More Than Storage of Information: What Working Memory Contributes to Visual Abductive Reasoning

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ABSTRACT

Abductive reasoning is the process of finding the best explanation for a set of observations. As the number of possible observations and corresponding explanations may be very high, it is commonly accepted that working memory capacity is closely related to successful abductive reasoning. However, the precise relationship between abductive reasoning and working memory capacity remains largely opaque. In a reanalysis of two experiments (*N* = 59), we first investigated whether reasoning performance is associated with differences in working memory capacity. Second, using eye tracking, we explored the relationship between the facets of working memory and the process of visuospatial reasoning. We used working memory tests of both components (verbal-numerical/spatial) as well as an intelligence measure. Results showed a clear relationship between reasoning accuracy and spatial components as well as intelligence. Process measures suggested that working memory seems to be a limiting factor to reasoning and that looking-back to previously relevant areas is compensating for poor mental models rather than being a sign of a particularly elaborate one. Following, high working memory ability might lead to the use of strategies to optimize the content and complexity of the mental representation on which abductive reasoning is based.

OPEN DATA

KEYWORDS

abductive reasoning
visuospatial reasoning
working memory
eye movements
process tracing

INTRODUCTION

"Data! Data! Data!' he cried impatiently. 'I can't make bricks without clay." In this quote from *The Adventure of the Copper Beeches* by Sir Arthur Conan Doyle, detective Sherlock Holmes emphatically declares that every inference must be based on a set of observations. As he analyses the scene and reaches conclusions based on his observations, Holmes engages in what is called abductive reasoning (even though Sherlock Homes himself called it deduction), which is a specific form of inference. In abduction, an explanation or cause (E) is derived from given data or observations (O) using a rule (R; Meder & Mayrhofer, 2017; Peng & Reggia, 1990; Peirce, 1931). In the second class of inference, deduction, a rule (R) and the explanation (E) are present, and the data (or observation; O) has to be inferred. For instance, taking an example from Sherlock Holmes' *Adventure of the Copper Beeches*, the rule is that "If the ladder was used, the man has escaped" (R). When Sherlock Holmes engages in abductive reasoning, he finds the room empty (O) and concludes that the ladder was used (E). In deduction, he would know the rule and find the ladder moved (E) and conclude that the man has gone. The third class of inference is induction. In this case, Sherlock Homes would find the ladder (E) and the man gone (O) and infer the rule that if the ladder is used, the man has gone.

According to newer discussions of the concept, abductive reasoning could also be understood as generating possible explanations, whereas deduction is the empirical test and induction the evaluation of its truth value (Magnani, 2015; Yu & Zenker, 2018). However, in this study, we aimed at improving the understanding of the process of abductive reasoning. In our view, the value of the term does not so much lie in its precise definition, as this is certainly up for debate, but in its practical use (see Urbański & Klawiter, 2018). We followed a line of research that sees abduction as the generation and evaluation of possible explanations in order to find the best one (Johnson & Krems, 2001; Josephson & Josephson, 1996; Thagard, 1977; Urbański & Klawiter, 2018). That is, we placed a strong emphasis on the use of abductive inferences in everyday reasoning.

Often, abductive reasoning tasks are very complex (Bylander et al., 1992; Jahn & Braatz, 2014; Krems et al., 1997), for instance, when there is a vast amount of data that has to be evaluated against several possible explanations. In the example above, one may observe that there is no one in the bed and no one at the table either, hence the room is empty. Possible explanations could be that the man used a skylight that is also part of the room, the ladder, or both to escape. Every observation is

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TABLE 1.
Overview Of Abduction, Deduction and Induction Based on an Observation (O), Explanation (E), and a Rule (if E then O)

	Givens			Derived
Abduction	R: if E, then O	O	→	E
Deduction	R: if E, then O	E	→	O
Induction	E	O	→	R: if E, then O

a piece of data that helps in reaching the correct conclusion about an underlying explanation. Therefore, all the existing information must be organized. The sequential integration of information in working memory in the form of mental representation enables the retrieval of critical information and is essential for successful abductive reasoning. Following, the functioning of working memory is crucially important to this form of inference. Even though there are a number of theories describing the process of abductive reasoning or parts thereof (e.g., theory of abductive reasoning [TAR], Johnson & Krems, 2001; theory of explanatory coherence [TEC], Thagard, 1989; HyGene, Thomas et al., 2008) and all of them give valuable insight into aspects of reasoning, most of these do not account for the role of working memory.

However, previous research suggests that specific working memory resources, rather than the general capacity of working memory, is the limiting factor when engaging in complex mental tasks (Süß et al., 2002). Therefore, investigating the memory capacity of specific working memory components may help to develop a better understanding of individual differences in reasoning ability (Oberauer et al., 2008), or more precisely, abductive reasoning ability. Therefore, we followed a twofold approach in this study. First, to investigate differences in reasoning outcomes, we correlated reasoning accuracy with different working memory tasks. Second, to also shed light on the process of reasoning, we investigated the relationship between gaze data during abductive reasoning and memory tests. To summarize, the aim of this study was to explore the relationship between eye movements, sequential abductive reasoning, and working memory ability.

Relationship Between Abductive Reasoning and Working Memory Capacity

Working memory is a multicomponent storage system that is controlled by attention and that determines the capacity of complex thought by managing the intersections between perception, attention, memory, and action (Baddeley, 2007). According to Baddeley and Hitch (1974, 1994) information is stored in one of two systems. The phonological loop is the first storage system and it manages phonological, verbal, and acoustic information, which has to be revived by articulatory control processes or subvocal rehearsal in order to keep memory traces from fading. The second storage system, the visuospatial sketchpad, organizes visuospatial information, relies on visual imagery and visual perception, and works with resources not used by the verbal system. The central executive (Baddeley & Hitch, 1974, 1994) controls the handling of information in working memory by attentional mechanisms. Further, Baddeley described both temporary maintenance and manipulation as the tasks of working memory in order to enable complex cognitive activities such as reasoning. Therefore, working memory extends beyond storage of information, enabling us to engage in tasks that require the manipulation of information within a representation in working memory (Hedge & Leonards, 2013). As a consequence, working memory is seen as an interplay of storage and processing mechanisms (Cowan, 2017; Danemann & Carpenter, 1980).

