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**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 the capacity of working memory is closely related to successful abductive reasoning. However, the precise relationship between reasoning and working memory capacity remains largely opaque. In a reanalysis of two experiments ($N = 59$), we first investigated whether reasoning performance differs due to 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 show a clear relationship between reasoning accuracy and spatial storage components as well as intelligence. Process measures suggest that 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. Results are discussed in relation to current theories and the existing literature on the effects of memory on eye movements.

Keywords: abductive 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 analyzes the scene and reaches conclusions based on his observations, Holmes engages in what is called abductive reasoning. Abduction is understood as one of three classes of inference. In it, an explanation or cause (E) is derived from given data or observations (O) using a rule (R; (1–3)). 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 (4,5). However, in this work, we aim at improving the understanding of the process. 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 (6)). We follow a line of research that sees abduction as the generation and evaluation of possible explanations in order to find the best one (6–9). That is, we place a strong emphasis on the use of abductive inferences in everyday reasoning.

Often, abductive reasoning tasks are very complex (10–12) 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 a piece of data that helps in reaching the correct conclusion about an underlying explanation. All the existing information must therefore be organized. The sequential integration of information in working memory in a 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., TAR (9); TEC (13), HyGene (14)) 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, are the limiting factors when engaging in complex mental tasks (15). Therefore, investigating the memory capacity of specific working memory components may help to develop a better understanding of individual differences in reasoning ability (16), or more precisely, abductive reasoning ability. We therefore 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.

Working memory

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 (17). That is, working memory organizes the

information that is active and needed in action and thought (18,19). In abductive reasoning, this entails the construction of a mental representation on which all reasoning processes are based.

According to Baddeley and Hitch (20,21) information is stored in one of two systems. The phonological loop is the first storage system and 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, called a “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 (20,21) controls the handling of information in working memory by attentional mechanisms. Further, Baddeley describes both, temporary maintenance and manipulation as 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 into tasks that require the manipulation of information within a representation in working memory (22). As a consequence, working memory is seen as an interplay of storage and processing mechanisms (18,23).

In a review of the concept and its definitions, Cowan (18) states that, on the one hand a multicomponent definition (consisting of a verbal and a spatial component) is very prominent. On the other hand, he emphasizes 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 (19).

It is not yet clear, what precise role processing and storage mechanisms as well as verbal and spatial modalities play in abductive reasoning. It is known, however, that in abductive reasoning, the increasing number of observations and the mental calculations needed to find a plausible explanation far exceed the working memory capacity of the

reasoner (14,24–28), making working memory a determining factor in successful abductive reasoning.

Relationship between abductive reasoning and working memory capacity

Working memory organizes the information that is active and needed in action and thought (18,19). 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 (18).

For example, according to TAR (9), the mental representation, called 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 (29). As it is well established that responses relying on information in working memory become slower as there are more things to remember (19), it seems highly plausible that a limited working memory capacity would have an effect (20,30) on performance in abductive reasoning tasks as well as on the process itself. Based on theories positing that storage is modality-specific (15,20,21,29,31), we assume that only working memory abilities that draw on the same modality as the abductive reasoning task 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 (32). Here, we use a visuospatial task based on applying a set of rules (see method section below).

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 (15,31). Spatial Span (33) and Reading Span (23) are

integrated measures of storage and processing (as working memory is seen as an interplay of storage and processing mechanisms; (18) that map each onto its own modality. As we use a spatial reasoning task, we also introduced a spatial storage task in our experiment. The Dot Memory test (34,35), only has indicators for the storage component of spatial material.

Fluid intelligence seems to be another factor that is related to both, working memory performance (19) and reasoning ability (15). Therefore, we added a short form of the Raven Matrices (36) 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.

Eye movements as a process tracing method

Attention is central to handling information in working memory, but it is also closely connected to eye movements (37) as it precedes eye movements to the target location (38,39). Even when navigating within a mental representation in working memory, eye movements are driven by internal attentional processes directed toward corresponding spatial areas (40). 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 in a number of studies (e.g. (41–43), for an overview see (44,45). Therefore, eye movements do 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.

