



# Learning of novel semantic relationships via sudden comprehension is associated with a hippocampus-independent network

Jasmin M. Kizilirmak<sup>a,\*,1</sup>, Björn H. Schott<sup>b,c,\*,1</sup>, Hannes Thuerich<sup>b</sup>,  
Catherine M. Sweeney-Reed<sup>e</sup>, Anni Richter<sup>b</sup>, Kristian Folta-Schoofs<sup>a</sup>,  
Alan Richardson-Klavehn<sup>d,\*</sup>

<sup>a</sup> Neurodidactics & NeuroLab, Institute of Psychology, University of Hildesheim, Universitätsplatz 1, 31141 Hildesheim, Germany

<sup>b</sup> Leibniz Institute for Neurobiology, Brenneckestraße 6, 39118 Magdeburg, Germany

<sup>c</sup> Department of Psychiatry and Psychotherapy, University Medicine Göttingen, von Siebold Strasse 5, 37075 Göttingen, Germany

<sup>d</sup> Memory and Consciousness Research Group, Departments of Neurology and Stereotactic Neurosurgery, Otto-von-Guericke-University, Leipziger Strasse 44, 39120 Magdeburg, Germany

<sup>e</sup> Neurocybernetics and Rehabilitation Research Group, Departments of Neurology and Stereotactic Neurosurgery, Otto-von-Guericke-University, Leipziger Strasse 44, 39120 Magdeburg, Germany

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## ABSTRACT

Sudden comprehension—or insight—during problem-solving can enhance learning, but the underlying neural processes are largely unknown. We investigated neural correlates of learning from sudden comprehension using functional magnetic resonance imaging and a verbal problem-solving task. Solutions and “solutions” to solvable and unsolvable verbal problems, respectively, were presented to induce sudden comprehension or continued incomprehension. We found activations of the hippocampus, medial prefrontal cortex (mPFC), amygdala, and striatum during sudden comprehension. Notably, however, mPFC and temporo-parietal neocortical structures rather than the hippocampus were associated with later learning of suddenly comprehended solutions. Moreover, difficult compared to easy sudden comprehension elicited midbrain activations and was associated with successful learning, pointing to learning via intrinsic reward. Sudden comprehension of novel semantic associations may constitute a special case of long-term memory formation primarily mediated by the mPFC, expanding our knowledge of its role in prior-knowledge-dependent memory.

## 1. Introduction

Sometimes during problem-solving, a solution is encountered suddenly, and the pieces of a puzzle are instantly seen in a new light, revealing a previously unseen relationship between the original pieces and the solution. A famous example is Karl Duncker's

\* Corresponding authors at: Neurodidactics & NeuroLab, Institute of Psychology, University of Hildesheim, Universitätsplatz 1, 31141 Hildesheim, Germany (J.M. Kizilirmak); Leibniz Institute for Neurobiology, Brenneckestraße 6, 39118 Magdeburg, Germany (B.H. Schott); Memory and Consciousness Research Group, Departments of Neurology and Stereotactic Neurosurgery, Otto-von-Guericke-University, Leipziger Strasse 44, 39120 Magdeburg, Germany (A. Richardson-Klavehn).

E-mail addresses: [kizilirmak@uni-hildesheim.de](mailto:kizilirmak@uni-hildesheim.de) (J.M. Kizilirmak), [bjoern.schott@lin-magdeburg.de](mailto:bjoern.schott@lin-magdeburg.de) (B.H. Schott), [alan.richardson-klavehn@med.ovgu.de](mailto:alan.richardson-klavehn@med.ovgu.de) (A. Richardson-Klavehn).

<sup>1</sup> Contributed equally.

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candle problem involving a candle, a book of matches, and a box of thumbtacks (drawing pins). One's task is to attach the candle to a wall and light it, but no wax is allowed to drip onto the floor. It is futile to try and use the thumbtacks to tack the candle directly to the wall, and a more creative solution is required: The thumbtacks can be used to tack the empty thumbtack box to the wall, and the candle can be attached to box using its own melted wax. Thus, well-known elements are used together in a novel way, and the comprehension of how to use them can occur suddenly.

Sudden comprehension of what seemed incomprehensible before (Auble, Franks, & Soraci, 1979; Bühler, 1907) is typically accompanied by feelings of both surprise and tension relief (Danek, Fraps, von Müller, Grothe, & Öllinger, 2014; Topolinski & Reber, 2010), and has been shown to enhance long-term memory (LTM) for the problem as well as its solution (Danek, Fraps, von Müller, Grothe, & Öllinger, 2013; Dominowski & Buyer, 2000; Kizilirmak, Galvao Gomes da Silva, Imamoglu, & Richardson-Klavehn, 2016; Kizilirmak, Wiegmann, & Richardson-Klavehn, 2016). Little is known, however, about the cognitive and neural mechanisms underlying the beneficial effect of sudden comprehension during problem solving on LTM encoding. The few previous empirical studies on this topic found support for several potential mechanisms (Auble et al., 1979; Danek et al., 2013; Ludmer, Dudai, & Rubin, 2011). Auble and colleagues proposed two mechanisms that can both be subsumed under the levels-of-processing framework for memory ( Craik & Lockhart, 1972), which has a very broad empirical basis (Craik, 2002; Craik & Tulving, 1975; Eysenck, 1979), with the general principle being that memory for new information usually is best when relevant prior semantic knowledge is activated during encoding. With regard to problem solving, the two mechanisms considered by Auble and colleagues were (1) effort towards comprehension or elaboration, and (2) sudden comprehension following a previous state of incomprehension (Auble & Franks, 1978; Auble et al., 1979). The second mechanism was also referred to as an “aha” reaction by Auble et al. (1979). They described such a reaction as a sequence of two encoding episodes: one without understanding the relationship of the presented items and without being able to successfully integrate those items into a coherent context, and hence prior knowledge, and another “aha” encoding episode following sudden comprehension.

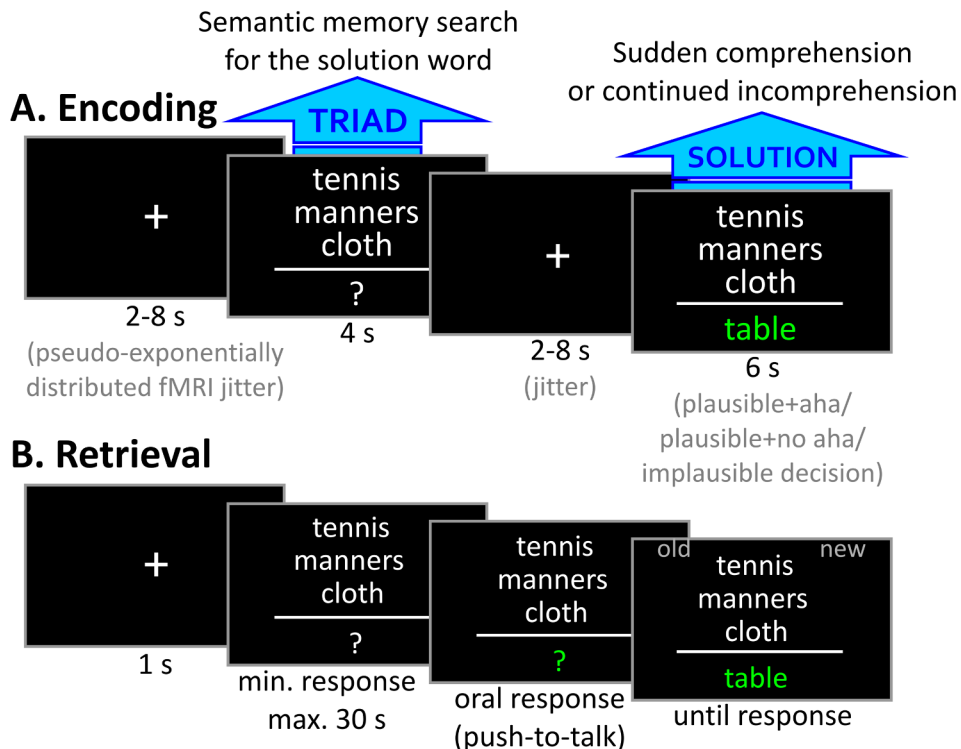
With a set of four experiments, Auble et al. (1979) tested whether effort towards comprehension (mechanism 1) or the sudden “aha”-like comprehension itself (mechanism 2) was more important for improving later memory, and found support for the latter. The authors used sentences that were incomprehensible without a certain critical word, such as *The notes were sour because the seam split* (cue word: *bagpipe*; see Auble & Franks, 1978; Bransford & McCarrell, 1974). Conditions included presenting the critical word either embedded in the sentence, or presenting the critical word 5 s after the sentence to induce sudden comprehension, or presenting a meaningless word (with respect to the sentence) 5 s after the sentence, or no word at all. Additionally, the difficulty of the to-be-comprehended sentences was manipulated. Whenever sudden comprehension followed a previous state of incomprehension, it was associated with superior later recall of the sentences and cues, independent of difficulty.

However, there is also evidence that effort towards comprehension during problem-solving plays a role in facilitating later recall, because even the generation of incorrect solution candidates potentially leads to more cues that can be used for retrieval (e.g., Wills, Soraci, Chechile, & Taylor, 2000). Additionally, when considering Auble and colleagues' definition of an “aha” experience, which is often used in the insight problem-solving literature, there are studies proposing further explanations for how sudden comprehension of a solution in a problem-solving task may facilitate later retrieval. In a functional magnetic resonance imaging (fMRI) study of perceptual insight, Ludmer and colleagues induced sudden comprehension, that is, the sudden recognition of the motif of a black and white image missing all shades of grey (a so-called Mooney image), by briefly flashing a greyscale version of the same image (Ludmer et al., 2011). They reported higher amygdala activations during successful compared to unsuccessful encoding of the suddenly comprehended solutions. The authors suggested that solutions that are understood when a previous state of incomprehension is changed into a state of comprehension are determined as internally relevant, thereby facilitating LTM encoding. Other evidence points towards a role of intrinsic reward or positive emotional responses and neural reward circuits in the successful encoding of suddenly comprehended solutions (Kizilirmak, Galvao Gomes da Silva, et al., 2016; Kizilirmak, Thuerich, Foltz-Schoofs, Schott, & Richardson-Klavehn, 2016), which is compatible with the previously well-documented enhancement of hippocampus-dependent memory by activation of the mesolimbic reward system (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Krebs, Schott, & Düzel, 2009; Wittmann et al., 2005).

Danek et al. (2013) propose that the representational change, which is thought to underlie insightful problem solving, may lead to long-lasting changes in the representation of a problem, thereby enhancing LTM formation for the problem and its solution. This interpretation is also in agreement with the study of Wills et al. (2000), who replicated the elements of the experiments of Auble et al. (1979) with fragmented line drawings (“connect the dots”). They interpreted the memory advantage of fragmented drawings whose solution was understood suddenly at some point during tracing the lines, in comparison to drawings immediately presented in their complete form, as being due to the considerable amount of reconfiguring of the original problem representation in the case of fragmented drawings. The representational change theory of the insight literature (Ohlsson, 1992) can probably be likened to the two-encoding-episodes account of Auble et al. (1979), and the interpretation accounts of Danek et al. (2013) and Wills et al. (2000).

We further suggest that the sudden comprehension of novel relational information also shares features with the role of schemas in memory (e.g., Ghosh & Gilboa, 2014). The acquisition of schemas occurs, for example, during gradual encoding and semantization of initially episodic information (Sommer, 2017), or during integration of distinct, but related, associative memory traces (e.g., as in transitive inference; Schlichting & Preston, 2015). This potential role of schema-related processes in sudden comprehension might become most apparent in relation to the Compound Remote Associates Task (CRAT) used in the current experiment.