In a review of the concept and its definitions, Cowan (2017) stated that, on the one hand a multicomponent definition (consisting of a verbal and a spatial component) is very prominent. On the other hand, he emphasized that storage and processing are seen as an inseparable combination. In the same vein, benchmarks set by the leading scientists on working memory discuss both the storage and processing mechanisms as well as the division in verbal and spatial modalities as fundamental aspects (Oberauer et al., 2018).

It is not yet clear what precise role processing and storage mechanisms as well as verbal and spatial modalities play in abductive reasoning. However, it is known that in abductive reasoning, the increasing number of observations and the mental calculations needed to find a plausible explanation may exceed the working memory capacity of the reasoner (Baumann, 2000; Böhm & Mehlhorn, 2009; Khader et al., 2013; Krems, 1997; Mohr et al., 2010; Thomas et al., 2008). Whether and how far these capacity boundaries of working memory are exceeded might be a determining factor in successful abductive reasoning. Working memory organizes the information that is active and needed in action and thought (Cowan, 2017; Oberauer et al., 2018). In abductive reasoning, this entails the construction of a mental representation on which all reasoning processes are based. In fact, the term working memory was first used by Newell and Simon (1956), who used it in terms of problem solving (Cowan, 2017).

For example, according to TAR (Johnson & Krems, 2001), the mental representation, called the situation model, represents the current explanation and is held in working memory. As more observations are made and need to be integrated into the situation model, the situation model increases in complexity (Klichowicz et al., 2020). As it is well established that responses relying on information in working memory become slower as there are more things to remember (Oberauer et al., 2018), it seems highly plausible that a limited working memory capacity would have an effect (Baddeley & Hitch, 1974; Johnson-Laird et al., 1992) on performance in abductive reasoning tasks as well as on the process itself. Based on theories positing that storage is modality-specific (Baddeley & Hitch, 1974, 1994; Oberauer et al., 2000; Süß et al., 2002), we assumed that only working memory abilities that draw on the same modality as the abductive reasoning task would show a strong relation to that task. Note that abductive reasoning can be based either on verbal or on spatial material, depending on the form of observations made. Verbal abductive reasoning tasks often draw on prior knowledge or learned associations (e.g., chemical accident paradigm, see Mehlhorn et al., 2011). Here, we used a visuospatial task based on applying a set of rules (see the Method section).

To investigate how the outcome and process of abductive reasoning interact with working memory capacity, we assessed verbal and spatial modalities. These components can be assessed with different tasks

(Oberauer et al., 2000; Süß et al., 2002). Spatial Span (Shah & Miyake, 1996) and Reading Span (Danemann & Carpenter, 1980) are integrated measures of storage and processing that map each onto its own modality (as working memory is seen as an interplay of storage and processing mechanisms, Cowan, 2017). As we used a spatial reasoning task, we also introduced a second spatial task in our experiment, the Dot Memory test (Ichikawa, 1983; Miyake et al., 2001), which only maps on the storage component of spatial material in working memory.

Fluid intelligence seems to be another factor that is related to both working memory performance (Oberauer et al., 2018) and reasoning ability (Süß et al., 2002). Therefore, we added a short form of the Raven Matrices (Kratzmeier & Horn, 1980) as an intelligence measure. To investigate the relationship between working memory and the outcomes of abductive reasoning, we assessed the accuracy with which abductive reasoning tasks were solved. Additionally, we used gaze data as a process tracing measure.

ABDUCTIVE REASONING OUTCOMES AND WORKING MEMORY ABILITY

As the mental representation is the most important structure in the reasoning process, its precision and completeness are crucial for successful reasoning. Therefore, we expected the spatial ability to maintain the representation to be relevant for successful abductive reasoning. It follows from this that the Dot Memory and the Spatial Span tests should show a positive relationship to reasoning accuracy. Still, the relationship between reasoning accuracy and working memory remains opaque even though it seems highly plausible that a limited working memory capacity would have an effect on reasoning outcomes (Baddeley & Hitch, 1974; Johnson-Laird et al., 1992).

As maintaining goal-relevant information (led by executive attention, Oberauer et al., 2003) is a facet of working memory as well as intelligence, we also expected to find positive relationships with the intelligence measure (Kane & Engle, 2000). This is because working memory provides resources for storage and processing, which are then used to remember relevant information in order to engage in reasoning.

To summarize, we expected spatial memory tests to map onto reasoning accuracy with a positive relationship, as the maintenance of the representation is crucial to the process. Further, we expected a positive relationship between the intelligence measure and reasoning accuracy. Regarding the working memory tests for the verbal (Reading Span) modality, we did not have concrete hypotheses. However, it seems likely that correlations between spatial tests and spatial reasoning would be more pronounced than correlations of the tasks that map onto verbal modalities.

ABDUCTIVE REASONING PROCESSES AND WORKING MEMORY ABILITY

Attention is central to handling information in working memory, but it is also closely connected to eye movements (Theeuwes et al., 2009) as it precedes eye movements to the target location (Deubel & Schneider, 1996; Godijn & Theeuwes, 2003). Even when navigating within a mental representation in working memory, eye movements are driven by internal attentional processes directed toward corresponding spatial areas (Scholz et al., 2018). That is, retrieving information activates information stored in a mental representation, resulting in gazes to the corresponding locations even if the underlying information is no longer present. This phenomenon, called looking at nothing, is described and discussed in a number of studies (e.g., Anderson et al., 2004, Johansson et al., 2006; Richardson & Spivey, 2000; Scholz et al., 2016, for an overview, see Ferreira et al., 2008; Richardson et al., 2009). Therefore, eye movements not only allow tracking which information is currently encoded and processed, but also the retrieval of information. Following, eye movements are a valuable source of data on what is stored in and retrieved from working memory.