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. We therefore expect the spatial storage ability to maintain the representation to be relevant for successful abductive reasoning. It follows from this that the Dot Memory test should show a positive relationship to reasoning accuracy. However, working memory is more than storage of information. It is an interplay of storage and processing mechanism (18). The construction of the mental representation (that is, information processing and integration) takes also place in working memory. 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 (20,30).

As working memory and intelligence both show the ability to maintain goal-relevant information (led by executive attention, (46), we also expected to find positive relationships to the intelligence measure (47). 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.

Summarizing, we expect mere storage tests to map onto reasoning accuracy with a positive relationship, as the maintenance of the representation is crucial to the process. Further do we expect a positive relationship between the intelligence measure and reasoning accuracy. Regarding the working memory tests for the spatial (Spatial Span) and verbal (Reading Span) modality, we do not have concrete hypotheses. However, it seems likely, that correlations between spatial tests and spatial reasoning are more pronounced than correlations of tasks that map onto different modalities.

Abductive reasoning processes and working memory ability

Given previous findings on the looking at nothing behaviour, 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. Since this study uses a visual, memory-based reasoning task, tests mapping on 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 (48). That is, enhanced working memory capacity leads to a more detailed mental representation as it allows to maintain more precise information (49), which in turn lead to more looking at nothing behaviour.

On the other hand, as looking at nothing behaviour (which is driven by attentional processes) can facilitate retrieval processes (40,43), it is enhanced when demands on memory are high. A study by Scholz et al., (50) showed that looking at nothing decreases when a task has been practiced well, as this aid to memory retrieval is not as necessary. Resulting, with an increasing ability to store information internally, people might look less at (now empty) locations to retrieve information (51). Kumcu and Thompson (52) studied looking at nothing in relation to visuospatial memory and found that participants with better visuospatial memory showed less looking at nothing behaviour. This suggests that looking at nothing may be more pronounced when spatial storage demands exceed the abilities of the reasoner.

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 to fixations to the most important elements of the tasks. If, however, eye movements are used as an aid to retrieval, fixations to relevant elements should be negatively correlated to test performance in the Dot Memory test.

Method

We reinvited participants, who took part in two reasoning experiments (29,53) one week later to the test their working memory capacity.

The first experiment (29) 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 Theory of Abductive Reasoning (9). The second experiment (53) aimed at explaining attentional guidance in form of eye movements and response behaviour as an artefact of information aquisition 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 two consisted of four conditions with a varying amount of information that had to be remembered. In the current study, we only include those trials of experiment two that had the exact same requirements to memory and storage of information as the first study. That is, only one condition (24 trials) was reanalysed in this work.

During a second session, which took place about one week after the first one, participants solved the three working memory tests and the Raven Matrices in randomized order. As the data from the second session are not reliable for each experiment individually, they were not analyzed and included in the studies mentioned above.

Participants

Twenty-nine participants took part in the first experiment. 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 ($SD = 3$).

For 34 participants, the eye tracker was calibrated successfully in the second experiment. 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 ($SD = 3.7$).

Sample size in both studies was chosen similarly to other studies on sequential diagnostic reasoning that engaged eye tracking as a process measure (10,54).

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. All participants were undergraduate students at the Chemnitz University of Technology, majoring in psychology (75%) or sensoric and cognitive psychology (25%). All participants had normal or corrected-to-normal vision. Participants in both experiments received course credit for their participation. None of the participants participated in both experiments.

Apparatus

During the two experiments, participants were seated in front of a 22" computer screen (1680 x 1050 pixels) at a distance of 63 cm from the screen. We presented the reasoning task as well as all memory and intelligence measures with 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 5-point calibration. Gaze data was analyzed with BeGaze 3.0 with fixations defined with a dispersion threshold of 100 pixels and a duration threshold of 80 milliseconds. Additionally, we used IBM SPSS Statistics 24, Microsoft Excel 2016, and JASP 0.8.4 for our analysis.