The CRAT was first described by Bowden and Jung-Beeman (2003), who had designed it based on the Remote Associates Task of Mednick (1962), which was originally developed as a test of creativity. A triad of three seemingly unrelated words (nouns or color words) are presented and participants are asked to find a fourth word that connects the other three words by building a compound word with each (e.g., *cloth*, *tennis*, *manners* as the clue words and *table* as the solution word; see Fig. 1). At first, participants are in a



**Fig. 1.** Exemplary trials for encoding (A) and the later memory test (B). During encoding (with fMRI scanning), triads were presented for which participants should attempt to find a common word to form compound words with. The triads were either solvable (for the sudden comprehension condition) or not (continued incomprehension). During the solution interval, either a real solution for sudden comprehension items or a pseudo-solution for continued incomprehension items was presented. Participants were required to press one button for plausible solutions with a feeling of “aha!”, another for plausible solutions without “aha!”, or both buttons simultaneously for implausible solutions. During the retrieval test 24 h later (not scanned), participants were presented only with solvable CRAT problems of which a quarter was new. They were asked to try to solve the problems regardless of recognizing them as old or not (incidental test). In case they found a solution, they should press a button for as long as they responded orally. Afterwards or when time was up, the solution was presented and participants performed an additional old/new decision on the complete item.

state of incomprehension, not seeing a meaningful relationship between all three words of the triad. This state of incomprehension is suddenly turned into comprehension when a solution is either found by the participant or presented by the experimenter, and previously remote associations (between the triad words) in the network that makes up our knowledge suddenly become more closely associated via the solution word.

With respect to schema-dependent memory, the associations between the triad words and the solution word are at first remote, but perhaps representing a “latent” schema, and become more directly and schematically related upon the sudden conscious realization of the association between the words. Congruency with schemas has been shown to enhance encoding by accelerating hippocampal memory formation or even bypassing hippocampal encoding via signals from the medial prefrontal cortex (mPFC), resulting in rapid neocortical storage of information (Sommer, 2017; Tse et al., 2007, 2011; van Kesteren et al., 2013). Schema-related enhancement of memory encoding via mPFC typically requires the presence of well-consolidated associative information (Sommer, 2017; van Kesteren, Rijpkema, Ruiters, Morris, & Fernández, 2014), which reflects the known prominent role of the mPFC in semantic memory (Binder & Desai, 2011; Schlichting & Preston, 2015). We hypothesized that the mPFC might additionally be involved in the kind of rapid activation of a latent schema involved in the CRAT problems, and in later learning of the solution words.

To summarize, multiple mechanisms are likely to play a role in LTM formation when a state of incomprehension during problem-solving attempts is suddenly changed into comprehension, either by coming up with a solution or by being presented with a solution. We identified as principal potential mechanisms: (1) effort towards comprehension, (2) the insight-like experience and representational change when the relationship of the problem components suddenly becomes meaningful via the solution and the previously remote association becomes more direct and schematic, and (3) intrinsic reward or a positive emotional response that accompanies the sudden comprehension, possibly in the form of tension relief.

In the present study, we aimed to elucidate the cognitive mechanisms and neural correlates of learning from sudden comprehension, focusing on these three candidate mechanisms. To this end, we performed a functional magnetic resonance imaging (fMRI) experiment, using an adapted version of the CRAT. Our version of the task consisted of two conditions: (1) a *sudden comprehension* condition, in which we presented the solution before participants could come up with a solution (see Fig. 1A for an exemplary trial), and (2) a *continued incomprehension* condition, in which we presented triad words that were not related via a common solution word

and a pseudo-solution word that could not be used to create compound words with the triad words. Effort towards comprehension should be involved during both the presentation of the triad, due to the search for a solution, and the presentation of the solution, due to the process of trying to comprehend how the solution word can be used to build compound words with each of the triad words. In contrast, only when the CRAT problem is solvable and the appropriate solution word is presented, should sudden comprehension occur. In both sudden comprehension and continued incomprehension conditions, participants were instructed to rate whether the presented solution (or pseudo-solution) was plausible or not, and if plausible, whether or not it elicited a subjective feeling of “aha”.

In accordance with Auble et al. (1979), the sudden comprehension condition should often be associated with a strong “aha” experience, because in most cases the participants should be able to suddenly comprehend the relationship between triad words and the solution word after the presentation of the latter. This experience should be absent in the continued incomprehension condition. Importantly, we used the same set of words in both conditions, counterbalanced across participants, with the only difference being that all triad and solution words of the continued incomprehension condition were put in a pool, shuffled, and redistributed into items (see 2 Material and Methods for details). Hence, differences between conditions could, across our group of participants, only be attributable to sudden comprehension versus continued incomprehension, but not to word frequency, emotional valence, or other semantic or perceptual differences between the individual words used in the two conditions.

To elucidate the neural correlates of learning via sudden comprehension, we contrasted successful with unsuccessful encoding of the problems based on a memory test administered 24 h after the encoding session (see Fig. 1B for an exemplary trial). To this end, old (from the sudden comprehension condition) and new solvable CRAT problems were presented, and participants were instructed to solve all problems presented, regardless of whether they were thought to be old or new (see Fig. 1B). This principal test was incidental (or indirect), because participants were simply asked to solve the problems, without making mental reference to the previous encoding episodes, but it could nevertheless be assumed that previous exposure to the solutions would enhance the solving of old compared with new problems (Richardson-Klavehn & Bjork, 1988; Richardson-Klavehn, 2010). Unlike the episodic recognition memory test that we employed previously (Kizilirmak, Thuerich, et al., 2016), the incidental conceptual memory test employed here (Ramponi, Richardson-Klavehn, & Gardiner, 2007) was thought primarily to reflect *semantic* memory formation, thus paralleling daily-life learning and retrieval instances (e.g., students being confronted with previously taught vs. untaught problems during an examination). We hypothesized that sudden comprehension might promote successful memory encoding by either primarily novelty-driven activation of the dopaminergic hippocampal-ventral tegmental area (VTA) loop (Lisman & Grace, 2005), or mPFC-dependent detection of schema congruency (van Kesteren, Ruitter, Fernández, & Henson, 2012). Considering previous investigations of comprehension-based successful encoding (Ludmer et al., 2011), we further hypothesized that the amygdala might participate in successful encoding of CRAT items.

Owing to the very nature of the continued incomprehension condition, the “solution rate” at test would have been essentially zero for both old and new items in our incidental test. Hence, we could not investigate neural correlates of learning via (or rather despite) continued incomprehension. Moreover, although each test trial also contained a recognition-memory component as well as the principal, incidental, component (see Fig. 1B), we have previously reported data on recognition memory following our version of the CRAT task, and we found that even recognition memory for the “solution” words of continued incomprehension items was too poor at 24 h to permit a meaningful fMRI contrast for later recognized compared with later forgotten items (Kizilirmak, Thuerich, et al., 2016). The recognition memory component included here was not of principal interest, but was included in order to provide an assessment of the extent to which learning in the incidental test for sudden comprehension items was also accompanied by episodic memory (see Richardson-Klavehn, 2010; Richardson-Klavehn & Gardiner, 1996).

As for the potential role of reward-mediated learning, we compared difficult with easy items of the sudden comprehension condition, because we assumed that comprehending the solution to a difficult problem would be associated with higher intrinsic reward and a stronger positive emotional response such as tension relief (difficult problem = higher tension during incomprehension). Based on pre-existing behavioral evidence (Kahana, 2012; Kirsner, Speelman, & Schofield, 1993), we hypothesized that suddenly comprehended solutions to items that were—based on normative data—difficult to solve would show greater later learning compared to easy items, owing in part to more room for later performance improvement, but possibly also to a higher degree of reward-facilitated learning. Hence, we expected a higher activation of reward-related brain regions, such as the dopaminergic midbrain, for difficult compared to easy items. We therefore also compared difficult and easy CRAT items with respect to fMRI activation and later memory performance.

## 2. Materials and methods

### 2.1. Participants

Twenty-six healthy young adults participated in the study after providing written informed consent. Three participants were excluded from the analysis, one because of an abnormality in the T1-weighted anatomical MRI, one due to nausea during scanning, and one due to technical difficulties during recording of the behavioral responses. The remaining 23 participants (12 male) had a median age of 25 years (range: 21–31; mean = 25.0, SD = 2.6). All had normal or sufficient uncorrected vision for reading the stimuli with ease in the scanner. All participants but one were right-handed\*. The study was approved by the Ethics Committee of the Otto-von-Guericke University, Magdeburg, Faculty of Medicine, and was carried out in line with the Declaration of Helsinki (World

\* The one left-handed participant was recruited accidentally. Since this participant's activation patterns showed no obvious divergence from those of the other participants, and excluding her data did not affect our results, we left her in the sample to increase statistical power.

Medical Association, 2013).

## 2.2. Stimulus material

We constructed 180 German CRAT items each consisting of four words (please refer to Bowden & Jung-Beeman, 2003, for details of such items in English). All words were nouns or color words, and the solution was always a word that formed a compound word when appended to the three others as a prefix or suffix. Before conducting the current fMRI study, we collected normative data for these items in a separate behavioral study with 20 participants. That study yielded data for each item concerning its probability of (1) being successfully solved (used to determine item difficulty), (2) having the correct solution judged as plausible, and (3) its probability of having the correct solution elicit an “aha!” experience, defined as subjective assessment of whether an insight—sudden comprehension accompanied by positive affect and strong conviction of the correctness of the solution—was experienced. The resulting normative data were used to divide the 180 items into four pools of 45 CRAT items that had approximately equal means on all three variables. Two of these pools were used as solvable sudden comprehension items presented in the encoding phase and the memory test, one was used to create unsolvable control items for the continued incomprehension condition presented in the encoding phase (see below), and the last item pool one was only presented in the memory test (new solvable sudden comprehension items). Assignment of pools to conditions was counterbalanced by means of a reduced Latin square, such that, across participants, each pool was used in the sudden comprehension, continued incomprehension, and new conditions. This procedure, along with the careful matching of item-pools, ensured that old and new solvable items at test had highly similar normative properties (e.g., *a priori* solution probability).

Items for the continued incomprehension condition were created by shuffling all words from each of the four pools of 45 solvable CRAT items to create four matched pools of 45 items, each composed of four words, in which the triad words could not be combined in a meaningful way with each other or the fourth “solution” word. The random permutation algorithm implemented in MATLAB 7.1 (The MathWorks, Inc., Natick, MA, USA) was used for shuffling, and the resulting sets of four words were manually inspected for any incidental meaningful relationships. When an item-pool fell into the continued incomprehension condition according to the counterbalancing scheme just described, the shuffled version of that item-pool was used. Owing to this procedure, differences between sudden comprehension and continued incomprehension conditions could only be due to differences in cognitive processing, and not to differences in perceptual, semantic, or affective properties between individual words, or differences in word frequency in the language.

