



Aha! and D'oh! experiences enhance learning for incidental information—new evidence supports the insight memory advantage

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Abstract

Research on creative problem-solving finds that solutions achieved via spontaneous insight (i.e., Aha! moment) are better remembered than solutions reached without this sense of epiphany, referred to as an “insight memory advantage.” We hypothesized that the insight memory advantage can spread to incidental information encoded in the moments surrounding insight as well. Participants ($N = 291$) were first given Rebus puzzles. After they indicated that they had found a solution, but before they could submit this solution, they were presented with scholastic facts that were incidental and unrelated to the problem at hand. Participants indicated whether they reached the solution via either insight or a step-by-step analysis. Memory results showed better performance for incidental scholastic facts presented when problem solving was accompanied by a spontaneous (Aha! experience) and induced (D'oh! experience) insight compared with solutions reached with analysis. This finding suggests that the memory advantage for problems solved via insight spreads to other unrelated information encoded in close temporal proximity and has implications for novel techniques to enhance learning in educational settings.

Keywords Memory · Problem-solving · Insight · Aha! moment · D'oh! moment · Creativity · Learning · Behavioral tagging

Introduction

People tend to have better memory for information they are incentivized to remember. These include intrinsically motivating events, such as novel or emotional experiences, as well as extrinsically motivating events, such as remembering information for reward or the risk of punishment for forgetting (Shohamy & Adcock, 2010; Murty & Adcock, 2014). Research on creative problem-solving shows that idea generation accompanied by a feeling of insight enhances memory for both the problem and the solution (Danek & Wiley 2020; Becker et al., 2022; Danek & Wiley, 2020;

Kizilirmak & Becker, 2023; Danek et al., 2013; Kizilirmak et al., 2015; Shen et al., 2020). Solving a problem is an intrinsically pleasing and rewarding event (Danek & Wiley, 2017; Shen et al., 2016, 2018). Such an experience often is externalized by exclamations, such as Aha!, when the solver achieves a solution surprise and excitement or D-oh! when the solution is revealed to the solver after having a failure, indexing a feeling of obviousness but also satisfied curiosity. The memory enhancement for solutions reached via insight, versus solutions reached without insight, is referred to as the “insight memory advantage” (Danek & Wiley, 2020). Interestingly, affective experiences not only promote long-term memory for the target information but can extend to neutral incidental information that happened to be presented close in time to the salient aspects of the experience (Murphy et al., 2021). Whether the insight memory advantage likewise spreads to incidental information encoded close in time to the moment of insight is unknown. We sought to leverage the insight memory advantage to capture memory for incidental information (scholastic facts) presented in temporal proximity to an epiphany.

The idea that insight-based solutions are associated with enhanced memory has a long history in the field of

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problem-solving (Dominowski & Dallob, 1995; Osgood, 1953; Woodworth & Schlosberg, 1954). A renewed interest in this matter was sparked by recent empirical evidence showing that problem solutions are better recalled, specifically, when accompanied by an Aha! moment (Danek et al., 2013; Danek and Wiley, 2020 but also Kizilirmak, et al., 2015; see Kizilirmak & Becker, 2022 for a review). Danek et al. (2013) found that when spontaneous (i.e., self-generated) correct solutions to magic tricks were accompanied by an Aha! experience they were more likely to be remembered after a 2-week period compared with solutions without Aha! experience. Later in 2020, Danek & Wiley used the same procedure and found that is the pleasurable affective experience associated with Aha! moments to be responsible for the insight memory advantage. Kizilirmak & colleagues (Kizilirmak et al., 2015) also found a similar memory advantage with a delay of 1 week on a perceptual problem-solving task (“Mooney images,” i.e., degraded picture), and one more time memory was associated with a higher rating of pleasure when accompanied by a subjective feeling of Aha! than without. Interestingly, they found that also the sudden revelation of the solution that induces a comparable feeling to the “Aha!” (i.e., the D’oh! experience) for self-solved items causes a memory advantage. They argued that this effect caused by the presented solutions accompanied by the “Aha!” could be due to the pleasurable experience associated with the discovery of the solution, as well as the representational change (i.e., restructuring).

Problem-solving is rewarding, and people like being engaged in crossword puzzles, riddles, trivia questions, murder mysteries, and escape rooms (Oh et al., 2020). Figuring out a problem solution is inherently pleasurable, sometimes regardless of succeeding in it. Whether the problem solution is achieved spontaneously or revealed, the restructuring of the initial representation of the problem that is now seen in a new light generates a feeling of surprise and pleasure. In addition to the affective response associated with the Aha! scholars suggest that the memorability of problems and their solutions also might be the result of the restructuring associated with finding a new organization for problem elements that occur both when people generate their problem solutions, but also when the solution is revealed (Danek & Wiley, 2020; Kizilirmak et al., 2015).