Given previous findings on looking at nothing, gaze data seems to reflect information retrieval from memory. People look at locations where elements of the mental representation were first presented to retrieve them when needed. Because this study used a visual, memory-based reasoning task, tests mapping on the spatial-visual components of working memory should show a stronger relation to gaze data than the Reading Span test mapping on the verbal-phonological component.

Eye movements could be mediated by working memory in two ways. On the one hand, working memory and mental imagery are conceptually related (Kosslyn & Thompson, 2003). That is, enhanced working memory capacity leads to a more detailed mental representation as it allows to maintain more precise information (Laeng et al., 2014), which, in turn, lead to more looking at nothing (Gurtner et al., 2021).

On the other hand, as looking at nothing (which is driven by attentional processes) can facilitate retrieval processes (Scholz et al., 2016, 2018), it is enhanced when demands on memory are high. A study by Scholz et al. (2011) showed that looking at nothing decreases when a task has been practiced well and memory demands are decreased, making this aid to memory retrieval no longer necessary. As a result, with an increasing ability to store information internally, people might look less at (now empty) locations to retrieve information (Johansson et al., 2011). Kumcu and Thompson (2016) studied looking at nothing in relation to visuospatial memory and found that participants with better visuospatial memory showed less looking at nothing. This suggests that looking at nothing may be more pronounced when spatial storage demands exceed the abilities of the reasoner. This is also underlined by the notion that easier tasks might take less time, causing fewer eye movements generally. Hence, eye movements contribute to understanding the role and importance of the mental representation during visual reasoning.

Therefore, if eye movements are an indicator for an improved mental representation due to good working memory capacity, the Dot Memory test should be positively correlated with fixations to the most important elements in the tasks. However, if eye movements are used as an aid to retrieval, fixations to relevant elements should be negatively correlated with test performance in the Dot Memory test. For the Spatial Span test, a similar picture was expected. However, eye movements give an insight into information that is retrieved from memory. As the Spatial Span test combines storage and processing requirements and looking at nothing does not allow clear inferences regarding information processing, we refrained from formulating a hypothesis regarding the Spatial Span test.

METHOD

We reinvited participants who took part in two different reasoning experiments (Klichowicz et al., 2020, 2021) one week later to the test their working memory capacity. For methodological details, please refer to these original articles.

Experiment 1 (Klichowicz et al., 2020) investigated what information is retrieved from memory in order to find a multicausal explanation for sequentially presented observations. Eye tracking was used to test process assumptions made by the TAR (Johnson & Krems, 2001). Experiment 2 (Klichowicz et al., 2021) aimed at explaining attentional guidance in form of eye movements and response behavior as an artefact of information acquisition and storage. The goal was to identify differences in abductive reasoning based on the amount of given compared to retrieved information with respect to experienced difficulty, the process, and the reasoning outcome. Therefore, Experiment 2 consisted of four conditions with a varying amount of information that had to be remembered. In the current study, we only included those trials of Experiment 2 that had the exact same requirements to memory and storage of information as the first study. That is, only one condition (24 trials) was reanalyzed in this study.

During the second session of Experiments 1 and 2, which took place about one week after the first one, participants solved the three working memory tests and the Raven Matrices in randomized order. Due to low participant numbers, data from the second session was not reliable for Experiments 1 (Klichowicz et al., 2020) and 2 (Klichowicz et al., 2021) individually. Therefore, the data of the second session from both experiments was not analyzed and published up until now.

Participants

Twenty-nine participants took part in the Experiment 1. One had to be excluded due to a loss of accuracy in the eye tracking measures. The remaining 28 participants (20 female, 8 male) had a mean age of 22.3 years ($SD = 3$).

In Experiment 2, the eye tracker was calibrated successfully in for 34 participants. Three participants had to be excluded due to data loss over the course of the experiment. The remaining 31 participants (17 female, 14 male) had a mean age of 22.7 years ($SD = 3.7$).

The sample size in both studies was chosen similarly to other studies on sequential diagnostic reasoning that used eye tracking as a process measure (Jahn & Braatz, 2014; Scholz et al., 2017).

The reanalysis was performed on a total of 59 participants. For all participants, calibration of the eye tracker was repeated until it reached a minimum accuracy of 2 degrees visual angle as the square-shaped areas of interest (AOIs) had a dispersion of about 2.64 degrees visual angle. All participants were undergraduate students at the Chemnitz University of Technology, majoring in psychology (75%) or sensoric and cognitive psychology (25%) and had normal or corrected-to-normal vision.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee. None of the participants participated in both experiments.

Apparatus

During the two experiments, participants were seated in front of a 22 in. computer screen (1680 × 1050 pixels) at a distance of 63 cm from the screen. A chin rest was used to avoid head movements. We presented the reasoning task as well as all memory and intelligence measures using E-Prime 2.0 and instructed participants to respond on a standard keyboard and using a mouse. An SMI RED remote eye tracker sampled data from the right eye at 120 Hz during the reasoning task. We recorded gaze data with iView X 2.5 and implemented a five-point calibration. Gaze data was analyzed with BeGaze 3.0, with fixations defined with a dispersion threshold of 100 px and a duration threshold of 80 milliseconds. Additionally, we used IBM SPSS Statistics 24, Microsoft Excel 2016, and JASP 0.8.4 for our analyses.