## 2.3. Design

During the encoding phase, functional MRI (3 Tesla) was performed. Participants were presented with items of the sudden comprehension and continued incomprehension conditions, while being scanned. During the presentation of the triad without the solution, they were instructed to search for one. When presented with the correct solution (sudden comprehension) or pseudo-solution (continued incomprehension), participants were asked to decide via button press whether the solution was plausible with the feeling of “aha”, plausible without “aha”, or implausible. Importantly, the “aha” feeling was described as commonly used in the insight-problem-solving literature, that is, a subjective feeling of being surprised, comprehending suddenly, a feeling of ease with which the solution is understood, being convinced of the correctness of the solution, and positive affect (see 2.4 Task and procedure). This differs from how Auble and colleagues (Auble & Franks, 1978; Auble et al., 1979) used the term as simply referring to comprehension following a state of incomprehension. Learning was incidental: Participants were not informed before the encoding phase that their memory would later be tested. For sudden comprehension items only, in the testing phase, an incidental test of memory (involving participants attempting to solve the problems themselves), as well as a supplementary test of recognition of the items as previously presented, was conducted outside the scanner on the following day (see 2.4 Task and procedure for further details). All sudden comprehension problems from the previous day were presented intermixed with new ones (i.e., solvable CRAT problems), allowing memory to be assessed behaviorally by comparing solution rates for new and old items or by considering the rate of old items correctly recognized as old. No memory test was conducted for continued incomprehension items, because they were unsolvable and hence testing whether they could be “solved” in the principal, incidental, test was impossible. Moreover, an earlier study had shown that even recognition-memory performance would not have resulted in a sufficient number of correct responses for a meaningful subsequent memory contrast (Kizilirmak, Thuerich, et al., 2016).

The fMRI responses to sudden comprehension and continued incomprehension during the encoding phase were contrasted to investigate the neural correlates of sudden comprehension. Additionally, the items of the sudden comprehension condition were median-split as a function of the solution rates from the normative sample. Items with a solution rate above the median of 0.35 were labeled as “easy” and those below as “difficult”. fMRI responses to difficult and easy sudden comprehension items were then compared, because we assumed comprehending solutions to difficult problems should feel more intrinsically rewarding (Satterthwaite et al., 2012). Based on the solution performance during testing, the sudden comprehension items of the encoding phase were categorized as later solved or later not solved to investigate neural correlates of learning by sudden comprehension.

## 2.4. Task and procedure

Exemplary trials of the encoding and test phases are depicted in Fig. 1.

*Encoding phase.* Each trial started with a fixation cross that was presented for 2–8 s with a pseudo-exponential distribution to



improve the sampling of the hemodynamic response for event-related fMRI (Hinrichs et al., 2000). Three stacked words were then presented for 4 s with a question mark below (placeholder for the solution). Again, a fixation cross followed for 2–8 s (jittered), to allow for a separation triad- and solution-related brain responses. Lastly, the triad was presented together with its solution for 6 s, and participants were instructed to respond as soon as they understood the solution or decided that it was implausible. There were three response options: (1) plausible with “aha!”, plausible without “aha!”, and implausible. In the case of a “plausible” judgment, they were instructed to press one of two buttons on MR-compatible response boxes to indicate whether they understood the solution with or without a subjective “aha!” feeling. We adapted the definition of an “aha!” experience from Jung-Beeman et al. (2004) to render it applicable to presented solutions, because the trial timing was designed to make it difficult for participants to solve the problems themselves before the solution was presented. From the normative study, we knew that only 7% of the items are usually (median solution rate) solved in under 6 s in a quiet lab. We therefore estimated that, with the pseudo-exponential blank-screen jitter (median duration 4 s), the triad offsetting after 4 s, and the noisy scanner environment, participants would probably still be unable to solve more than 10% of all items. The “implausible” response was given by pressing both buttons simultaneously. Because no behavioral differences for the subjective distinction between “aha!” and no “aha!” were found (see Section 3.1, Behavioral Results), and neither were there neural or behavioral differences in our previous study (Kizilirmak, Thuerich, et al., 2016), we collapsed the data from these response categories for the fMRI analysis. In addition to counterbalancing the assignment of the four item pools to old solvable items (sudden comprehension), unsolvable items (continued incomprehension) and new solvable items (not presented in the encoding phase), the order of item presentation was randomized separately for each participant.

**Test phase.** The test phase was conducted on the following day, approximately 24 h after encoding (median: 24 h, range: 20.5–29.5 h). The task largely mirrored the encoding phase, except that participants were given enough time to solve the items themselves and that the “aha!” and “plausible” questions were replaced by an “old”/“new” decision. A fixation cross was presented for 1 s, followed by the triad for 30 s or until a response was made. Participants were instructed to try to solve the items regardless of whether they thought they were old or new. This served to split sudden comprehension trials during encoding into those later solved and those later unsolved for the subsequent memory contrast. As soon as the participants thought of a solution, they pressed the space bar, keeping it pressed during the oral response. These overt responses were recorded by the experimenter (in written format) and later compared with the correct solutions. The old/new question was then presented, together with the triad and the correct solution, until a response was made. Responses during the encoding and test phases were given with the index fingers of the right and left hand for “aha!”/“no aha!” and “old”/“new” respectively, counterbalanced across participants. The order of the old and new items was randomized separately for each participant.

## 2.5. fMRI recording and analysis

MRI data acquisition was conducted using a 3 Tesla Siemens Verio MRI scanner located at the University Hospital of Magdeburg. The scanning session consisted of two anatomical scans and three functional runs. Scanning started with a localizer to set the orientation of a 3D high-resolution T1-weighted scan (MP-RAGE,  $1 \times 1 \times 1$  mm, field of view (FOV) =  $256 \text{ mm}^3$ , 192 slices, time to repetition (TR) = 2500 ms, time to echo (TE) = 4.06 ms,  $7^\circ$  flip-angle) that was used for later co-registration of the functional scans. BOLD-sensitive fMRI was performed using T2\*-weighted echo-planar imaging (EPI), acquired in an interleaved ascending order (FOV =  $192 \text{ mm}^3$ , 34 slices, TR = 2000 ms, TE = 30 ms, in-plane resolution of  $2 \times 2$  mm, slice thickness 3 mm with a 0.3 mm interslice gap,  $80^\circ$  flip-angle). Each of three functional runs comprised 400 scans. EPIs were acquired parallel to the AC-PC line, and the field of view covered almost the whole brain. Small parts of the most dorsal motor and sensory cortices absent, because we required coverage of the ventral-most part of the anterior temporal lobe, which had been previously found to be involved in insight problem-solving. Head motion was restricted by foam cushions to minimize movement-related artifacts.

Data were preprocessed and analyzed using Statistical Parametric Mapping (SPM12; Wellcome Trust Centre for Neuroimaging, UCL, London, UK). EPIs were first corrected for acquisition delay (*slice timing*), using the first slice of each image as reference slice. Next, correction for head motion was performed using SPM’s *realignment* procedure. During realignment, parameters of the six rigid-body transformations (x y z translation, y p r rotation) were determined for each image, but no physical reslicing of the acquisition-corrected images was performed (reslicing was only used to generate a mean image). Individual T1-weighted anatomical images (MP-RAGE) were co-registered to the mean EPIs obtained from realignment and segmented into gray matter, white matter and cerebrospinal fluid, using the automatic segmentation algorithm provided by SPM and the Montreal Neurological Institute (MNI) reference frame. EPIs were then normalized into MNI space using the transformation parameters derived from segmentation ( $2 \text{ mm}^3$  isotropic voxels) and smoothed with a Gaussian kernel of 6 mm full width at half maximum. A high-pass filter of 1/128 Hz was applied to the data.

Statistical analysis was performed using the two-stage mixed-effects model approach implemented in SPM. At the first stage, individual general linear models (GLMs) were constructed to estimate the individual BOLD signal changes related to (1) the presentation of the triads (4 s) and (2) the presentation of the solutions (6 s) as a function of sudden comprehension/continued incomprehension, later memory, and difficulty. Short box-car functions of 4 and 6 s, respectively, were used to model the events. Because incorporation of all factors into a single model was deemed to result in too few trials per condition (for forgotten easy sudden comprehension items, there would have been 6 participants with < 7 trials, and 13 participants with < 10 trials), three different GLMs were applied. The first GLM was used to contrast sudden comprehension and continued incomprehension conditions and included four regressors of interest (triads and solutions of both conditions). The average number of trials per condition was 83.9 (SD = 4.5) for sudden comprehension and 33.2 (SD = 10.3) for continued incomprehension items. In this GLM, the regressors representing the solutions were parametrically modulated trial-by trial with their respective reaction times (RTs) to control for

potential RT differences between items rated as plausible versus implausible, and the resulting parametric modulators were included as additional regressors in the model. Ambiguous items (i.e., sudden comprehension items rated as implausible and continued incomprehension items rated as plausible) were modeled by a separate regressor of no interest. In the second GLM, which was designed to compare successful to unsuccessful encoding of the solutions of the sudden comprehension condition, six covariates of interest were included (later solved and later unsolved sudden comprehension items, and continued incomprehension items, separately for triad and solution events). The mean numbers of trials were 52.1 (SD = 9.1) for later solved sudden comprehension items, 31.7 (SD = 10.0) for later unsolved sudden comprehension items, and 33.2 (SD = 10.3) for continued incomprehension items. The third GLM was employed to compare difficult and easy sudden comprehension items, using six covariates (difficult sudden comprehension, easy sudden comprehension, and continued incomprehension items, separately for triad and solution events). Mean numbers of trials included in this model were 42.7 (SD = 3.2) for difficult sudden comprehension items, 41.2 (SD = 3.1) for easy sudden comprehension items, and 33.2 (SD = 10.3) for continued incomprehension items.

For all three GLMs, short epochs were modeled at stimulus onset of the triads (4 s) and solutions (6 s) and convolved with the canonical hemodynamic response function (HRF) provided by SPM. The resulting time courses were down-sampled to the TR (2000 ms), yielding the condition-specific regressors. Additionally, all three GLMs contained the six rigid-body motion parameters obtained from realignment as covariates of no interest, plus a single constant representing the mean over scans.

At the second stage, contrasts of interest (i.e., parameter estimates divided by their standard errors) from the first-level analysis served as covariates in second-level GLM analyses, and pair-wise comparisons were carried out between sudden comprehension versus continued incomprehension (first GLM), later solved versus later not solved sudden comprehension (second GLM), and difficult versus easy sudden comprehension (third GLM), for both the triad and solution events, using paired *t* contrasts in both directions. In all whole-brain analyses, we employed a family-wise error (FWE) correction at cluster level ( $p < .05$ ) with an *a priori* significance threshold of  $p < .001$ , uncorrected, as recommended for cluster-based corrections (Eklund, Nichols, & Knutsson, 2016; Woo, Krishnan, & Wager, 2014).

Based on our specific anatomical hypotheses, activation differences in the amygdala, hippocampus, striatum and dopaminergic midbrain were tested using a region of interest (ROI)-based approach. To this end, we generated bilateral ROIs of the amygdala and hippocampus using the probabilistic cytoarchitectonic maps provided with the SPM Anatomy Toolbox (Eickhoff et al., 2005). The striatum ROIs were obtained from the AAL atlas (Tzourio-Mazoyer et al., 2002) as implemented in the WFU Pickatlas (Wake Forest University). ROIs of the SN/VTA were generated using a previously described literature-based probabilistic approach (Schott et al., 2013; Schubert, Ritter, Wüstenberg, Preuschhof, Curio, Sommer, & Villringer, 2008; Zweynert et al., 2011). The extent of the ROIs is depicted in Supplementary Fig. S1. The significance level of the ROI analyses was set to  $p < .05$ , FWE-corrected for the ROI volume at voxel level, with an *a priori* search threshold of  $p < .001$ , uncorrected.

### 3. Results

#### 3.1. Behavioral results

We first examined the proportions of implausible responses to sudden comprehension and continued incomprehension items in the encoding phase. Confirming the utility of our approach, only a small minority of sudden comprehension items (mean = 0.05, SD = 0.05), but most continued incomprehension items (0.75, SD = 0.23), were rated as implausible. The difference between the two conditions was highly significant [ $t(22) = 15.97$ ,  $p < .001$ , Cohen's  $d = 3.755$ ]. Furthermore, significantly more subjective reports of “aha!” were given along with the “plausible” responses for sudden comprehension (absolute proportion of responses: mean = 0.54, SD = 0.24) compared with continued incomprehension items (absolute proportion of responses: mean = 0.11, SD = 0.14) [ $t(22) = 9.00$ ,  $p < .001$ , Cohen's  $d = 3.019$ ].