While used indistinctively, spontaneous and induced insights are emotionally indexed by different exclamations, such as Aha! and D’oh! While the term Aha! experience has been largely used for spontaneous insights we refer to the “D’oh! experience”, as those moments where people fail to solve a problem and the solution is revealed to them. The frustration of not having been able to figure out the solution, which when it is revealed feels obvious, mixed with the satisfaction of now knowing the solution is indexed by the exclamation “D’oh!” While this is different from having an Aha! experience (i.e., when the problem solution rises suddenly as an insight), the D’oh! experience is still associated with a feeling of pleasure

and reward, as a matter of fact when the solution to a problem is not revealed to us that generates frustration. Kizilirmak referred to what we name the “D’oh” experience” as an induced insight, and in 2021 showed how this phenomenon evokes a positive feeling, which serves as an intrinsic reward, because they are associated with brain regions, as the striatum, associated with reward and reinforced-based learning (Knutson et al., 2001; Wittmann et al., 2005; Haruno et al., 2004; Kahnt et al., 2009) as well as the hippocampus (important for explicit memory, detection, and encoding of novel stimuli, contexts, and associations; Ranganath & Rainer, 2003) and the amygdala (important for emotional memory) (McGaugh, 2004; Phelps & LeDoux, 2005).

Collectively, these components link the insight memory advantage to research on emotional enhancements in memory, which consistently shows superior memory for emotional versus neutral information (Danek et al., 2013; Kizilirmak, et al., 2015; McGaugh, 2015). An intriguing byproduct of salient events on memory includes effects on neutral information that is presented in close temporal proximity (Dunsmoor et al., 2022). Whether the insight memory advantage enhances memory for other incidental information encoded close in time to the problem and solution is unknown. There is, however, increasing evidence that phasic changes in motivational states, such as those generated during creative problem-solving, boost memory for irrelevant information that is presented in temporal proximity (for example in advertisements see Shen et al., 2020).

Not all the events we live in life are stored in long-term memory, most are forgotten. For example, we probably do not remember what we ate two Mondays ago; however, we are more likely to remember what we ate on the first date with our significant other. Some episodes are remembered for a longer time thanks to consolidation, many of them occur when information is emotionally charged, and thus subject to long-term stabilization (Squire, 1992; Dudai & Morris, 2000). Initial retention occurs when a novel, or a rewarding event, happens shortly before or after the time of memory encoding (McGaugh, 2004; Brown, & Kulik, 1977; Dunsmoor et al., 2015). For example, Gruber & colleagues find that high states of curiosity to know the answer to a trivia question improves memory both for the answer and for incidentally presented visual stimuli (i.e., faces) presented during an anticipation phase before receiving the answer. The state of curiosity generated by a trivia question and the state of insight generated by realizing the solution to a puzzle share common elements both psychologically and neurobiologically (e.g., activation throughout the dopaminergic midbrain and striatum) (Danek & Wiley, 2017, 2020; Kizilirmak et al., 2016, 2019, 2021; Gruber et al., 2014; Oh et al., 2020; Tik et al., 2018). However, there are important distinctions in the temporal dynamics between states of curiosity generated by trivia questions and insight-based problem-solving that

may affect memory for incidental information presented in temporal proximity.

While Gruber & colleagues find that high states of curiosity to know the answer to a trivia question improves memory both for the answer and for incidentally presented visual stimuli (i.e., faces) shown during an anticipation phase before receiving the answer, the relationship between the curiosity of knowing the solution of a problem and memory is unknown.

In the present study, we examined whether insight-based problem solving enhances memory for unrelated incidental information presented in temporal proximity to a spontaneous insight. Expanding upon recent work on incidental memory during states of reward and curiosity, the incidental memoranda were scholastic facts, rather than visual items. The goal of using scholastic facts was to draw this line of work closer to potential applications for education. For example, if the insight memory advantage spreads to other information, then one application could involve embedding study material with recreational problem solving to improve learning and retention.

To investigate this relationship, we asked participants to solve a series of word puzzles (Rebus puzzles) and indicated whether or not they reached an answer. Then, we presented an unrelated scholastic fact either immediately after subjects indicated they reached a solution (before providing the answer, either with or without Aha! moment) or immediately after receiving the solution to a problem they indicated they could not solve (D'oh! moments). Importantly, we distinguished between solutions reached via spontaneous insight (Aha!) and problems solved without an accompanying sense of insight, referred to as a step-by-step solution, or unsolved problems to which a solution was provided (D'oh! moments). Given the conceptual and potential mechanistic overlap between the insight memory advantage and emotional memory enhancements, we predicted an enhancement in memory for incidental facts presented at the moment accompanying a sense of insight versus a problem solution reached without insight. Given research indicating the insight memory advantage also occurs for induced insights (Kizilirmak et al., 2015, 2021), we did not predict a difference in memory for incidental facts presented after puzzles solved via insight (Aha! moments) versus incidental facts delivered after the solution for puzzles subjects could not answer (an induced insight, what we refer to as D'oh! moments).

Methods

Participants and data cleaning

Participants were recruited online via the CloudResearch platform (Littman et al., 2017) on Amazon Mechanical

Turk (MTurk). To mitigate data quality concerns that can arise with online participants (Kennedy et al., 2020), we used CloudResearch's Approved Participants feature to recruit only vetted MTurk workers (i.e., participants who have shown previous evidence of attention and engagement). Eligibility was restricted to individuals aged 18–50 years, in the United States, with American English as a first language. Participants took ~1 hr (median completion time: 42.3 min) to complete the study for a total of \$4 upon completion. Study procedures were approved by the institutional review board at the University of Texas at Austin, and all participants provided written, informed consent.