Material

REASONING TASK

The so-called Black Box Task (BBX) consisted of a 10 × 10 grid presented on a computer screen. Participants were asked to imagine this grid to be a box containing a number of hidden atoms. They were given the task of locating the atoms by interacting with the box. Atom locations were to be derived by watching where light rays entered and exited the box. As the atom location explaining the current entry and exit position was inferred, participants placed it by mouse clicks in the corresponding squares of the black box. The current atom appeared and remained visible until a new observation (entry and exit position of the ray) was obtained. Participants obtained fixed observations in a fixed order in each trial. This method allowed us to generate consistent observations for each participant. Participants did not see the path of the light rays. Only the current entry/exit positions of the rays were visible and located in the grey border of the grid (see Figure 1). The actual path the rays took through the box had to be deduced following specific rules. Each atom had a field of influence (depicted as a circle around the atom, see Figure 1). When a ray did not hit an atom, it went straight through the box. If a ray hit the field of influence straight in the middle, it was absorbed and did not exit the box. If a ray hit the field of influence of an atom at an angle, it was reflected at a 90 degree angle, resulting in a L-pattern. Combinations of two L-patterns could result in a Z- or U-pattern. With this paradigm, it was possible to observe memory processes that take place in sequential abductive reasoning. Participants decided when to move to the next observation by pressing the space bar. During a trial, participants had to place two to four atoms, depending on the observation pattern. A trial was solved succes fully when all observations were explained without any contradictions[1].

WORKING MEMORY SPAN TASKS

We aimed to assess storage and processing as well as both content modalities of working memory. Each modality was measured with one working memory test. Additionally, participants completed an intelligence test.

Dot Memory. In each trial of the Dot Memory test (Ichikawa, 1981, 1983; Miyake et al., 2001), participants first saw a 5 × 5 grid with some of the fields colored black. Each field had a size of 2.73 × 2.73 degrees

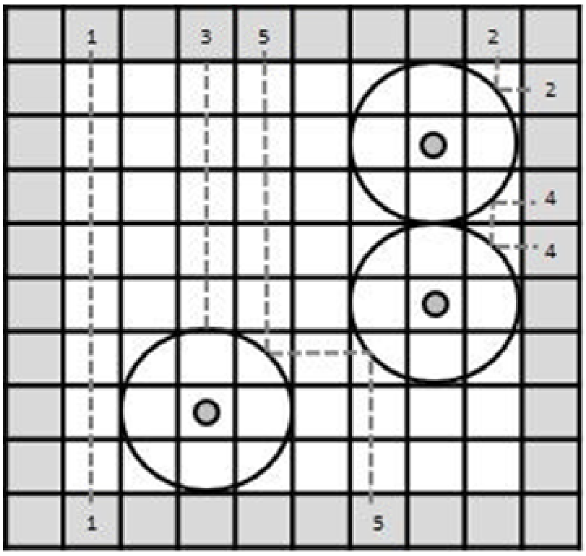

FIGURE 1.

Rules in the Black Box: 1 = Straight through, 2 = L-Pattern, 3 = Absorption, 4 = U-pattern, 5 = Z-pattern. Note that the ray paths (illustrated as dotted lines) were not visible for the participants.

visual angle (105 × 105 px). The black-colored fields appeared for 750 ms and were then removed, leaving the grid empty. Participants' task was to mark the fields that were previously colored black (the dot positions) using the mouse. They received feedback: Correctly marked fields were green, missing dot positions were blue, and incorrectly marked fields were red. The number of dot positions increased from two to seven, with five trials for each number of dot positions. Performance was determined by the number of dots that were placed correctly (out of all 135).

Reading Span. During the Reading Span test (Danemann & Carpenter, 1980), participants saw a sentence presented on an empty computer screen. For each sentence, participants had to decide if it was true (processing component). A number of sentences was summarized to a trial. After each trial, the participants had to name the last word of each sentence from the current trial (storage component). Five trials were summarized to one block. There were five blocks, with the first having two sentences per trial and the last consisting of six sentences per trial. For analysis, a point was assigned to each block in which participants remembered all the items correctly in at least three out of five trials. Blocks were presented with increasing difficulty. Points were counted up to the block in which participants did not gain a point. If higher set sizes earned a point with unsuccessful blocks earlier, half a point was added.

Spatial Span. During the Spatial Span test (Shah & Miyake, 1996), a series of rotated positions of a letter that had been presented previously (*F, J, L, P*, or *R*) were displayed. For each letter position, the participants had to decide whether the letter was mirrored (processing component). After each trial, all letter positions had to be recalled in the presented order by pressing a corresponding number on the number pad (storage component). The number of the letter positions that had to be remembered increased from two to five per trial over four blocks, each consisting of five trials. Participants earned a point for each block in which they remembered all the items correctly in at least two out of three trials. As in the Reading Span test, blocks were presented with increasing difficulty and points were counted up to the block in which participants did not gain a point. If higher set sizes earned a point with unsuccessful blocks earlier, half a point was added.

Raven Matrices. In the Raven Matrices test (Kratzmeier & Horn, 1980), participants saw a pattern with a gap. The task was to choose the piece out of eight section pieces that fills the gap by fitting in and completing the pattern. Pieces were numbered and chosen by the corresponding number on the keyboard. The test consists of 12 trials (12 patterns that had to be completed). The total number of correctly solved trials was analyzed.

Procedure

During Experiment 1, participants solved 48 memory-based trials following an instruction phase and two training phases. Whereas the atom and observation positions remained visible during the first training phase, the second training phase was under the test conditions. This meant that participants had to retain the former atom and observation positions in memory, as only the current observation and the corresponding atom was visible in the visual display (see Klichowicz et al., 2020, for further information).