We further analyzed whether the distribution of response options (plausible + “aha!” vs. plausible + no “aha!” vs. implausible) was dependent on problem difficulty of sudden comprehension items (difficult, easy) by means of subject-wise  $\chi^2$  tests.<sup>†</sup> Problem difficulty was determined by the relative number of participants who could solve the item in a normative study conducted before the actual experiment (see Materials and Methods for details). No dependency was identified [minimum  $p = .682$ , maximum  $\chi^2$  (N = 6) = 1.50].

Memory performance was tested using the incidental memory test described above (solution rate of old vs. new items), and an additional intentional memory test (recognition rate of old items via old/new decision) was conducted on each test item after the solution attempt (see Materials and Methods, and Richardson-Klavehn, 2010; Richardson-Klavehn & Bjork, 1988; Richardson-Klavehn & Gardiner, 1996).<sup>‡</sup>

In the incidental test, participants correctly solved significantly more old (mean = 0.62, SD = 0.11) than new sudden comprehension items (0.34, SD = 0.09) [ $t(22) = 14.78$ ,  $p < .001$ , Cohen's  $d = 3.154$ ], indicating substantial learning during the encoding phase in the scanner on the previous day, even though participants had not been informed of a later memory test. Participants were also approximately 3000 ms faster when producing correct solutions to old (6925 ms, SD = 1832 ms) compared with correct solutions

<sup>†</sup> These tests had to be done subject-wise, as each participant contributes a different number of cases per cell. Hence, there could be dependency between variables for several subjects, but in an overall cross-table, this effect may be “averaged out”.

<sup>‡</sup> As explained under 2.3, only sudden comprehension items were analyzed in regard to later memory performance. Solution rates in the test phase could not be assessed for the continued incomprehension items, because they were unsolvable to begin with.

to new items (9826 ms, SD = 2472 ms) [ $t(22) = 5.22, p < .001$ , Cohen's  $d = 1.108$ ]. There was no significant difference in solution rates during the memory test when comparing items that were rated as plausible with “aha!” (mean = 0.64, SD = 0.15) versus plausible without “aha!” (mean = 0.61, SD = 0.22) during encoding [ $t(22) = 0.51, p = .614$ , Cohen's  $d = 0.634$ ].

The hit rate in the intentional recognition memory test was high (proportion of old items correctly identified as old: mean = 0.84, SD = 0.12), and the false alarm rate was relatively high (proportion of new items incorrectly identified as old: 0.20, SD = 0.13), as might be expected after 24 h. Participants were nevertheless able to discriminate well between old and new items, as indicated by a high mean  $d'$  of 2.06 (SD = 0.64), which is significantly different from zero [ $t(22) = 15.44, p < .001$ , Cohen's  $d = 3.22$ ]. As with the solution rates, there was no significant difference in hit rates for items that were rated as plausible with “aha!” (mean = 0.83, SD = 0.11) versus plausible without “aha!” (mean = 0.79, SD = 0.23) [ $t(22) = 0.83, p = .416$ , Cohen's  $d = 0.328$ ] ( $d'$  could not be calculated, because there was no “aha!”/“no aha!” differentiation for new items, ergo no false alarms specific for “aha!” and “no aha!”). The high recognition memory hit rate meant that contingency analysis of solution performance in the incidental test for old items (solved vs. unsolved) and recognition memory performance (hit vs. miss) was not feasible. Furthermore it precluded fMRI analysis of subsequent recognition memory owing to there being too few recognition memory misses.

Lastly, we conducted a 2 by 2 repeated-measures ANOVA with the factors DIFFICULTY (hard, easy) and OLDNESS (old, new) for the solution rate at test, to assess whether participants learned the solutions for difficult and easy items to a comparable degree. Difficult old items had a mean solution rate of 0.48 (SD = 0.12) at test, difficult new items a mean solution rate of 0.18 (SD = 0.08), easy old items a mean solution rate of 0.76 (SD = 0.11), and easy new items a mean solution rate of 0.55 (SD = 0.16). We found a main effect of DIFFICULTY [ $F(1, 22) = 320.50, p < .001, \eta_p^2 = 0.936$ ] and a main effect of OLDNESS [ $F(1, 22) = 193.73, p < .001, \eta_p^2 = 0.898$ ], as well as a significant interaction [ $F(1, 22) = 4.33, p = .049, \eta_p^2 = 0.165$ ]. To clarify the interaction in the ANOVA, we subtracted the solution rate for new items from the solution rate for old items, yielding a derived learning measure. Learning (i.e., the solution-rate advantage for old over new items) was significantly greater for difficult items (mean = 0.30, SD = 0.11) compared with easy items (mean = 0.23, SD = 0.14) [ $t(22) = 2.08, p = .049$ , Cohen's  $d = 0.410$ ]. As elaborated in the Discussion (see 4.3 [The DMN supports both self-referential processing and associative memory](#)), this relationship between item difficulty and learning makes it hard to attribute the learning for sudden comprehension items to simple ease of processing during the encoding phase. Learning was inversely related to ease of processing.

### 3.2. fMRI results

For all whole-brain comparisons, the significance threshold was set to  $p < .05$ , family-wise error (FWE)-corrected at cluster level with an *a priori* significance level of  $p < .001$ , uncorrected (see 2.5 [fMRI recording and analysis](#)).

**Neural correlates of sudden comprehension:** During presentation of triads, the only significant difference between sudden comprehension and continued incomprehension items was observed in the left inferior frontal gyrus, pars triangularis ( $[x\ y\ z] = [-50\ 40\ 0]$ ). An exploratory analysis at  $p < .05$ , cluster level, with an *a priori* significance level of  $p < .005$ , uncorrected, further revealed activation clusters in left dorsolateral prefrontal, lateral parietal and lateral occipito-temporal cortices. During the presentation of solutions, on the other hand, there were pronounced brain-activity differences between the sudden comprehension and continued incomprehension conditions. Higher brain responses to sudden comprehension solutions were observed in midline brain structures, including the mPFC and adjacent rostral anterior cingulate cortex (rACC), and the posterior cingulate cortex (PCC) and adjacent precuneus, and also in the ventrolateral and dorsolateral prefrontal cortices (superior/middle frontal gyrus), as well as in the hippocampus bilaterally, in the striatum/caudate nucleus, and in the amygdala (see [Table 1](#) and [Fig. 2](#)). Further activation clusters were observed in the frontopolar cortex (FPC, BA 10) and in temporo-parietal regions, namely in bilateral middle temporal gyrus (MTG), bilateral inferior temporal gyrus (ITG), bilateral inferior parietal lobe (IPL), spanning supramarginal (SMG) and angular gyrus (ANG).

As the pronounced activations of midline structures (rACC/mPFC, PCC) and of lateral parietal cortex showed considerable overlap with the Default Mode Network (DMN), we next conducted a masked analysis to explore the possibility that the observed activations might simply result from reduced cognitive effort during processing of sudden comprehension compared to continued incomprehension items. This could have been the case, for example, if participants had ceased processing efforts after comprehending the solution for sudden comprehension items while still trying to grasp the connection between solution and triad for (unsolvable) continued incomprehension items. To this end, the contrast sudden comprehension > continued incomprehension ( $p < .001$ , uncorrected, with cluster-level FWE-corrected  $p < .05$ ) was exclusively masked with functional masks of the ventral and dorsal DMN as obtained from a published independent component analysis (ICA; [Shirer, Ryali, Rykhlevskaia, Menon, & Greicius, 2012](#)). While the analysis confirmed that particularly parts of the medial prefrontal and posterior cingulate activations did, to a large extent, indeed overlap with the DMN, other activation clusters associated with sudden comprehension, most prominently the dorsolateral and ventrolateral PFC, bilateral inferior parietal lobe, and also the left anterior hippocampus, were clearly located outside the DMN masks. The extent to which the observed activation patterns did and did not overlap with the DMN masks is depicted in [Fig. 2C](#).

In the reverse contrast (continued incomprehension > sudden comprehension), we primarily observed higher activation in brain structures implicated in motor and also visual processing, most prominently bilateral primary and supplementary motor cortices, and left extrastriate cortex ([Supplementary Table S1](#)). The bilateral motor cortex activation likely resulted from the “implausible” responses in the continued incomprehension condition, which required a bimanual response (see 2.4 [Task and procedure](#)). To address the possibility that activation of DMN structures during sudden comprehension versus continued incomprehension might reflect reduced cognitive processing in the sudden comprehension condition, for example as a result of ceased cognitive effort after reaching comprehension, we aimed to assess whether “task-positive” networks (typically anti-correlated to the DMN) would respond



**Table 1**

Peak locations of BOLD responses ( $p < .05$  FWE corrected at cluster level) to sudden comprehension compared with continued incomprehension items during presentation of the solutions. All coordinates are given in MNI space. BA: Brodmann area, NoV: number of voxels (i.e., cluster size), HS: hemisphere.

Anatomical label	BA	NoV	HS	x	y	z	Peak $t$	Z
Inferior parietal lobe, angular gyrus	39	3998	L	-48	-60	38	6.83	7.54
Inferior parietal lobe	40		L	-56	-48	44	4.37	7.11
Inferior parietal lobe	7		L	-46	-62	50	1.51	6.49
Middle temporal gyrus, inferior temporal gyrus	21, 20		L	-64	-32	-10	9.66	5.98
Superior frontal gyrus	6	10,487	L	-20	30	52	1.97	6.60
Middle frontal gyrus	6		L	-44	14	46	1.88	6.58
Superior frontal gyrus	8		L	-16	50	36	1.05	6.37
Anterior cingulate gyrus, medial frontal gyrus	32, 9		L	-4	38	14	10.71	6.28
Inferior parietal lobe	39, 40	3437	R	44	-58	40	11.32	6.44
Inferior parietal lobe	40		R	56	-40	44	10.76	6.29
Inferior parietal lobe, supramarginal gyrus	40		R	54	-42	28	9.99	6.08
Precuneus	19		R	42	-70	44	9.55	5.94
Precuneus	31, 7	4049	R	0	-28	42	10.14	6.12
Precuneus, posterior cingulate gyrus	31		L	-8	-42	34	9.21	5.84
Precuneus	31		L	-10	-52	32	8.73	5.68
Posterior cingulate gyrus	23, 30		L	-2	-48	22	8.09	5.46
Posterior cerebellum		149	R	42	-58	-40	6.35	4.74
Posterior cerebellum			R	42	-74	-38	6.29	4.71
Posterior cerebellum			R	42	-46	-42	5.00	4.04
Posterior cerebellum, inferior semi-lunar lobule			R	40	-78	-30	3.71	3.24
Middle frontal gyrus, inferior frontal gyrus	10, 46	128	R	46	44	8	5.26	4.19
Middle frontal gyrus	10	3998	R	36	52	-2	4.57	3.79

Note. Only the maximum peak of each cluster is reported. Significant results for the reverse contrast are listed in the Supplementary Table S1. The table shows 4 local maxima more than 8.0 mm apart. Height threshold:  $T = 3.50$ ,  $p = .001$  (1.000). Extent threshold:  $k = 100$  voxels,  $p = .001$  (0.034). Expected voxels per cluster,  $\langle k \rangle = 7.981$ . Expected number of clusters,  $\langle c \rangle = 0.03$ . FWEp: 6.913, FDRp: 5.544, FWEc: 128, FDRc: 64. Degrees of freedom = [1.0, 22.0]. FWHM =  $9.4 \times 9.3 \times 8.7$  mm<sup>3</sup>; 4.7 4.6 4.3 {voxels}. Volume: 1367992 = 170999 voxels = 1666.8 resels. Voxel size:  $2.0 \times 2.0 \times 2.0$  mm<sup>3</sup>; (resel = 94.92 voxels).