Data were collected between April and June 2021. A total of 351 participants completed the study. From that sample, we excluded participants who did not fully complete the task or did not understand the instruction (e.g., instead of trying to solve the problems they were typing in the scholastic fact), never attempted to solve the Rebus puzzles (i.e., they always pressed “NO” when they have to report if they had the solution of the problem), did not solve any problem correctly, did not remember any of the scholastic facts, or missed the catch trials. We also removed participants who declared they solved all the problems via insight or via step-by-step and those who solved less than $M \pm 2.5$ SD of the problems correctly. After the data cleaning, the sample included 291 participants (177 females, 108 males, and 6 nonbinary or genderfluid; $M_{\text{age}} = 34.5$ years, $SD_{\text{age}} = 7.7$, age range 18–55 years). For included subjects, we eliminated trials for which subjects' reaction time was shorter than 2 s, because participants might impulsively report those as insights (Cranford & Moss, 2012; Salvi et al., 2015a, 2015b, 2016; Yu et al., 2023), and longer than 30 s, and trials for which participants gave an unspecified solution, such as scrambled letters or sentences as “I forgot the solution.”

Procedure

Participants were first directed to an informational page and online consent form. Following written consent, participants completed a short demographic survey, the experimental paradigm (consisting of an incidental learning phase and surprise recognition memory phase), and a series of questionnaires. Each of these components is detailed below.

Demographic information The demographic section included a series of self-report questions assessing participants' age, gender identity, marital status, level of education, occupation, country of residence, and political ideology.

Questionnaires As this study was conducted amidst the Covid-19 pandemic, we included a variety of questionnaires

to assess the rise in anxiety, fear of COVID-19, uncertainty, xenophobia, as well as belief in conspiracy theories and vaccine acceptance (Cancer et al., 2023).

Experimental paradigm

Following a short practice of one trial participants were asked to attempt solving 44 randomized Rebus Puzzles taken from (Gregor, 2009; MacGregor & Cunningham, 2008). Several studies, both online and in person, show how these types of puzzles are an established measure of insight problem-solving (Salvi, Costantini et al., 2015b, Salvi, Costantini et al.,

2020a; Salvi, et al., 2016, 2021; Threadgold et al., 2018). To solve these puzzles, participants were instructed to identify a common phrase from the verbal and visual clues provided on screen (e.g., “cycle, cycle, cycle” would be solved as “tri-cycle,” for another example see Fig. 1). After each puzzle, participants were presented with different scholastic items that were unrelated to the problem they were asked to solve. The 44 scholastic items were selected from three topic areas: English, history, and science. The content of these facts did not pertain to general knowledge, but rather information that could be learned in a high school or college setting. Participants were not instructed to remember the scholastic items (incidental encoding), just to read the sentences carefully.