Experiment 2 consisted of 60 trials organized in five blocks with varying memory demands (i.e., the amount of information that had to be kept in memory was manipulated; see Klichowicz et al., 2021, for further information). Two blocks (24 trials) had the same amount of information given as in Experiment 1 and were therefore included in the current analysis.

The second session was similar for both experiments. Participants solved computer-based versions of the three memory tests and the Raven Matrices in randomized order, each test taking five to ten minutes. All participants completed all trials of all tests even if errors occurred. The results of the memory tests were not included in the previous studies.

RESULTS

As both gaze data and performance were similar when controlling for experiment, we collapsed data from the reasoning task over both experiments. That is, results from 28 participants in Experiment 1 and 31 participants in Experiment 2 resulted in a sample of 59 participants.

Analysis

We defined each square of the grid as a single AOI to analyze eye movements of the participants. This resulted in gaze data being distributed over 100 separate AOIs that were each sized 2.64 × 2.64 degrees of visual angle (102 × 102 px). We coded and integrated only relevant AOIs into further analyses. Relevant AOIs were those marking the observation locations of the rays, the field where the rays hit an atom's field of influence, and the AOIs where atoms should be placed according to the rules of the BBX. The atom location labelled "atom" always consisted of the field where the ray hit the field of influence and the AOI with the actual atom. For each new observation within a trial, we designated the current observation "current observation location" and the current atom "current atom." Accordingly, we designated the information location of all already seen observations in a trial as "previous observation locations" and "previous atoms." This way, no fixations were double-counted as both current and previous. The measure of attention was defined by summarized fixation times in milliseconds to each AOI in the visual display[2].

When controlling for the amount of time participants spent on each observation by calculating fixation proportions, the analyses yield similar results. Note that we also analyzed fixation counts as the number of fixations to relevant AOI and strike rate as the probability that an AOI was fixated on even once. As those measures yielded very similar results, and for reasons of clarity, we only report fixation times. Irrelevant AOIs served as a baseline measure.

For each trial, an irrelevant AOI in the grey border was defined for comparison with observation locations, and an irrelevant AOI in the white grid was defined for comparison with the atom locations. That is, we picked an AOI that never contained either an observation location or an atom or field of influence at any point in the trial.

For all analyses, we report the Bayes factors. These factors represent an integrated probability to the predictive power of a model. BF_{10} indicates to what extent an alternative hypothesis stating a difference between the variables dominates a null-hypothesis that does not expect any differences. Bayes factors between one and three are commonly agreed to represent noteworthy support whereas *BF*s between 3 and 10 indicate positive support and above ten indicate very strong support (Raftery, 1995). The advantage of *BF*s for our study is that they can lend statistical support to hypothesis that do not state any differences as statistically non-significant test results alone do not allow such a conclusion. For all our analyses, we set stretched beta prior width to .5. However, due to our sample size, its influence remained small (see Raftery, 1995, p. 127). Using different priors (e.g., 1.0) did not change the pattern of the results.

Participants looked at both current and previous atoms more than at any irrelevant field of the grid, $t_{cur}(58) = 10.43$, $p < .001$, $d = 1.36$, BF10 > 1000; $t_{prev}(58) = 5.60$, $p < .001$, $d = 0.73$, $BF_{10} > 1000$, and at current and previous observation locations more than at a randomly chosen irrelevant field in the grey border, $t_{cur}(58) = 8.29$, $p < .001$, $d = 1.08$, $BF_{10} > 1000$; $t_{prev}(58) = 8.03$, $p < .001$, $d = 1.05$, $BF_{10} > 1000$. That is, results show that AOIs that contain(ed) information throughout a trial received significantly more visual attention than those that did not. Thereby, AOIs that were still occupied by current information received more looks than AOIs which held information that was no longer visible but still relevant for the current trial. We therefore concluded that we identified the relevant features of the situation model (see Figure 2).

Accuracy of the reasoning task (ACC) was calculated as the percentage of trials that were solved correctly. Participants solved an average of 79.9% of the trials correctly ($SD = 14.9$).

Memory test data from both experiments were pooled as there were no statistically significant differences (all *ps* > .05). For the Dot Memory test, we calculated the sum of all dots that were placed in the right location. Spatial Span and Reading Span tests were analyzed according to Shah and Miyake (1996) by assigning a point to each block in which participants remembered all items correctly in at least in two out of three (Spatial Span) or three out of five (Reading Span) trials. In both tests, blocks were presented with increasing difficulty. That is, the number of items to remember increased from block to block. Analysis was continued up to the block in which the participant did not manage to gain a point. If later blocks (higher set sizes) earned a point with unsuccessful blocks earlier, half a point was added. Raven Matrices were analyzed as the total number of correctly solved trials. During the Dot Memory test, participants placed an average of $M_{DM} = 128.97$ ($SD = 4.5$) correct dots out of all 135 dot positions (which is about 95.5%). Participants scored an average of $M_{SSP} = 0.40$ ($SD = 0.52$) points during the Spatial Span test and $M_{RS} = 2.79$ ($SD = 1.09$) points during the Reading Span test. Out of the 12 trials of the Raven Matrices, $M_{Raven} = 7.09$ ($SD = 2.61$) were solved correctly (which is about 59%).

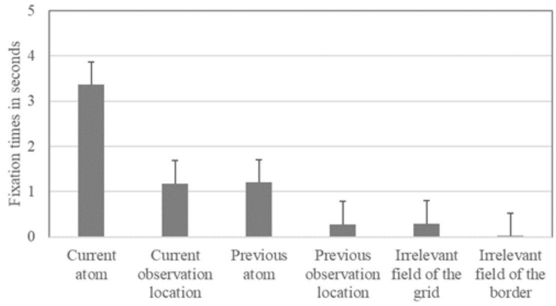

FIGURE 2.

Summarized fixation times in seconds on current and previous atoms as well as observation locations and irrelevant areas. Error bars represent standard errors.