Material

The reasoning task

261 The so-called Black Box Task (BBX) consisted of a 10 x 10 grid with a size of 25.92 x 26.27
262 degrees of visual angle (1015 x 1029 pixels). Participants were asked to imagine this grid to be
263 a box containing a number of hidden atoms. They were given the task of locating the atoms
264 by interacting with the box. Atom locations were to be derived by watching where light rays
265 entered and exited the box. Participants thus obtained fixed observations in a fixed order in
266 each trial. This method allowed us to generate consistent observations for each participant.
267 Participants did not see the path of the light rays. Only entry/exit positions of the ray were
268 visible and located in the grey border of the grid (see Fig 1). The actual path the rays took
269 through the box had to be deduced following specific rules. Each atom had a field of
270 influence (depicted as a circle around the atom, Fig 1). When the ray of light did not hit an
271 atom, it went straight through the box. If a light ray hit the field of influence straight in the
272 middle, the ray was absorbed and did not exit the box. If the ray hit the field of influence of an
273 atom at an angle, it was reflected at a 90 degree angle, resulting in a L-pattern. Combinations
274 of two L-patterns might result in a Z- or U-pattern. With this paradigm, it was possible to
275 observe memory processes that take place in sequential abductive reasoning. Participants
276 decided when to move to the next observation by pressing the space bar.

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

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 worked through a test measuring intelligence.

Dot Memory. In each trial of the Dot Memory test (34,35,55), participants first saw a 5 x 5 grid with some of the fields colored black. Each field had a size of 2.73 x 2.73 degrees visual angle (105 x 105 pixels). The black-colored fields appeared for 750 milliseconds 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.

Reading Span. During the Reading Span test (23), participants saw a sentence presented on an empty computer screen. For each sentence, participants had to decide if it was true (processing component). After a number of sentences, the participant had to name the last word of each sentence from the current trial (storage component). The number of sentences per trial increased from two to six over five blocks, each consisting of three trials.

Spatial Span. During the Spatial Span test (33), 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 participant had to decide whether the letter was mirrored (processing component). After each block, all letter positions had to be recalled in the order presented by pressing a corresponding number on the number pad (storage component). The number of letter positions that had to be remembered increased from two to five per trial over four blocks, each consisting of five trials.

Raven Matrices. In the Raven Matrices test (36), participants had to complete a pattern, choosing one of eight section pieces by pressing a corresponding number on the keyboard. The test consists of 12 trials.

Procedure

During the first experiment, 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 test conditions. That meant that participants had to retain the former atom and observation positions in memory (see 29 for further information).

The second experiment consisted of 60 trials organized in five blocks with varying demands to memory (see 53 for further information). Two blocks (24 trials) had the same amount of information given as in study one 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 worked through all trials of all tests even if errors occurred. The results of memory tests were not included in the previous studies.

Results

Analysis

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

We defined each square of the grid as a single area of interest (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 x 2.64 degrees of visual angle (102 x 102 pixels). We coded and integrated only relevant AOIs into further analysis. 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 "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. When controlling for the amount of time participants spend on each observation by calculating fixation proportions,

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 even once. As those measures yield very similar results and for clarity reasons, 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 a random 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 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 variables dominates a null-hypothesis that does not expect any differences. In turn, BF_{01} is a measure of how much a null-hypothesis should be preferred. Bayes Factors between one and three are commonly agreed to be noteworthy support whereas BFs between 3 and 10 indicate positive support and above ten even very strong support (56). The advantage of Bayes Factors for our study is that they can lend statistical support to hypothesis that do not state any differences as insignificant test results alone do not allow such a conclusion.

Participants looked at both current and previous atoms more than at any irrelevant field of the grid ($t_{cur}(58) = 10.43, p < .001, d = 1.36, BF_{10} > 1000$; $t_{prev}(58) = 5.60, p < .001, d = 0.73, BF_{10} > 1000$) and at current and previous observation locations more than at a randomly chosen irrelevant field in the grey border ($t_{cur}(58) = 8.29, p < .001, d = 1.08, BF_{10} > 1000$; $t_{prev}(58) = 8.03, p < .001, d = 1.05, BF_{10} > 1000$). We therefore conclude that we identified the relevant features of the situation model (Fig 2).

Fig 2. Summarized fixation times in seconds on current and previous atoms as well as observation locations and irrelevant areas. Error bars represent standard errors.