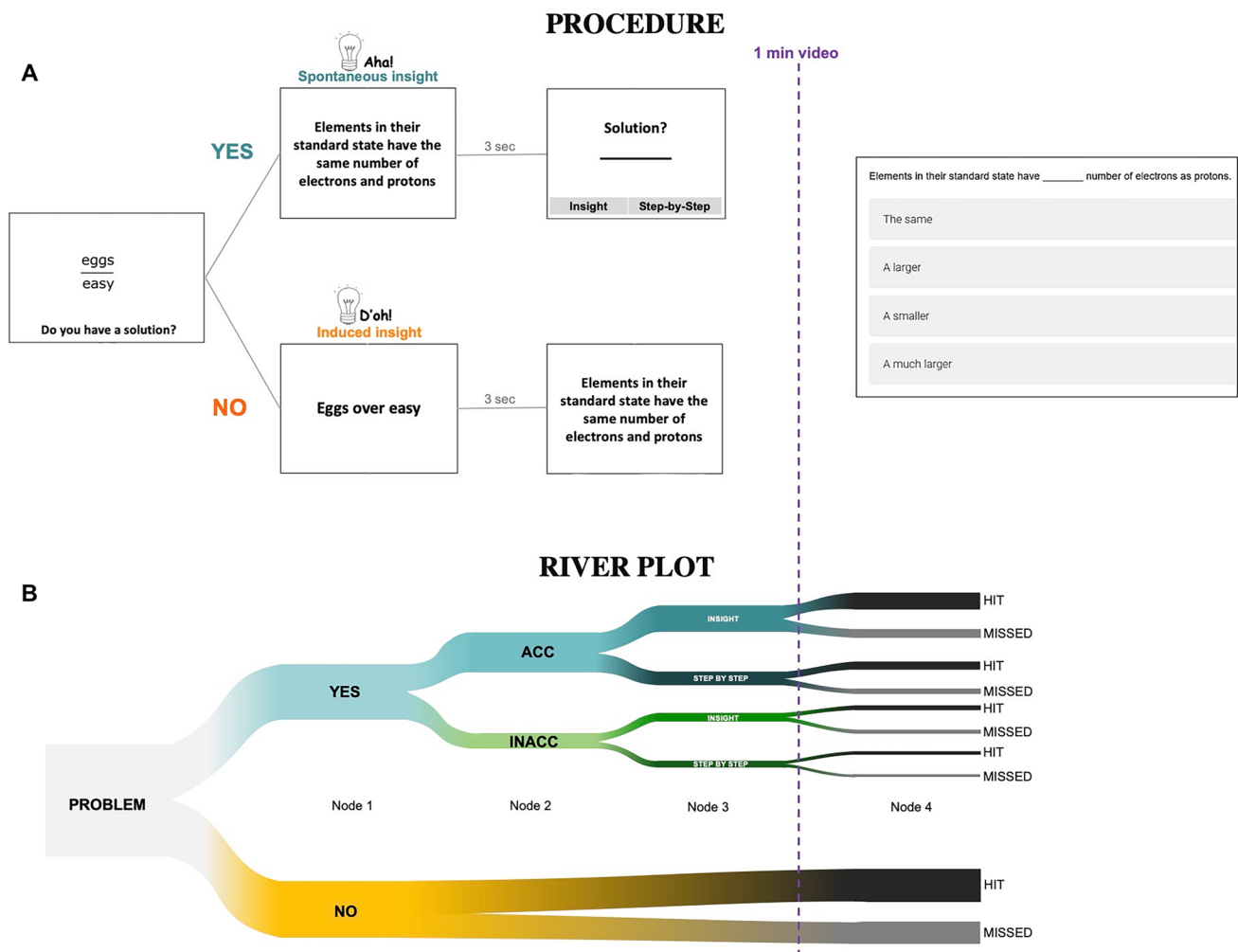


Fig. 1 Summary of the experimental procedure (**A**) and river plot of the results (**B**). **A** procedure: Participants first had to report when they were ready for each problem to appear on the screen. They were given 15 s to solve each problem. If they found a solution, participants had to press the YES button; then, the trial with scholastic material would appear immediately. Afterward, they had to type the solution phrase manually and report how they had solved the problem, either via insight or via step-by-step. If participants claimed that they did not have the solution, they were asked to press the NO but-

ton if they ran out of time. In that case, the solution would appear on the screen followed by the scholastic fact. **B** River plot of the number of responses at each step of the procedure. Node one represents whether participants claimed they had a solution; node two of the YES branch represents the accuracy of those trials where participants claimed they had a solution; on node three, the solution type (i.e., insight or step-by-step) of each accurate or inaccurate provided solution; on node four, “Hit” or “Miss” bins of the memory task for each condition

Participants had 15 s to solve each puzzle within which they had to indicate whether they had found the solution of the Rebus. If they thought they had a solution, they were asked to “immediately” press the YES button, and the scholastic item appeared immediately and remained on the screen for 3 s. Participants had to type in the problem solution and report whether that solution was achieved via insight or via step-by-step.¹

If participants did not have a solution to the Rebus, they pressed the NO button, or the trial would time out and ask them if they had a solution to the Rebus. If participants pressed the NO button, the problem solution would immediately appear on-screen for 1 s, followed by a scholastic item that lasted 3 s. After all trials were completed, there was a brief 1-min washout period where participants watched a neutral video clip of a boat moving through water.

Surprise Recognition Memory Phase Participants completed an immediate surprise recognition memory test (i.e., participants had to recognize the correct answer among a list of 4, see Dunsmoor et al., 2012) on the neutral facts encountered in the incidental learning phase. The test consisted of 44 multiple-choice trials assessing their memory for the neutral facts, plus three catch trials that served as attentional checks. Multiple-choice trials were formatted as either questions or fill-in-the-blanks (e.g., “Elements in their standard state have _____ number of electrons and protons.”). Participants were given the 20 s per question to select the correct answer from four options (e.g., “the same,” “a larger,” “a smaller,” or “a much larger”; correct answer: “the same”).

Analytic plan Primary analyses consisted of binomial (i.e., logistic) generalized linear mixed models (GLMM) fitted with the lme4 library (Bates et al., 2015) in the R environment (R Core Team, 2018). All models contained, at minimum, memory accuracy (hit or miss, coded 1 and 0 respectively) as the outcome variable and participant as a random intercept. To test for the significance of terms of interest, we constructed GLMMs with and without the term and used likelihood ratio tests (LRTs; χ^2 distribution) to assess model fit improvement. Follow-up analyses on estimated marginal

Table 1 Number of observations: solution type vs. accuracy

	Problem accuracy		
	Correct	Incorrect	Total
Induced insight (D’oh!)	-	-	6257
Spontaneous insight (Aha!)	2932	998	3930
% within row	74.61%	25.39%	
% within column	66.50%	58.91%	
Noninsight/Step-by-step	1477	696	2173
% within row	67.97%	32.03%	
% within column	33.50%	41.09%	

means were conducted with the *emmeans* library (Lenth, 2021) in line with *a priori* hypotheses. To assess individual model terms and estimated marginal means for significance, we used Wald z-tests, per standard recommendations for GLMMs without overdispersion (Bolker et al., 2009). All fitted models did not show signs of overdispersion (dispersion ratios $\geq .92$, all $ps = 1$). When applicable, we present unstandardized beta coefficient (b) in odds ratio (OR) form for estimated marginal means tests to facilitate the interpretation of relative improvements of predictors on memory performance.

Results

Overall, participants indicated that they had a solution to the puzzle (regardless of accuracy) 49.38% of the times (6103 observations), whereas they said they did not have a solution 50.62% of the time (6257 observations). Trials without an attempted solution are considered the induced insight condition (i.e., D’oh!). See Table 1 for the breakdown of problem-solving.