Abductive Reasoning Accuracy and Working Memory Ability

We correlated reasoning accuracy (percentage of correctly solved trials) with the scores of all working memory tests (see Figure 3) and complemented the results with BFs as explained above. Reasoning accuracy showed no statistically significant relationship with the Spatial Span test. As the Dot Memory test did show a relationship, the picture remains rather unclear. However, *BF*s for the Dot Memory test gave rather strong support that spatial storage abilities are correlated with performance accuracy in our reasoning task, as they were near 1 for the Spatial Span task and showed positive support for the Dot Memory test. The Raven Matrices showed noteworthy relationships with reasoning accuracy in the BBX task. The Reading Span, which maps onto the verbal component of working memory, did not show any relationship with the visuospatial reasoning task. Bayes factors below 1 support this result (Raftery, 1995). An analysis investigating whether working memory moderates the effect on Raven Matrices was not conclusive and was not included in the current article, but can be found in the Supplementary Materials online.

Abductive Reasoning Processes and Working Memory Ability

To investigate the relationship between the process of abductive reasoning and working memory, we only included trials that were solved cor-

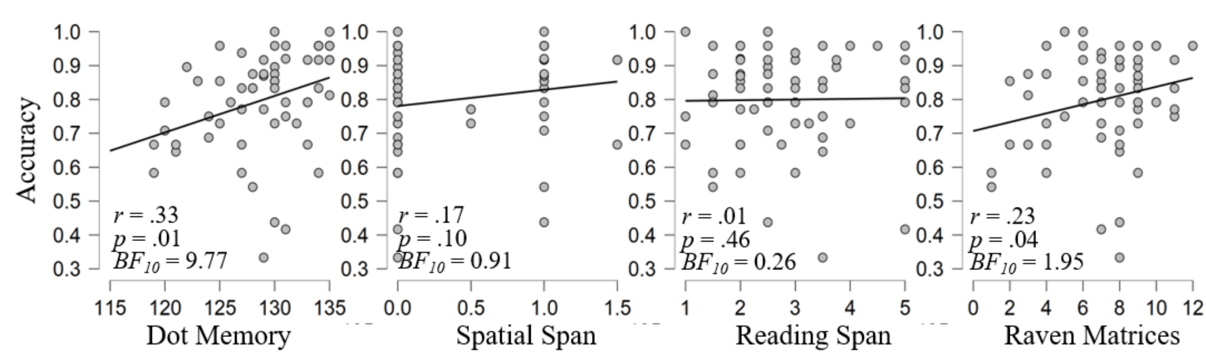

FIGURE 3.

Correlations between the reasoning task accuracy and test performance on the Dot Memory test, the Spatial Span test, the Reading Span test, and Raven Matrices. Each dot represents the data of one participant.

rectly, as we were interested in successful reasoning. An analysis of errors was not conclusive, as trial numbers were very low, and is therefore not reported in the current article. We expected the Dot Memory test, as it maps on spatial storage, to influence eye gaze. The direction of the correlation depends whether eye movements reflect a more detailed mental representation (positive correlation) or act as an aid to retrieval (negative correlation). Verbal components were not expected to be correlated with eye gaze. The Spatial Span test and Raven Matrices were introduced due to explorative ideas and were not connected with any specific hypotheses.

None of the tests showed statistically significant relationships ($p < .05$) between fixations to the current atom (see Figure 4[5]). This is no surprise as this was the most important feature in the setup and was currently visible on the screen. The negative correlation between the gaze data, previous atom locations, and performance in the Dot Memory test shows that looking at nothing might be increased when visuospatial storage capacity is rather low, $r_{\text{prev.atom}} = -.25$, $p = .03$, $BF_{10} = 72.76$. Therefore, looking at nothing acts as an aid to the retrieval of relevant information from working memory. Further, higher test scores in the Dot Memory test were associated with shorter summed fixation times to current observation locations, $r_{\text{cur.observation}} = -.32$, $p = .01$, $BF_{10} = 7.91$.

All other tests showed no relationships with eye gaze, which was evident in the BF analyses (see Figure 4, $ps \geq .05$; most $BF_{10} < 1.0$, see Raftery, 1995).

DISCUSSION

In this study, we explored the relationship between abductive reasoning, which is understood as a class of inferences in which explanations are derived from given data using rules, and working memory. We examined two main questions. First, we studied the relationship between different aspects of working memory that result in reasoning. We were interested in whether specific working memory abilities are linked to successful visual abductive reasoning. As expected, we found relationships between spatial skills as well as intelligence and successful reasoning in a visuospatial task. Second, we explored the relationship between memory-based eye movements during abductive reasoning and working memory capacity. Our aim was to investigate the influence of working memory ability on the actual process of reasoning, irrespective of the outcome. Results suggest that looking at nothing is decreased when visuospatial storage abilities are high. This means that looking at nothing may act as an aid to memory retrieval. Besides that, no statistically significant relationships between eye tracking data and memory tests (Spatial Span, Reading, Span, and Raven Matrices) were found.

The Interaction of Reasoning Accuracy and Memory Ability

The TAR (Johnson & Krems, 2001) assumes that the situation model, a mental representation on which all reasoning processes are based, is the most important structure for successful reasoning. This theory states that all relevant information is organized within this structure and is activated as needed for the comprehension of new information as well as for regular consistency checks. Since the Dot Memory test and the Raven Matrices test showed a meaningful statistical relationship to reasoning accuracy, we suspect that spatial storage abilities draw on successful reasoning outcomes by creating a strong and complete situation model. The fact that storage as well as intelligence, as measured with the Raven Matrices, were accompanied by good reasoning performance is in line with previous research claiming that building a mental representation is one of the key tasks of working memory (Oberauer et al., 2008) and that intelligence is also strongly connected with working memory (Oberauer et al., 2018). However, working memory is more than storage of information. It is an interplay of storage and processing mechanisms (Cowan, 2017). The construction of the mental representation (that is, information processing and integration) also takes place in working memory. Still, in our study, the relationship between the Spatial Span test and reasoning accuracy remained opaque and has to be subject of further research.

