefs and current observations (Yoshida and Ishii, 2006; Rushworth and Behrens, 2008). We also found ACC activation during solution correlated with the degree to which the search space is constrained (*Search extension* variable). However, this correlation became non-significant when contrasting the *Search extension* with the *Prime* variable. Thus, it is possible that ACC activation in this task setting represents rather general aspects of task difficulty or the discrepancy between the prime and the semantically distant solution word.

In summary, changing the problem representation by reinterpreting the dominant but solution-irrelevant (primed) meaning of the first target word or what we refer to as search space extension is a key concept in creative cognition. We provided evidence that this process is related to semantic control and search space extension already takes place during search (of correctly solved trials) involving the left angular gyrus.

Moreover, during solution specifically the rostral part of the IFG is involved in extending the search space leading to correct retrieval of semantic content during verbal creative problem solving.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

This work was supported by the German Science Foundation (SFB 936/C7) [MB], the German Science Foundation (DFG KU 3322/1-1) [SK], the European Research Council (ERC-2016-StG-Self-Control-677804) [SK] and a Fellowship from the Jacobs Foundation (JRF 2016–2018) [SK].

We want to thank Dr. Gregor Wiedemann for providing the semantic distances between the word pairs and Daniel Kutzner as well as Christoph Schäde for acquiring the fMRI data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.116294.

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