Participants solved $M_{\text{nop}} = 32$, $SD_{\text{nop}} = 12.8$ via spontaneous insight (Aha!)² (correctly $M_{\text{nop}} = 23.6$, $SD_{\text{nop}} = 11.9$; incorrectly $M_{\text{nop}} = 8.3$, $SD_{\text{nop}} = 8.9$), and solved $M_{\text{nop}} = 17.7$, $SD_{\text{nop}} = 11.6$ via non insight/step-by-step (correctly $M_{\text{nop}} = 11.9$, $SD_{\text{nop}} = 9.9$; incorrectly $M_{\text{nop}} = 5.8$, $SD_{\text{nop}} = 6$); the total of unsolved problems (i.e., induced insight – D’oh!) was $M_{\text{nop}} = 50.3$, $SD_{\text{nop}} = 12.7$.

Number of observations for induced insights, spontaneous insights, and noninsight/step-by-step for problems solved correctly and incorrectly as well as the percentages within row/column.

¹ The same instructions used by Salvi et al. (2015a, 2015b) were given to participants to explain how to distinguish solutions *via* insight from those *via* step-by-step. The original instructions are: “[. . .] by INSIGHT means that the answer suddenly (i.e., unexpectedly) came to your mind, while you were trying to solve the problem, even though you are unable to articulate how you achieved the solution. This kind of solution is often associated with surprise exclamations, such as ‘Aha!’; STEP-BY-STEP means that you figured out the answer after you deliberately and consciously tested out different words until you found the correct one. In this case, you are able to report the steps that you used to reach the solution.

² Average of the problems per participant, calculated on the number on the total number of given problems. For each participant, we divided the number of problems by the total problems given and averaged those. Nop = number of problems.

Table 2 Number of observations: memory for scholastic facts vs. problem solving types and accuracy

Memory	Unsolved	Solved correctly		Solved incorrectly		Total
	Induced insight	Insight	Noninsight	Insight	Noninsight/step-by-step	
	(D'oh!)	(Aha!)		(Aha!)		
Missed	2429	1034	557	466	299	4785
% within row	50.76%	21.61%	11.64%	9.74%	6.25%	
% within column	40.42%	36.26%	38.76%	48.80%	44.30%	
Hit	3581	1818	880	489	376	7144
% within row	50.13%	25.45%	12.32%	6.84%	5.26%	
% within column	59.58%	63.74%	61.24%	51.20%	55.70%	
Total	6010	2852	1437	955	675	11929

Participants attempted to recall 96.5% of the scholastic trials (11,929 trials, 6,010 after unsolved problems, 4,289 after problems solved correctly, and 1,630 after problems solved incorrectly). Failures to recall the scholastic material collapsed into failures of memorization. Participants recalled 59.88% of scholastic facts correctly (hits 7,143 trials). Of all the hits, 50.13% were on scholastic material that was presented after induced insights (3,581 trials), and the remaining 49.87% (3,562 trials) after people declared to have found the solution to a problem (correct and incorrect). Of all the problems solved correctly (4,289 trials), 67.38% of the scholastic facts were recalled after a spontaneous insight (1,818 trials) and 32.61% after a noninsight/step-by-step solution (880 trials) (Fig. 1; Table 2).

Number of observations for scholastic facts remembered (hit) or nonremembered (missed) presented after failing to solve a problem, i.e., induced insight, or after having solved a problem correctly with an insight or without an insight (step-by-step) as well as the percentages within row/column.

Relationship between accuracy, insight, and memorization (corroboration of Danek and Wiley's results)

To test the main question of whether the spontaneous insight (Aha! experience) leads to increased memorization of the scholastic material presented after solving a problem correctly, we constructed a GLMM predicting memory accuracy with fixed effects for reported solving method (spontaneous insight or noninsight/step-by-step) and trial number, and a three-level random effects structure of trial nested within method, which was nested within subject. This structure allowed for the estimation of a separate intercept and slope for each participant (multiple trials nested within each method for each participant) and helped to account for different numbers of observations for each type of method for each participant. For this model, we excluded memory on trials in which participants pressed NO and/or

timed out. Crucially, we also included an interaction term of method (insight vs. noninsight/step-by-step) and per-trial problem accuracy (hit vs. missed, coded as 1 or 0), which was the term of primary interest in this analysis. To account for between-subject differences in overall problem accuracy, we also included each participant's mean problem-solving accuracy as a fixed effect. Finally, we included the number of trials in which participants indicated that they did not have a solution as a fixed effect to adjust estimates for differing numbers of available outcome observations. Addition of the method x problem accuracy interaction resulted in significantly improved model fit, $\chi^2(2) = 4.97$ $p = .025$. In support of increased memory accuracy, when solving a problem correctly using spontaneous insight, the differences in estimated marginal means between correct versus incorrect insight responses are significant, odds ratio (OR) = 1.2, 95% confidence interval (CI) 1.01–1.42, $z_{\text{wald}} = 2.13$, $p = .033$, but not correct versus incorrect noninsight/step-by-step responses, OR = 0.89, 95% CI 0.72– 1.10, $z_{\text{wald}} = -1.05$, $p = .290$. In this analysis, we decided to include incorrect insights because of former literature on the phenomenology of false insights (Danek & Wiley, 2017; Grimmer et al., 2023; Laukkonen et al., 2020, 2022). Furthermore, the contrast of these two differences was significant, OR = 1.34, 95% CI 1.04–1.73, $z_{\text{wald}} = 2.26$, $p = .023$, in favor of an overall increased memory in relation to insight responses on correct problems Fig. 2 and 3.