As expected, we found no statistically significant connections between a visuospatial reasoning task and working memory abilities that map onto the verbal component (Baddeley & Hitch, 1994; Oberauer et al., 2000; Süß et al., 2002). We presume that relationships exist between verbal working memory skills and verbal reasoning tasks (Mehlhorn et al., 2011). However, this was not the subject of our research.

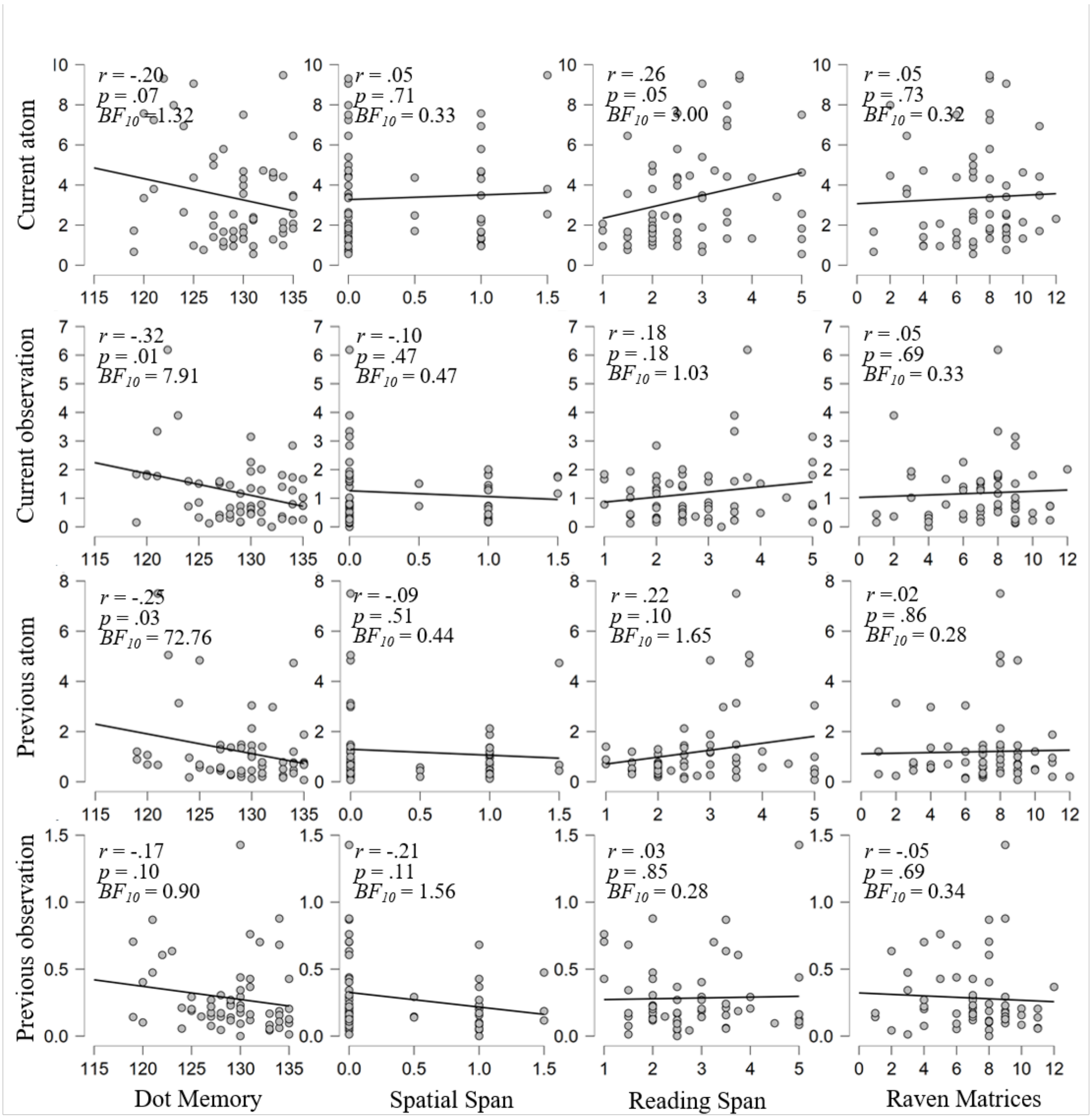

FIGURE 4.

Correlations between fixation times to the current atom, previous atoms, current observations, and previous observations in the Black Box task and test performance in the Dot Memory test, Spatial Span test, and Reading Span test, and as well as Raven Matrices. Each dot represents the data of one participant.

The Interaction Between the Process of Reasoning and Memory Ability

To our knowledge, no previous study has explored the relationship between looking at nothing in sequential abductive reasoning and working memory ability. We implemented working memory tests for verbal and spatial material (Oberauer et al., 2000; Süß et al., 2002) that map onto either the intertwined mechanisms between storage and processing (Spatial Span, Reading Span) or storage only (Dot Memory). However, only the Dot Memory test allowed for precise hypotheses. It correlated statistically significantly with eye movements to current observations and previous atom locations. This indicated that high spatial storage abilities are related to a reduction in the amount of attention needed to transfer and rehearse information in working memory. More importantly, the negative correlation to previous atom locations shows that participants with high visual storage ability do not need to use information location as a retrieval cue. However, the Spatial Span test did not yield similar results. This can be due to the object of the test (storage vs. storage/processing) or the different materials used in both tests. Whereas participants were presented with locations in the Dot Memory test, they were required to memorize the orientation of the stimuli in the Spatial Span test. One may conclude that not only the working memory component addressed by the task but also the concrete form of the material is of interest. Although global visuospatial ability may not be related to reasoning performance, very defined and closely task-related skills do show dependencies on reasoning performance. It is also possible that looking at nothing was not able to show dependencies between processing and eye movements, and other process measures should be introduced in future research.