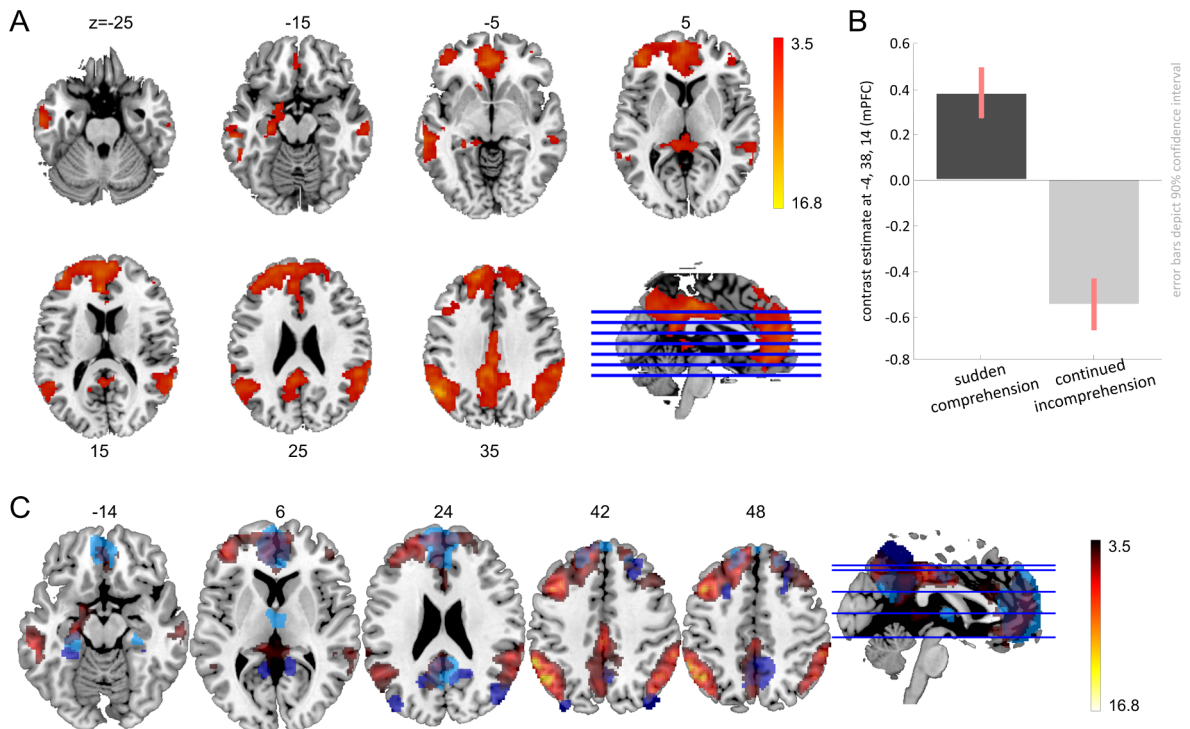
preferentially in the continued incomprehension condition. To this end, we performed a masking analysis with the left and right central executive networks, the salience network, and the visuo-spatial network, using masks also obtained from Shirer et al. (2012). There was no overlap with the left or right central executive networks and only marginal overlap with the salience network and the visuo-spatial network (Supplementary Fig. S2).

The principal purpose of this study was to investigate neural correlates of learning from sudden comprehension. To examine learning, we compared BOLD responses during the encoding phase to later solved versus later unsolved sudden comprehension items. This comparison was a classical “subsequent memory” comparison, but with the unusual feature that an incidental conceptual test of learning was used (Ramponi et al., 2007). In contrast to the comparison between sudden comprehension and continued incomprehension, no differences were found during processing of the triads. During processing of solutions, later solved compared to later unsolved items elicited increased BOLD responses in mPFC/rACC and PCC/precuneus, as well as in lateral prefrontal cortices (see Table 2 and Fig. 3). Similarly to the comparison of sudden comprehension and continued incomprehension items, activations were also observed in MTG and lateral parietal regions.

Despite the considerable overlap between these areas and brain structures activated in the sudden comprehension versus continued incomprehension contrast, we observed no significant hippocampal activation for later solved versus unsolved sudden comprehension items, that is, no significant voxels were found within a probabilistic anatomical map of the left or right hippocampus (including dentate gyrus, CA regions, and subiculum) generated with the SPM Anatomy Toolbox (Eickhoff et al., 2005), even at  $p < .005$ , uncorrected. At  $p < .001$ , minimum cluster size = 10 voxels, a small cluster in the right anterior MTL became apparent, but as assessed with the SPM Anatomy Toolbox, this cluster was localized in the amygdala rather than the hippocampus (see Fig. 4), and it survived small-volume FWE correction for a probabilistic anatomical amygdala mask ( $[x \ y \ z] = [26 \ -4 \ -16]$ ;  $t(22) = 3.98$ ;  $p = .049$ , FWE-corrected for amygdala ROI).

Unlike in our previous study (Kizilirmak, Thuerich, et al., 2016), where whole-brain voxel-wise analyses had revealed a subsequent memory difference in the striatum, neither whole-brain nor ROI analyses yielded activations related to later learning in the striatum or midbrain, suggesting that the mesolimbic system might be differentially involved in the encoding processes leading to successful later solution as compared to episodic recognition memory for the solution words (Kizilirmak, Thuerich, et al., 2016).

Finally, we compared neural processing of difficult versus easy items of the sudden comprehension condition. This analysis was conducted by comparing BOLD responses to difficult and easy items at the single-subject level, followed by a one-sample  $t$  contrast at group level. There were no significant BOLD signal differences between difficult and easy sudden comprehension items during the presentation of the triads. During the presentation of the solutions, on the other hand, marked differences were observed between the brain responses to difficult versus easy items (see Fig. 5 and Table 3). Based on the previously demonstrated role of the dopaminergic midbrain in the processing of difficult tasks (Boehler et al., 2011), as well as our specific anatomical hypotheses regarding the



**Fig. 2.** Neural correlates of sudden comprehension. (A) The BOLD contrast of sudden comprehension (solvable CRAT) > continued incomprehension (unsolvable control) conditions is depicted at  $p < .05$ , cluster-level corrected, a priori search threshold of  $p < .001$ , uncorrected. Z coordinates for the presented slices are provided in MNI space. The contrast revealed stronger hippocampal ( $z = -15$ ) and mPFC ( $z \geq -15$ ) activations as well as further temporo-parietal activations during sudden comprehension compared with continued incomprehension. (B) The contrast estimates at the peak voxel in the mPFC ( $[x\ y\ z] = [-4\ 38\ 14]$ ). (C) An overlay of the contrast in A with DMN masks obtained from Shirer et al. (2012). While several midline brain structures, such as the rACC/mPFC and the PCC and ventral precuneus, showed considerable overlap with the dorsal (light blue) and ventral (dark blue) DMN, the left ventrolateral and dorsolateral PFC and anterior hippocampus were clearly located outside of the DMN masks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

potentially more rewarding nature of comprehending the solution to difficult compared with easy items (see Introduction), we conducted a region of interest (ROI)-based analysis in this region. To this end, we used combined anatomical and probabilistic ROIs comprising the SN and VTA (Supplementary Fig. S1). In line with our hypothesis, solutions of difficult compared to easy items were associated with activation of the SN/VTA ( $[x\ y\ z] = [4\ -18\ -14]$ ;  $T = 3.92$ ; see Fig. 5). We further conducted a ROI-based analysis in the left and right striatum. A cluster in the left striatum ( $[x\ y\ z] = [-24\ 4\ 2]$ ) showed a stronger response to difficult compared to easy items at  $p < .001$ , but remained only as a trend after small-volume correction ( $p = .070$ , FWE-corrected for ROI volume). No activity differences related to item difficulty were observed in the amygdala or hippocampus.

#### 4. Discussion

Using fMRI, we aimed to elucidate the cognitive mechanisms and neural correlates of successful learning for suddenly comprehended solutions during a verbal problem-solving task. We considered three potential mechanisms for learning during problem-solving: (1) effort towards comprehension, (2) the “aha”-like experience and representational change when the relationship of the problem components suddenly becomes meaningful, and (3) the intrinsically rewarding feeling that accompanies the sudden comprehension.

Neural activity during the *search process* (i.e., presentation of the triads) differed with respect to a small cluster in the left ventrolateral PFC for sudden comprehension compared with continued incomprehension, suggesting a slightly higher degree of semantic processing, possibly due to the few items that could be solved before the solution was presented, but also possibly reflecting implicit activation of remote associative connections that could potentially lead to a solution. The *moment of comprehension* during the presentation of the solution of an until then unsolved problem was identified as the critical time point at which study items started to show a high number of neural activation differences between items in the sudden comprehension and continued incomprehension conditions. Moreover, for the sudden comprehension condition, significant BOLD signal differences between later solved and unsolved items (subsequent learning difference), as well as difficult versus easy problems, became apparent only during the presentation of the solutions, suggesting that this period was the critical one for successful learning.

Suddenly comprehended solutions elicited activations in both the mPFC and the hippocampus compared to the continued

**Table 2**

Peak BOLD responses ( $p < .05$  FWE corrected on cluster level) to later solved compared with later unsolved sudden comprehension items. All coordinates are given in MNI space. BA: Brodmann area, NoV: number of voxels (i.e., cluster size), HS: hemisphere.