Does having an insight (induced or spontaneous) predict memorization?

To test the main question of whether the spontaneous insight (Aha! experience) induced insight (D'oh! experience) or noninsight/step-by-step solutions would lead to increased memorization of the scholastic material presented after receiving/achieving the problem solution, we used a modified version of

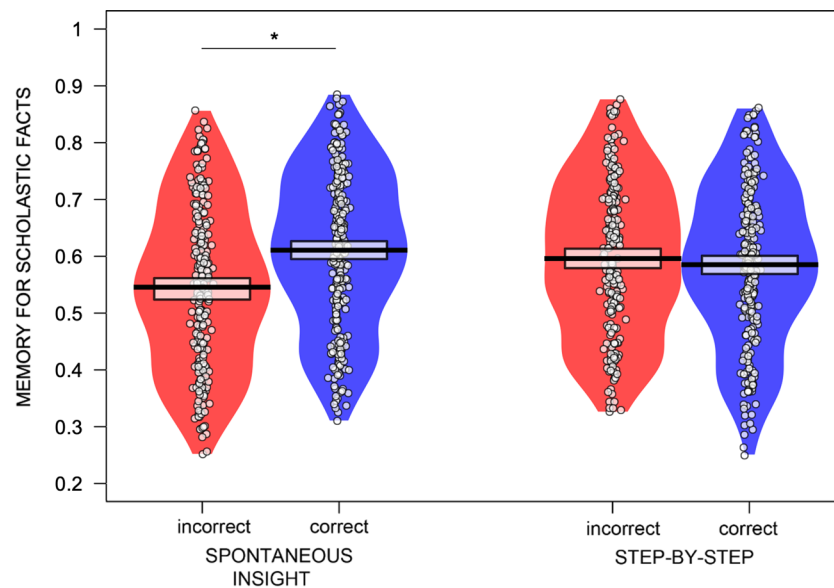


Fig. 2 Recognition memory performance for scholastic facts for spontaneous insight and noninsight/step-by-step solutions. The Y-axis shows on a scale from 20–100% how many times the scholastic fact has been remembered. The X-axis shows the distribution of when the scholastic fact has been presented: after having solved a problem correctly or incorrectly with an insight (Aha! experience) or without

an insight (step-by-step). *Difference between tests of two estimated marginal means from the GLMM specified. Distributions show predicted values. Bolded horizontal bars represent the mean and boxes represent 95% HDI. Points represent the average memory for each participant within each condition. GLMM = generalized linear mixed model; HDI = highest density interval

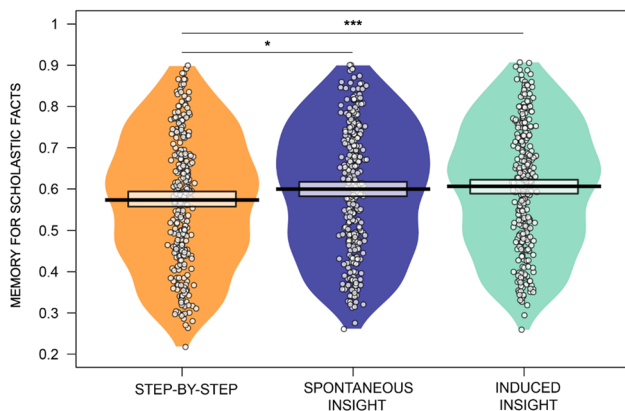


Fig. 3 Recognition memory performance for scholastic facts for noninsight/step-by-step solutions, spontaneous insight, and induced insight solutions. The Y-axis shows on a scale from 20–100% how many times the scholastic fact has been remembered. The X-axis shows the distribution of when the scholastic fact has been presented: after having solved a problem correctly via noninsight/step-by-step, after a correct spontaneous insight (Aha! experience) or after an induced insight (D’oh! experience), i.e., when participants did not solve the problem and the solution was presented to the followed by the scholastic fact. *Difference between tests of two estimated marginal means from the specified GLMM. Distributions show predicted values. Bolded horizontal bars represent the mean and boxes represent 95% HDI. Points represent the average memory for each participant within each condition. GLMM = generalized linear mixed model; HDI = highest density interval

the previously described GLMM predicting memory accuracy. In this model, we included data from all trials, including those in which participants pressed “NO” and/or timed out. Fixed effects for this model included type of insight (induced, spontaneous, or noninsight/step-by-step) and trial number. Again, we used a three-level random effects structure of trial nested within method, which was nested within subject. We did not include any of the other terms from the previous GLMM. Addition of the method fixed-effect yielded significant model improvement: $\chi^2(2) = 12.626$; $p = .001$. Estimated marginal means analysis revealed that both induced, OR = 1.22, 95% CI 1.09–1.37, $z_{\text{wald}} = 3.57$, $p < .001$, and spontaneous, OR = 1.14, 95% CI (1.01–1.29, $z_{\text{wald}} = 2.16$, $p = .031$, insights yielded increased memory performance relative to noninsight/step-by-step. There was no significant difference between induced versus spontaneous insight: OR = 1.07, 95% CI 0.91–1.18, $z_{\text{wald}} = 1.53$, $p = .124$.