Our research showed a relationship between spatial working memory ability and the process of visual abductive reasoning. This is also evident in the fact that fixations to different information locations did not show any connection to the facets of the Reading Span test.

Our results indicate that visuospatial storage ability is important to reason successfully. In our view, this is in line with the dominant role of the mental representation in the process. This study concentrated on a visual reasoning task that differed in its information presentation from the symbolic form of abduction that was originally proposed (Peirce, 1931). However, our task still represented a form of abductive reasoning that is common in everyday life. For example, when a physician has to interpret the development of symptoms such as a temperature chart, or when an economist analyses stock market progress, they engage in a visual form of abductive reasoning.

At this point, we cannot say whether inconclusive results in some of the tests are due to how we measured the constructs, simply the sample size, or the fact that the process itself does not differ substantially between individuals with different working memory abilities, but rather differs only in terms of outcomes. It is possible that different mechanisms (improved representation vs. eye movements as an aid to retrieval) cancel each other out. Gurtner et al. (2021) found a positive correlation between eye movements during mental imagery and working memory capacity. In their study, participants had to describe pictures that were encoded earlier. In their view, re-enacted eye movements either retain the mental representation or keep other visual stimuli from interfering with the memory task. As our visual stimuli were rather simple and the challenge was the actual reasoning task, different mechanisms may apply to the function of eye movements. First, the complexity of stimuli may play an important role, as was suggested by Gurtner et al. (2021) regarding temporal gaze dynamics. A number of studies investigated eye movement with very different stimuli (e.g., Johansson et al., 2006; Spivey & Geng, 2001). However, to our knowledge, there are no systematic comparisons of the influence of stimulus complexity. Second, in Gurtner et al. (2021) re-enacted eye movements were found through a phase of rehearsal in imagery. During this phase, participants were not asked to retrieve certain details or solve concrete tasks based on the stimuli they held in imagery. In contrast, we never actively asked our participants to remember the entire stimuli. The task was to solve a reasoning task. To successfully do so, the retrieval of certain features was needed. Free rehearsal and active manipulation of information held in working memory might lead to different gaze patterns. Careful manipulations on the visual material and task could shed further light on this question. For instance, implementing a second spatial task could help to investigate the trade-off between functional eye movements and a less fine-grained representation. Further, to draw a better picture of relations between gaze patterns, reasoning outcomes, and working memory measures, structural equation models should be implemented (see Oberauer et al., 2005). Unfortunately, our very complex reasoning task already took two hours and made a second session necessary for working memory tests. To produce a larger sample and allow for sophisticated analyses such as structural equation models, the task needs to be modified. Another possible step could be to examine whether it is merely a question of different strategies and under which circumstances and personal traits certain strategies become more likely.

Further, an investigation of the research questions and results of this study with regard to different (e.g., verbal) abductive tasks or even tasks that are deductive or inductive is of interest. Our results may not be specific for abduction, but may hold true for a number of reasoning tasks. However, since we used a visual abductive task, this study makes a first step on a long road towards understanding individual differences in the process of abductive reasoning. To our knowledge, there are some early attempts at modeling reasoning processes (Laird et al., 1987; Lovett et al., 2012, 1997). Further, process measures are well established in research on judgment and decision making. However, we aimed to assess process measures independent of reasoning outcomes (i.e., accuracy). To our knowledge, not much research exists that applies these process measures on reasoning in order to describe and assess actual reasoning behavior. Our study provides some of the first evidence of how memory has an influence on complex reasoning tasks.

Looking at nothing proved to be a useful process measure to analyze the influence of memory on abductive reasoning (Jahn & Braatz, 2014). Based on our results, future research on looking at nothing and reasoning should continue to consider individual differences in order to improve the understanding of their relation.

CONCLUSION

As working memory is the interface between perception, action, memory, and thought, we are confident that further investigation of its relationship to abductive reasoning—a process that involves all the aforementioned mechanisms—is promising.

This study assessed memory test data of participants from two different reasoning experiments and showed that spatial storage abilities affect abductive reasoning: the outcome as well as the process. As the analyses were mainly exploratory, no causal inferences can be drawn. However, we found some interesting contributions in our results.

Our participants appeared to use eye movements to empty areas (looking at nothing) to gain insight in the task by assessing the mental representation in order to retrieve task-relevant information. Further, as proposed by previous research, intelligence was connected to successful reasoning. The verbal storage modality of working memory did not interact with a spatial reasoning task, underlining the presence of different storage modalities in working memory.

However, some questions remain unanswered. For example, we cannot draw a conclusion between the process of abductive reasoning and spatial abilities, especially with regard to processing mechanisms, which are an important part of working memory. There is a lot to be learned yet about the process of abductive reasoning, or as Sherlock Homes put it: "Education never ends, Watson. It is a series of lessons, with the greatest for the last." (Sir Arthur Conan Doyle, *His Last Bow*).

FOOTNOTES

1. For stimulus material of Experiment 2 (Klichowicz et al., 2021), see https://osf.io/b2yhx/?view_only=789ebfad8c924c74b9d1f50990613f9a

2. We only used fixation durations in our analysis. Dwell time includes all fixations and saccades within an area of interest (AOI). However, since our AOI were rather small, saccades were probably small in number and length, making fixation times and dwell times very similar.

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All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee.

DATA AVAILABILITY

All data used in this analysis is available at https://osf.io/rhysd/?view_only=b569b4dec6294af9a704cf39084e6992

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