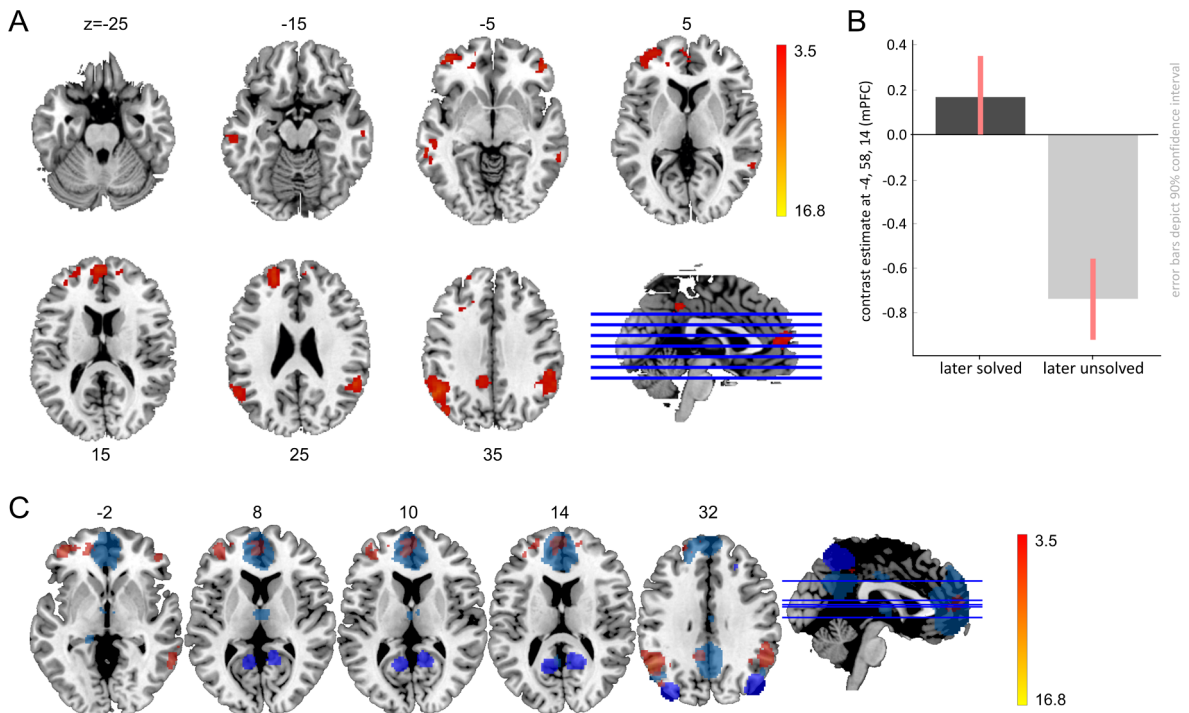
Anatomical label	BA	NoV	HS	x	y	z	Peak <i>t</i>	Z
Inferior parietal lobe	40	1323	L	-52	-56	48	8.24	5.51
Inferior parietal lobe	40		L	-50	-56	36	7.92	5.39
Precuneus, angular gyrus	19, 39		L	-44	-74	34	5.61	4.37
Supramarginal gyrus	40	920	R	56	-50	26	6.89	4.98
Supramarginal gyrus	40		R	54	-38	34	5.89	4.52
Inferior parietal lobe	40		R	46	-52	56	5.89	4.51
Middle temporal gyrus	21	255	L	-62	-26	-12	6.75	4.92
Middle temporal gyrus	21		L	-62	-40	-8	6.36	4.74
Middle temporal gyrus	20		L	-54	-34	-8	4.36	3.66
Superior/middle frontal gyrus	10	335	L	-20	48	24	6.26	4.69
Superior frontal gyrus	9, 10		L	-22	56	24	6.13	4.63
Superior frontal gyrus	8		L	-12	46	44	4.31	3.63
Medial frontal gyrus	9, 10	352	L	-4	58	14	6.20	4.67
Medial frontal gyrus, anterior cingulate	10, 32		L	-6	48	10	5.26	4.19
Superior/medial frontal gyrus	9, 10		R	10	56	20	5.26	4.19
Middle frontal gyrus	10	395	L	-42	50	-6	6.12	4.63
Middle frontal gyrus	10		L	-36	44	10	5.07	4.09
Superior/middle frontal gyrus	10		L	-32	56	4	4.87	3.97
Middle/inferior frontal gyrus	47	76	R	48	42	-6	6.11	4.63
Middle/superior frontal gyrus	6, 8	236	L	-40	14	46	5.99	4.56
Middle frontal gyrus	8		L	-34	24	44	4.37	3.67
Precentral gyrus	9		L	-40	20	38	4.37	3.67
Medial frontal gyrus	10	96	L	-18	58	2	5.37	4.25
Medial frontal gyrus, anterior cingulate	10		L	-20	48	-2	5.34	4.23
Medial/middle frontal gyrus	6, 8	152	L	-18	30	38	5.32	4.22
Superior frontal gyrus	6		L	-18	24	54	4.67	3.85
Middle/superior frontal gyrus	8	146	R	32	28	46	5.28	4.20
Superior frontal gyrus	6		R	12	30	56	3.96	3.41
Middle/superior frontal gyrus	6, 8		R	28	22	54	3.96	3.40
Precuneus	31	161	L	-8	-50	32	5.20	4.16
Cingulate gyrus, precuneus	31, 7		L	-4	-42	42	4.75	3.90
Middle/inferior temporal gyrus	21, 37	133	R	58	-54	0	4.97	4.03
Middle temporal gyrus	21		R	62	-42	-6	4.88	3.97
Middle temporal gyrus	21	74	R	64	-18	-10	4.83	3.95
Inferior/middle temporal gyrus	20, 21	1323	R	62	-30	-12	4.50	3.75

Note. Only the maximum peak of each cluster is reported. Significant results for the reverse contrast are listed in the Supplementary Table S2. The table shows 3 local maxima more than 8.0 mm apart. Height threshold:  $T = 3.50$ ,  $p = 0.001$  (1.000). Extent threshold:  $k = 70$  voxels,  $p = 0.002$  (0.057). Expected voxels per cluster,  $\langle k \rangle = 5.913$ . Expected number of clusters,  $\langle c \rangle = 0.06$ . FWEp: 6.932, FDRp: 7.258, FWEc: 74, FDRc: 45. Degrees of freedom = [1.0, 22.0]. FWHM =  $8.5 \times 8.4 \times 7.9$  mm<sup>3</sup>;  $4.2 \times 4.2 \times 3.9$  {voxels}. Volume: 1367992 = 170999, voxels = 2249.8 resels, Voxel size:  $2.0 \times 2.0 \times 2.0$  mm<sup>3</sup>; (resel = 70.32 voxels).

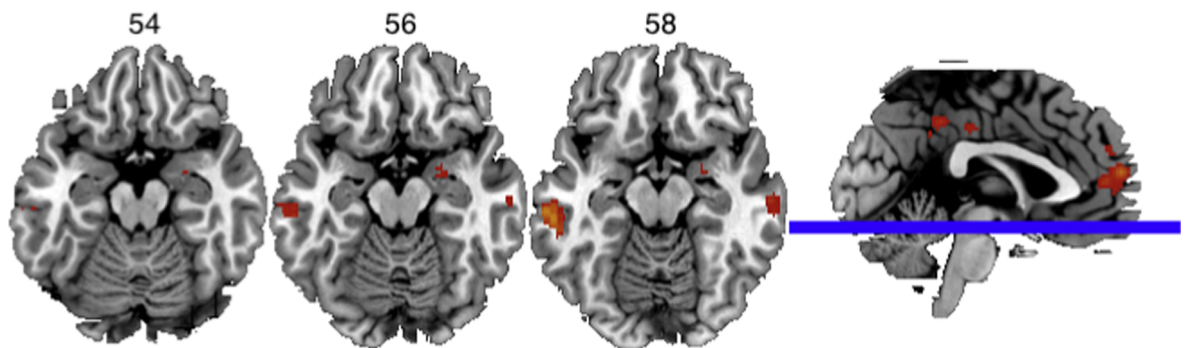
incomprehension condition, compatible with both associative novelty (Nyberg, 2005; Schott et al., 2004) and congruency with prior knowledge (van Kesteren et al., 2012), respectively. Item difficulty was further associated with activation of dopaminergic midbrain nuclei and increased learning for difficult compared with easy items, supporting our hypothesis that intrinsic reward plays a role in learning during problem-solving and sudden comprehension. Notably, activation of the mPFC rather than hippocampus predicted successful learning of suddenly comprehended solutions.

#### 4.1. Sudden comprehension, associative novelty and semantic processing

Solutions involving sudden comprehension, compared to continued incomprehension, elicited BOLD signal increases in the hippocampus bilaterally as well as in the amygdala and the striatum. Moreover, posterior parietal regions, as well as prefrontal brain regions, namely the mPFC/rACC, the frontal pole, the ventrolateral (VLPFC) and the dorsolateral PFC (DLPFC), were involved in sudden comprehension compared with continued incomprehension. The lateral prefrontal cortex regions and the hippocampus are thought to form a network processing cues and selectively retrieving information from long-term memory to fulfill the task at hand (Simons & Spiers, 2003). The VLPFC has been strongly associated with semantic processing, especially selection from memory and the maintenance of retrieved information, and a left-sided activation is often observed for verbal stimulus material (Nee & Jonides, 2009; Nee, Wager, & Jonides, 2007). Based on an extensive review and several fMRI studies to test this view, Badre put forward the hypothesis that the VLPFC is associated with maintaining retrieval rules (here: "Is there a compound word relating each triad word and the solution word?"), while the DLPFC tests those first-order relationships (Badre & Wagner, 2002, 2007; Badre, 2008). Moreover, the left VLPFC has been implicated in post-retrieval interference resolution (Nee, Jonides, & Berman, 2007), in this case perhaps resolving conflicts between incorrect candidate solutions that the participant had developed and the correct solution that was presented. In this context, the hippocampus is thought to compare retrieval cues and stored representations (e.g., Simons & Spiers,



**Fig. 3.** Neural correlates of successful encoding of triad solutions for the sudden comprehension condition. (A) The BOLD contrast of later solved > later unsolved items (subsequent learning difference) is depicted at  $p < .05$ , FWE-corrected at cluster level (a priori search threshold of  $p = .001$ , uncorrected). The contrast revealed mainly mPFC, MTG, and inferior parietal activations. (B) The contrast estimates at the peak voxel in the mPFC. (C) An overlay of the contrast in A with a DMN mask derived from Shirer et al. (2012).

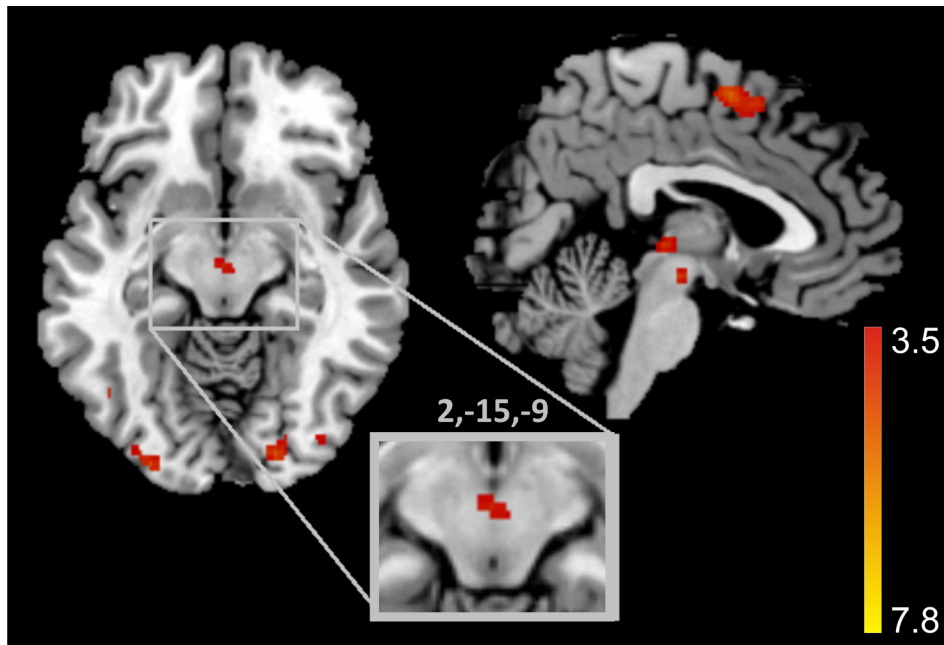


**Fig. 4.** Results of the amygdala ROI analysis for the contrast of later solved > later unsolved sudden comprehension items. The BOLD contrast is depicted at  $p < .05$ , FWE-corrected for the ROI volume at voxel level (a priori search threshold of  $p = .001$ , uncorrected). The ROI was chosen from the SPM anatomy toolbox.

2003). While one might, at first, consider the hippocampal activation to reflect more retrieval from semantic memory during processing of suddenly comprehensible versus continuously incomprehensible solutions, this interpretation does not, in our view, capture the underlying cognitive processes sufficiently. Although the VLPFC activation is indeed compatible with enhanced semantic processing of comprehensible solutions (see above), semantic *retrieval* in particular is associated with increased hippocampal responses to novel rather than familiar items (Düzel et al., 1999). The hippocampal and mesolimbic activations may thus be interpreted in the context of novelty processing, as the hippocampus has previously been shown to exhibit significantly higher responses to novel compared to familiar items (Maass et al., 2014; Ranganath & Rainer, 2003). Specifically, the hippocampus has been implicated in the detection of several different types of novelty: stimulus novelty (completely unfamiliar stimuli), contextual novelty (familiar stimuli in the context of other novel stimuli), and associative novelty (familiar stimuli in a novel arrangement) (Knight, 1996; Nyberg, 2005; Ranganath & Rainer, 2003). Here, items of both the sudden comprehension and the continued incomprehension conditions consisted of four known words in a novel arrangement, precluding an influence of stimulus novelty and resulting in comparable levels of both contextual and associative novelty.