Discussion

In 1917, Köhler suggested that learning may be enhanced when the solution to a problem is comprehended suddenly thanks to a sudden insight (Köhler, 1917). It is well-known that emotional arousal enhances memory, and thus events happening around the time of learning affect the strength

and persistence of a memory (McGaugh, 2015). There also is substantial evidence that people are more likely to remember the solution to a problem when it is achieved via insight, whether it is spontaneous or induced (Ash et al., 2012; Auble et al., 1979; Becker et al., 2022; Danek & Wiley, 2020; Danek et al., 2013; Kizilirmak et al., 2015, 2019; Kizilirmak & Becker, 2023). It is possible that the persistence in memory of a problem solution is related to the emotional arousal triggered by the insight. Accordingly, we hypothesized that the memory advantage for a problem solution would spread to information encountered around the moment of excitement that follows having found the solution to a problem.

An adaptive memory system helps to ensure that seemingly mundane events are selectively remembered if the information was encoded around the time of a meaningful event; for example, suddenly remembering the person we bumped into an hour earlier on the street once we realize we were pickpocketed. This retroactive memory system helps us to remember information that we may have neglected or poorly encoded along the way but that gains relevance because of a temporal proximity to a more salient event (e.g., the moment of realization that we were pickpocketed). While our study was purely behavioral and did not incorporate a long-term memory test, one model supporting memory enhancements for otherwise mundane information is known as behavioral tagging (Ballarini et al., 2009; Redondo & Morris, 2011), based on the synaptic tag-and-capture (Frey and Morris, 1997). This model proposes that weakly learned information is consolidated in long-term memory if it is learned within a critical time window surrounding a more salient and meaningful event. While solving a problem or being told a solution to a problem is not as emotionally charged as being pickpocketed, for example, behavioral and neuroimaging research indicates that insight problem-solving is associated with pleasure, reward, and excitement (Danek & Wiley, 2017, 2020; Oh et al., 2020; Salvi, 2023; Shen et al., 2016, 2018; Tik et al., 2018). In this way, the more salient event (solving a challenging problem) could serve to “capture” mundane information encoded in close temporal proximity. Our results support the hypothesis that the affective component of insight enhances memorization, as participants showed better memory performance for scholastic material when it was presented after spontaneous insight, compared with step-by-step solving, and after an induced insight, but not after an inaccurate solution, i.e., when the affective component of knowing the solutions of a problem is probably milder.

Furthermore, our experiment represents the first comparison between spontaneous and induced insight and the effect of their emotional components (Aha! and D’oh! experiences) on nonrelevant-to-problem memorization. Previous studies treated these two as eliciting the same insight. While they differ in the way the problem solution is achieved, and so is

the associated emotion (Aha! vs. D’oh!), the fact that they both elicit an emotional response because of restructuring, they consolidate the associated memory compared with the problem solutions where this feeling is missing.

Reaching a correct solution via restructuring may make the solution more memorable, because the new organization leads to a coherent and integrated representation of the problem and solution (Viello & Salvi, 2023). Our study provides more evidence that restructuring may play a part in the privileged status of solutions in memory.

Future directions

Ludmer et al. (2011) were among the first to shed light on the neurobehavioral mechanisms that explain the insight memory advantage. They recorded the neural activity of people trying to disambiguate camouflage images (similar to those used by the Gestalt psychologists) where the underlying objects were hard to recognize, followed by brief exposures to the uncamouflaged image (i.e., they revealed the solution), which triggered a D’oh! induced insight experience. When they tested participants’ memory 1 week later, they found that those remembered images were pronouncedly associated with the amygdala activation, whose activity predicted which solutions remain in long-term memory. The authors concluded that the role of the amygdala in the study is to promote long-term memory of “the sudden reorganization of internal representations” (Ludmer et al., 2011, page 1). In another study, Zhao & colleagues (Zhao et al., 2013) found more activity in several regions associated with memory and emotions, including the amygdala, hippocampus, and middle frontal gyrus, while participants solved Chinese idiom riddles. It is well known that the amygdala is responsible for processing and encoding emotions (Hamman et al., 1999; McGaugh, 2004; Phelps & LeDoux, 2005), and its activity modulates the strength of emotional memories (McGaugh et al., 1996). The amygdala’s involvement in problem-solving thought reflects the experience of insight, providing support for the affective experience associated with the restructuring, i.e., of the “Aha!” or “D’oh!” experience. Further evidence of the importance of memory in insight was corroborated by the involvement of the hippocampus found in at least two more studies (Luo & Niki, 2003; Zhao et al., 2013). The hippocampus is well known to be important for the neural manifestation of explicit memory, and its role in memory includes the detection and encoding of novel stimuli, associations, and contexts (Ranganath & Rainer, 2003).