Recently, a special form of associative novelty, *conceptual novelty*, has been shown to modulate hippocampus-dependent memory





**Fig. 5.** Neural correlates of item difficulty during processing of sudden comprehension solutions. The BOLD contrast of difficult > easy items is displayed at  $p < .001$ , uncorrected. The contrast revealed stronger activation of the dopaminergic midbrain (VTA/SN) for difficult compared with easy solutions ( $p < .05$ , small-volume FWE-corrected). This finding was accompanied by greater behavioral later learning for difficult compared with easy items.

**Table 3**

Peak locations of BOLD responses ( $p < .05$  FWE corrected) to difficult compared with easy sudden comprehension items. All coordinates are given in MNI space. BA: Brodmann area, NoV: number of voxels (i.e. cluster size), HS: hemisphere.

Anatomical label	BA	NoV	HS	x	y	z	peak <i>t</i>	Z
Precentral gyrus	4, 6	393	L	-50	-4	50	7.86	5.37
Precentral gyrus	4, 6		L	-46	0	40	6.68	4.88
Middle frontal gyrus	6		L	-50	6	36	6.25	4.69
Insula, inferior frontal gyrus	13, 45	141	R	36	22	2	7.56	5.25
Medial frontal gyrus	6	465	L	-2	4	58	6.15	4.64
Superior frontal gyrus	6, 8		R	8	16	48	5.11	4.11
Superior/medial frontal gyrus	6		L	-6	10	52	5.01	4.05
Fusiform/lingual gyrus	18	113	R	20	-88	-8	5.58	4.36
Lingual gyrus	17, 18		R	16	-94	-4	4.99	4.04
Precuneus	7	289	L	-22	-62	38	5.42	4.28
Precuneus, superior parietal lobe	7		L	-30	-44	48	5.26	4.19
Superior parietal lobe	7		L	-30	-58	50	4.82	3.94
Inferior/middle occipital gyrus	18	81	R	34	-88	4	5.06	4.08
Middle occipital gyrus	18, 19	393	R	36	-80	14	3.76	3.27

Note. Only the maximum peak of each cluster is reported. Significant results for the reverse contrast are listed in the Supplementary Table S3. The table shows 4 local maxima more than 8.0 mm apart. Height threshold:  $T = 3.50$ ,  $p = 0.001$  (1.000). Extent threshold:  $k = 70$  voxels,  $p = 0.002$  (0.061). Expected voxels per cluster,  $\langle k \rangle = 6.053$ . Expected number of clusters,  $\langle c \rangle = 0.06$ . FWEp: 6.932, FDRp: 7.561, FWEc: 81, FDRc: 52. Degrees of freedom = [1.0, 22.0]. FWHM =  $8.5 \times 8.4 \times 8.1 \text{ mm}^3$ ;  $4.2 \times 4.2 \times 4.0$  {voxels}. Volume:  $1367992 = 170999$  voxels = 2197.7 resels. Voxel size:  $2.0 \times 2.0 \times 2.0 \text{ mm}^3$ ; (resel = 71.99 voxels).

formation (Reggev, Bein, & Maril, 2016). Encoding-related hippocampal activation was found to be more pronounced for previously unfamiliar compared to familiar semantic associations. Importantly, Reggev and colleagues employed relatively meaningless associations in their novelty condition (e.g., “bad forehead”) and compared them to well-represented close associates (e.g., “yellow banana”). The involvement of the hippocampus in response to contextual and associative novelty as well as spatial navigation and other tasks gave rise to a relational processing account of the hippocampus, proposing that it is generally involved in all types of relational processing, be it comparing a presented item with a memory representation, as in recognition memory tests, or navigating through an environment (Eichenbaum & Cohen, 2001).

Previous neuroimaging studies have also reported hippocampal activation during insight-based problem-solving (Ludmer et al., 2011; Luo & Niki, 2003), and the authors of those studies suggested that the hippocampal activation might reflect, for example,



breaking mental fixation or pattern completion. While we cannot exclude the presence of such relatively unspecific mechanisms in our study, the specific hippocampal activation to meaningful versus to comparably meaningless associative novelty, as exemplified by our sudden comprehension and continued incomprehension conditions, points to a thus far underestimated role of the hippocampus in semantic memory, namely the *detection of novel meaningful relationships between existing memory representations*. Recent evidence from a neuropsychological study demonstrates impaired CRAT performance after hippocampal damage, which the authors interpreted as a deficit in problem-solving creativity (Warren, Kurczek, & Duff, 2016). Our results are compatible with that observation and expand it by suggesting that the hippocampus might contribute to problem solving by mediating the detection of novel, meaningful, semantic associations.

In addition to the VLPFC and the hippocampus, the medial prefrontal cortex (mPFC) and adjacent rostral anterior cingulate cortex (rACC) were among the brain structures that differentiated reliably between the sudden comprehension and continued incomprehension conditions. The simultaneous activation of the hippocampus and mPFC during sudden comprehension is in line with the recently described role of hippocampal-mPFC interactions in insight-mediated rearrangement of pre-existing memory representations (Milivojevic, Vicente-Grabovetsky, & Doeller, 2015), and with other works suggesting that the rACC/mPFC forms part of a hippocampus-dependent network for processing related pieces of information (for a review, see Schlichting & Preston, 2015).

The different roles of the hippocampus and mPFC during relational processing are thought to reflect hippocampal involvement in processing specific relationships between memory representations (e.g., Guitart-Masip, Bunzeck, Stephan, Dolan, & Düzel, 2010; Nyberg, 2005; Schott et al., 2004; Shimamura, 2010) and the more abstract formation or activation of an overarching concept by the mPFC (Spalding et al., 2018; Spalding, Jones, Duff, Tranel, & Warren, 2015; Warren, Jones, Duff, & Tranel, 2014). Both types of relational processing are probably involved in the processing of solutions of the sudden comprehension compared with the “solutions” of the continued incomprehension condition: The hippocampus is most likely involved in the evaluation of how the solution word can form compound words with the triad words, whereas the mPFC may be involved in activating the conceptual knowledge linked to the meaning of the compound words.

Increased BOLD responses to plausible solutions were also observed in the striatum/caudate nucleus, a brain structure that has been shown to respond to motivationally salient stimuli or, more generally, to reward processing (Delgado, Stenger, & Fiez, 2004; Packard & Knowlton, 2002). The striatum is part of the hippocampal-VTA loop (Lisman & Grace, 2005) and, as such, likely to contribute to dopaminergic enhancement of hippocampus-dependent encoding of novel, salient events (Krebs et al., 2009; Wittmann et al., 2005). In a similar task to the one used here, we have recently observed striatal activations predicting episodic recognition of meaningful solutions (Kizilirmak, Thuerich, et al., 2016), and the current results are also compatible with previously described striatal activation in other tasks requiring insight-like problem-solving (Huang, Holcombe, & Pashler, 2004).

#### 4.2. Sudden comprehension promotes long-term memory formation

A subset of the brain regions that responded to the solutions of sudden comprehension items versus the “solutions” of continued incomprehension items was also involved in the successful learning of the solutions of the sudden comprehension items. Notably, despite the pronounced hippocampal BOLD response associated with sudden comprehension, we found no hippocampal activation when comparing later solved to later not solved sudden comprehension items, as corroborated by our hippocampus ROI analysis. Instead, brain areas dissociating later solved from later unsolved items included again the mPFC and adjacent rACC, and also lateral PFC regions (inferior, middle, and superior frontal gyrus), the MTG, the temporo-parietal junction (ANG/SMG), and the PCC/pre-cuneus. Moreover, conforming to previous findings on learning from perceptual insight (Ludmer et al., 2011), we also found a higher activation of the amygdala for later solved compared with later unsolved items. This finding supports the idea that learning by sudden comprehension is partially promoted by the affective salience of the items.

As discussed above, mPFC activations related to successful encoding have previously been associated with the detection and encoding of novel information congruent with prior knowledge (Tse et al., 2011; van Kesteren et al., 2012; van Kesteren, Rijpkema, Ruiters, & Fernández, 2010). Furthermore, in prior-knowledge-dependent encoding, the role of the hippocampus decreases over time while the role of the mPFC increases (Euston, Gruber, & McNaughton, 2012; Tse et al., 2007). Using functional connectivity analyses, van Kesteren and colleagues further showed that the mPFC likely suppresses hippocampal engagement during the encoding of information congruent with prior knowledge or schemas (van Kesteren et al., 2013). We suggest that sudden comprehension of relationships between pre-existing concepts (here, the different compound words that have the same solution word in common) may facilitate the rapid strengthening of these previously remote associations (Tse et al., 2011; van Kesteren et al., 2013, 2010), when the connection becomes suddenly accessible to consciousness (here, via the presentation and comprehension of the solution). Hippocampal novelty detection probably occurs faster than mPFC-mediated congruency detection, and mPFC may well inhibit the hippocampus afterwards. This hypothesis would provide an explanation for the observed congruency effect (i.e., associated with sudden comprehension) in both hippocampus and mPFC, with a subsequent learning difference, by contrast, only being found in the mPFC.

An important consideration is the retrieval task employed. We have previously used the CRAT in conjunction with an episodic recognition task, and the neural signature of successful encoding differed considerably from the mPFC-centered pattern observed in the present study (Kizilirmak, Thuerich, et al., 2016). In our previous study, subsequent recognition of CRAT solutions was primarily recollection-based and was associated with activation of the striatum and amygdala. We interpreted that finding as reflecting intrinsic reward and emotional arousal related to the sudden comprehension of the relationship between the triad words, an interpretation in line with the more episodic nature of the memory traces tested in that study. In the present study, on the other hand, by testing the successful solution of the problems, irrespective of conscious recollection of the study episode, we instead tested the successful encoding of the newly formed associations into semantic memory, which has previously been linked to mPFC function (Binder &

Desai, 2011).

Notably, while we found no differences in mesolimbic activation during successful (semantic) encoding in the present study, there was a midbrain activation difference in the fMRI contrast comparing difficult to easy sudden comprehension items, which was, at the behavioral level, accompanied by greater learning. This difference may in part be related to the negatively accelerated learning curve observed in numerous previous studies (Kahana, 2012; Kirsner et al., 1993), which, applied to the current study, would imply that solutions of difficult items benefitted more from prior encoding, partly due to a higher likelihood of easy items being solved based on existing knowledge, leaving less room for improvement (Kirsner et al., 1993). At the neural level, this hypothesis is consistent with previously reported differences in SN/VTA involvement depending on task demands (Boehler et al., 2011), possibly reflecting intrinsically motivating factors (Daniel & Pollmann, 2010). This finding is also in line with a recent high-field fMRI study on insight also using the CRAT (Tik et al., 2018). Tik et al. reported reward and novelty-related activations, that is, activations of the hippocampus, VTA, and caudate nucleus for strong compared to weak insights. As the positive emotional response and surprise is part of the insight experience, more difficult items may lead to stronger insights.

Besides mPFC/rACC, other structures that were activated during successful learning of the suddenly comprehensible solutions included the PCC/precuneus, MTG, and ANG/IPL (i.e., the temporo-parietal junction, TPL), which have previously been associated with semantic unification/integration (Hagoort, Baggio, & Willems, 2009; Seghier, 2013; Shimamura, 2011). This finding may reflect the phenomenon that a solution that could be better semantically integrated could later be better remembered. More effective semantic integration would also conform with the proposal of Jung-Beeman et al. (2004) that the anterior part of the right superior temporal gyrus—which we found, from its Talairach coordinates [41, -6, -12], in addition to the posterior part of the MTG—is likely to be involved in semantic integration across remote associations such as given in the CRAT. Beyond the aforementioned processes, it should be mentioned that both lateral (Uncapher & Wagner, 2009) and medial (Brodt et al., 2016, 2018; Schott, Wüstenberg, Lücke, Pohl, Richter, Seidenbecher, & Richardson-Klavehn, 2018) parietal structures have also been suggested to be more directly involved in memory encoding processes than previously thought.