Again, in 2019 Kizilirmak & colleagues showed how people are more likely to remember problem solutions when they are revealed to participants, inducing a D’oh! experience, in association with the activation of the hippocampus and the amygdala. As the Ludmer & colleagues’

(Ludmer et al., 2011) study points out, the amygdala activation found in these studies probably represents the rapidly changing value of visual stimuli that are associated with a rewarding or aversive unconditioned stimulus (Paton et al., 2006). However, the stimuli in these studies did not have any emotional valence, nor they were paired with external rewards. Thus, it is the sudden insightful solution, which is associated with the distinct saliency of the insight, that is rewarding. Following studies corroborated insights are associated with the reward system and dopamine activation, therefore, rewarding (Oh et al., 2020; Salvi et al., 2015a, 2015b; Laukkonen et al., 2023; Tik et al., 2018). Other researchers emphasize the feelings associated with insight, or the emotional or hedonic component of the insightful solution process (Cosmelli & Preiss, 2014; Gick & Lockhart, 1995; Gruber, 1995; Laukkonen et al., 2020, 2022, 2023; Topolinski & Reber, 2010).

The association between insight and the dopamine/reward salience network, together with further evidence showing the activation of brain areas implicated in learning, including limbic structures, such as the hippocampus and the amygdala (Kizilirmak et al., 2019; Ludmer et al., 2011; Kizilirmak et al., 2016) suggests that insight problem-solving relates to evolutionary ancient areas of the brain that are responsible for basic functions, such as reward and emotions (Salvi, 2023; Salvi et al., 2024). The positive experience of insight may have a number of practical consequences, such as motivating future problem-solving, increasing persistence, affecting a person's willingness to take a risk based on the solution (Salvi & Bowden, 2020; Yu et al., 2023), and making solutions more memorable (Danek et al., 2013; Danek & Wiley, 2020) or even making them sounding truer (Laukkonen et al., 2020, 2023).

Recent studies on the phenomenology of insight and the associated neural markers suggest that the emotional response associated with insight may be a signal of accuracy and be evolutionally advantageous (Danek & Salvi, 2018; Salvi et al., 2016; Laukkonen et al., 2020, 2022, 2023; Salvi, 2023). Indeed, the emotion associated with insight could be an adaptive mechanism for the reinforcement of the exploration of new strategies when solving problems (Oh et al., 2020). Most emotions have an adaptive function, and feelings of pleasure that accompany an insight seem to signal the probable utility of a solution since solutions via insight are more likely to be correct and are better remembered than those via step-by-step (Danek & Salvi, 2018; Danek & Wiley, 2020; Laukkonen et al., 2023; Salvi et al., 2016). Thus, the emotional response associated with insight may be evolutionally advantageous (Danek & Salvi, 2018; Laukkonen et al., 2023; Salvi et al., 2016; Salvi, 2023). This hypothesis also would explain the involvement of subcortical areas responsible for alertness, reward, and emotions, but also learning and memory, which are evolutionary and more ancient than the cortex.

So, if they are more likely to be accurate, it makes sense that they are better remembered.

In a recent review, Laukkonen et al. (2023) argue that “*the feeling of insight* is an adaptive signal that humans use to guide their judgments about new ideas.” Similar to the way that fear signals danger, Aha! moments signal accurate solutions that pop into awareness pervasively, attracting attention and forcing us to ignore the other myriad thoughts that crowd our train of thoughts. They named this effect the *Eureka Heuristic*. According to this proposal, the intensity of the Aha! moment provides a useful heuristic signal about the accuracy of the idea, based on experience and existing knowledge, and which involves an interpretation of phenomenology to guide judgments (e.g., altering our perception of veracity; Laukkonen et al., 2020, 2022). Recent development of this perspective involves predictive processing, a framework grounded in the notion that learning is governed by surprise (Friston et al., 2017; Laukkonen et al., 2023; Vitello & Salvi, 2023). In this study, we provided evidence in support of this hypothesis by showing that the emotional response associated with insight strengthens unrelated memory. Furthermore, our evidence supports the idea that insight problem-solving involves subcortical areas that are evolutionarily older and responsible for processing reward, emotions, and memory, allowing us to speculate that the phenomenology that accompanies Aha! moments might have an adaptive function. The Aha! might serve as an indirect indicator of the accuracy or quality of ideas and enhance memory for these ideas (Salvi, 2023).

Limitations and practical implications

While our study is the first finding a spread of the insight memory advantage to scholastic information that is irrelevant to the problem *per se*, with implications for learning and education, we acknowledge that we tested memory via a multiple-choice trial and immediately after people experienced an insight. Thus, we cannot draw strong conclusions on long-term retention of information. We therefore relay to future studies to unveil the persistence of this effect over time.

Another limitation of the study is that we did not measure the intensity of the Aha!/D'oh! feeling, because former studies show that there is no difference between spontaneous and induced insight in Aha! rating or EEG measures (Kizilirmak et al., 2021 p.14 “overall (EEG) amplitudes differed less for true and induced insights compared to true and false insights”). That said, we do not know whether the intensity of the feeling might cause a difference in the memory effect; thus, we relay to future studies to unveil this potential relation.

The purpose of utilizing scholastic data was to bring this field of study more in alignment with potential educational applications or even in the field of marketing (Shen et al.,

2020). For instance, one practical application could be creating interactive, gamified learning modules that combine educational content with problem-solving challenges. Another could be the development of educational apps and platforms that incorporate elements of problem-solving to enhance memory.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.3758/s13415-024-01184-x>.

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