Notably, the observed activation patterns in our fMRI contrasts, with exceptions such as the lateral PFC regions, seem to overlap to a large degree with the default mode network (DMN; see Figs. 2C and 3C). The potential implications of this overlap are discussed next.

#### 4.3. The DMN supports both self-referential processing and associative memory

The mPFC and adjacent rACC, as well as the PCC/precuneus and the temporo-parietal junction (TPJ), constitute core structures of a brain network that is best-known for its increased activation and functional connectivity during conditions of relative rest (Greicius, Krasnow, Reiss, & Menon, 2003) and has hence been termed the Default Mode Network (DMN) (Buckner, Andrews-Hanna, & Schacter, 2008; Raichle et al., 2001). A possible explanation for the observed activation of DMN structures in response to sudden comprehension (compared with continued incomprehension) would be that, upon comprehending the solutions, participants might have quickly endorsed these solutions and subsequently engaged in mind-wandering or spontaneous cognition, which has been suggested to drive the DMN activity commonly observed during resting conditions (Andrews-Hanna, 2012; Buckner et al., 2008). If this were the case, however, one would expect that solely the DMN would show a response to sudden comprehension compared with continued incomprehension. By contrast, as displayed in Fig. 2C, the activations elicited by sudden comprehension included clusters that are clearly outside the DMN, most prominently the left dorsolateral and ventrolateral PFC, or the left striatum/caudate nucleus. Furthermore, while the parietal activation clusters associated with sudden comprehension did show a partial overlap with the DMN masks, they were considerably larger, extending into more dorsal parietal cortices. We additionally observed a dorsal PCC activation cluster outside the DMN masks, that was more rostrally located than the PCC portions typically considered part of the DMN (Fig. 2C, fourth slice from the left). This activation pattern during sudden comprehension bears strong resemblance to the recently suggested parietal memory network (PMN; Gilmore, Nelson, & McDermott, 2015). The PMN as proposed by Gilmore and colleagues plays a prominent role in long-term memory retrieval and, despite its close anatomical proximity and partial overlap with the DMN, can be reliably distinguished from the latter during both task performance and resting state. Beyond the activation of non-DMN structures during sudden comprehension, if the activation of DMN structures in response to sudden comprehension versus continued incomprehension was indeed a mere correlate of task difficulty, one would expect the reverse contrast to reveal activation of “task-positive” networks like the left and right central executive networks, the salience network, or the visuospatial networks. Our masking analysis with the respective networks revealed negligible overlap with the salience and visuospatial networks, possibly resulting from blurring of neighboring brain structures (e.g., the supplementary motor area being directly adjacent to the dorsal anterior cingulate, a hub region of the salience network). The left and right central executive networks, which typically respond to attention-demanding tasks and which are strongly anticorrelated with the DMN (Fox et al., 2005), were not found to be activated in our masking analysis of the continued incomprehension versus sudden comprehension contrast (Supplementary Fig. S2), suggesting that a mere task-positive versus task-negative interpretation, with sudden comprehension constituting the easier condition, is not convincingly supported by our results.

In addition to the incomplete overlap between the activation patterns associated with sudden comprehension and the DMN (Fig. 2C), reduced cognitive effort during processing of sudden comprehension compared to continued incomprehension items does not provide a satisfying explanation of the observed subsequent learning differences for sudden comprehension items (Fig. 3C). As confirmed by a meta-analysis of subsequent memory fMRI studies (Kim, 2011), DMN structures such as mPFC, PCC and ventral precuneus are typically associated with subsequent forgetting rather than remembering. In our study, however, the mPFC was positively associated with subsequent learning of the solutions to the sudden comprehension items.

Following up on the possibility that increased DMN activity for successful learning could primarily reflect reduced cognitive effort, this possibility would imply that insight-like sudden comprehension constitutes a highly exceptional case, in which more conscious effort to comprehend the solution is associated with less learning. Indeed, evidence from creativity research supports a so-called transient hypofrontality theory, suggesting that creative and meditative states are associated with a relatively lower activation of the PFC (Dietrich & Haider, 2017; Dietrich, 2003). While this intriguing possibility cannot be completely excluded, it is also not supported by the current dataset. Besides an involvement of DMN-overlapping brain regions, there was an activation of the VLPFC (Brodmann areas 45 and 47) for both the sudden comprehension versus continued incomprehension contrast and the subsequent learning contrast for sudden comprehension items. The VLPFC is highly associated with semantic retrieval, cognitive control during memory search (BA 45), and post-retrieval competition resolution among memory representations (BA 47) (e.g., Badre & Wagner, 2002, 2007; Wimber et al., 2008), and its involvement is thus at odds with the reduced cognitive effort hypothesis. Most importantly, however, we found greater behavioral learning for difficult compared to easy sudden comprehension items, which was associated with midbrain activation (see Behavioral Results, Section 3.1, and Fig. 5; see also Table 3). It suggests a feeling of relief or intrinsic reward when suddenly comprehending the solution to a difficult problem, which facilitates long-term memory formation. Taken together, these findings are, in our view, mostly inconsistent with the view that ease of processing (and, for that reason, a DMN activation) predicts later learning.

There is accumulating evidence suggesting that the DMN is more complex than just a task-negative network. A more likely explanation for the increased mPFC response to subsequently learned solutions may be related to a prominent exception to the common pattern of negative subsequent memory effects in DMN structures, namely encoding tasks that involve self-referential processing. Previous studies have repeatedly implicated the DMN in social and self-referential processing (Schilbach et al., 2012), and Macrae, Moran, Heatherton, Banfield, and Kelley (2004) were further able to demonstrate an association between mPFC activations and both self-relevance and successful episodic encoding of the self-related stimuli. Similarly, Zhu et al. (2012) found that self-reference compared to reference to a famous person elicited a subsequent memory difference in the mPFC. Focusing on encoding-related functional connectivity, Schott et al. (2013) observed increased functional coupling between the left hippocampus and DMN structures specifically during deep (i.e., semantic) encoding. In that study, the deep encoding task consisted of a pleasantness judgment, which engages affective processing and is inherently self-relevant. Here, the subsequent learning difference in the mPFC and other core DMN structures such as the PCC/precuneus was observed during the successful encoding of complex prior knowledge-congruent information that often included a subjective “aha!” experience, thereby sharing the characteristics of affective salience and self-relevance.

Greater activation of the DMN—and of the adjacent PMN (Gilmore et al., 2015)—in the sudden comprehension condition (in addition to the non-DMN structures) could potentially increase the number of associations made between the CRAT solution and pre-existing knowledge and memories, increasing the likelihood of later learning of the item. The hippocampus coordinates the cortical activations underlying a memory representation and is engaged during associative memory processing (Schlichting & Preston, 2015). The hippocampal and DMN activations observed here could reflect the establishment of associations between different features of a memory.

Considering further the role of the mPFC in coding subjective value (Grabenhorst & Rolls, 2011; Ludwig et al., 2013), one plausible explanation for the DMN involvement in the successful encoding of sudden comprehension items would be the affective experience that accompanies the sudden comprehension of the connection. Compatibly, the DMN, and particularly the mPFC, is strongly connected with the amygdala, which was also activated during successful learning of the sudden comprehension items (Fig. 4), and the amygdala-mPFC circuitry has been implicated in the cognitive evaluation and regulation of affective states (Kalisch, Wiech, Critchley, & Dolan, 2006; Kim et al., 2011).

One caveat regarding the aforementioned explanation of encoding-related DMN activity reflecting affective salience and self-relevance comes from the observation that items of the sudden comprehension condition which were reported to be associated with a subjective feeling of “aha” showed no learning advantage over sudden comprehension items that did not elicit an “aha!”. Affective salience or self-relevance does not, furthermore, in our view sufficiently explain the observed greater learning for difficult compared to easy items. It is therefore plausible that the DMN activation related to successful learning of the solutions also reflects cognitive processing.

The DMN receives strong input from the left VLPFC (Soch et al., 2016), a brain structure involved in semantic processing that was also strongly activated during both sudden comprehension and successful learning in the present study (see above), and the mPFC is critically involved in the integration of novel information into prior knowledge or schemas (van Kesteren et al., 2012). Given the notable overlap of brain structures involved in self-referential memory encoding and schema-dependent memory formation, one can argue that the Self may be considered a powerful schema that facilitates encoding (de Caso et al., 2017). Andrews-Hanna and colleagues proposed that the mPFC “is well positioned to integrate salient external or internal information (perhaps relayed from the PCC) with one’s current affective experience and prior conceptual or episodic knowledge” (Andrews-Hanna, Smallwood, & Spreng, 2014, p. 8). With respect to our study, the activation of core DMN structures during the processing of solution words is well in line with this view of DMN function, because it involves the integration of novel semantic associative information both with prior knowledge about the words and their meaning and with the internal affective state related to the “aha!” experience. More generally, the emerging overlap of brain structures involved in social processing and self-reference with those associated with schema-dependent memory may also help to explain the previously described role of brain regions commonly considered part of the DMN (i.e. PCC/precuneus, MTG, and ANG/IPL, i.e., the temporo-parietal junction, TPJ) in semantic integration (Hagoort et al., 2009; Seghier, 2013; Shimamura, 2011), a phenomenon that is likely to have contributed to successful learning of the solutions of the sudden comprehension condition in our study (see above).

#### 4.4. Limitations of the study

One limitation concerns our decision to induce sudden comprehension instead of letting participants solve items on their own. This was done (1) to ensure a high number of trials per condition without having to split trials into solved and unsolved triads, and (2) to have a relatively clearly defined time frame during which sudden comprehension would take place. However, even when the solution is presented after a brief problem-solving attempt, sometimes participants might have already come up with a solution themselves. We initially considered including a button press, allowing participants to report whether they had arrived at a solution. However, we ultimately decided against this approach, because we could not analyze those trials due to the button press versus no button press difference, and because of considerable variation in the timing of the button press when pilot testing was performed. Moreover, such a procedure would have been problematic for the comparison of sudden comprehension and continued incomprehension items, because no successful problem-solving and thus no motor response could have reasonably been expected for continued incomprehension items. We therefore decided to accept the additional noise introduced by spontaneous problem solving in return for more homogeneous trials, in terms of a no-motor-response phase during problem-solving. Importantly, (1) our normative data indicate that participants would have been able to solve the problems themselves within the time allowed on only about 10% of trials in the sudden comprehension condition, and (2) we still found robust brain-activity differences between the sudden comprehension and continued incomprehension conditions time-linked to presentation of the solution and pseudo-solution words.

#### 4.5. Conclusions

Our results suggest that sudden comprehension of associative relationships likely promotes long-term learning via prior knowledge-dependent memory processing in a fronto-temporo-parietal network, including the mPFC, that highly overlaps with the DMN, supporting the idea that the DMN is more than just a task-negative network, and that it likely represents a self-referential integrative memory network. While the sudden comprehension of novel meaningful relationships during processing of solutions to problems was associated with increased hippocampal activation, this activation did not predict successful learning of the solutions. This finding further suggests that learning by sudden comprehension may constitute one of the special cases when novel information is directly encoded into semantic memory, similarly to previous accounts of schema- or prior-knowledge-dependent memory. Our results also provide further insights into how mnemonic schemas may rapidly be formed from previously remotely associated semantic representations.

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#### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.concog.2019.01.005>.

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