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

Memory test data from both experiments were pooled as there were no significant differences (all $ps > .05$). For the Dot Memory (DM) we calculated the sum of all dots that were placed in the right location. Spatial Span (SSP) and Reading Span (RS) were analyzed according to Shah and Miyake (33) by assigning a point to each block in which participants remembered at least in two out of three (Spatial Span) or three out of five (Reading Span) trials all items correctly. 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 on average $M_{DM} = 128.97$ ($SD = 4.5$) dots out of all 135 dot positions correct (which is about 95.5%). Participants reached on average $M_{SSP} = 0.40$ ($SD = 0.52$) 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.

Abductive reasoning accuracy and working memory ability

We correlated reasoning accuracy (percentage of correctly solved trials) with all assessed working memory tests (Fig 3) and complemented the results with Bayes Factors as explained above. Reasoning accuracy showed no significant relationship to the Spatial Span test and the Reading Span. The Dot Memory test and Raven Matrices show positive relationships with reasoning accuracy in the BBX task. Bayes Factors support these results. The Reading Span, which maps onto the verbal component of working memory, does not show any relationship to the visuospatial reasoning task. Bayes factors in favor of the null-hypothesis (BF_{01}) above three support this result (56).

Fig 3. Correlations between accuracy in the reasoning task and test performance in the Dot Memory test, the Spatial Span test, as well as the Reading Span and Raven Matrices. Each dot represents the data of one participant. Bayes factors are stated according to the hypotheses. That is, we report BF_{10} where we expected a relationship, and we report BF_{01} where we did not expect correlation.

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 correctly, as we are interested in successful reasoning. An analysis of errors was not conclusive as trial numbers are very low and is therefore not reported. We expected the Dot Memory test, as it maps on spatial storage to have an influence on the eye tracking behaviour. 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 to gaze behaviour. Spatial Span and Raven Matrices were introduced due to explorative ideas and are not connected with precise hypotheses.

None of the tests show significant relations to fixations to the current atom (see Fig 4). This is no surprise as this is the most important feature in the setup and also currently visible on the screen. Decreased looking at nothing behaviour is only evident in the data of previous atom locations and the Dot Memory test. This is an indicator that people seem to use looking at nothing when their visuospatial storage capacity is rather low. 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 are associated with shorter summed fixation times to current observation locations are supported by the data ($r_{\text{observation}} = -.32, p = .01, BF_{10} = 5.88$).

All other tests show no relationship to the gaze behaviour, which is evident in Bayes factors analyses (see Fig 4, most $BF_{01} > 3.0$, see (56)).

Fig 4. Correlations between fixation times to the current atom, previous atoms, current observation, and previous observations compared to test performance in the Dot Memory test, Spatial Span and Reading Span test and as well as Raven Matrices. Each dot represents the data of one participant. We report BF₁₀ where data speaks in favour of a relationship and we report BF₀₁ where correlations do not indicate a relationship.

Discussion

In this study, we aimed to explore 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 facets 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 storage 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, suggesting that looking at nothing may act as an aid to memory retrieval. Besides that, no relationships between eye tracking data and memory tests (Spatial Span, Reading, Span, and Raven Matrices) are found.

The interaction of reasoning accuracy and memory ability

TAR (9) assumes that the situation model, a mental representation on which all reasoning processes are based, is the most important structure for successful reasoning. The 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 show 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 are 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 (16) and that intelligence is also strongly connected with working memory (19).

As expected, we found no connection between a visuospatial reasoning task and working memory abilities that map onto the verbal component (15,21,31). We presume that relationships exist between verbal working memory skills and verbal reasoning tasks (32). However, this was not the subject of our research.

The interaction between the process of reasoning and memory ability

To our knowledge, no previous study has systematically 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 (15,31) that map onto either the intertwined mechanisms between storage and processing (Spatial Span, Reading Span) or only storage (Dot Memory). However, only the Dot Memory test correlated significantly with eye movements to current observation and previous atom locations. This indicated that high spatial storage abilities lead to a reduction in the amount of attention needed to transfer information to and rehearse information in working memory. More importantly, the negative correlation to previous atom locations show that participants with high 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.

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 do 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 originally proposed (2). However, our task still represents a form of abductive reasoning that is common in everyday life. When a physician has to interpret the development of symptoms such as fever, or when an economist analyzes stock market progress, for instance, they engage in a visual form of abductive reasoning.

Besides the Dot Memory test, no relationships are found between working memory and the process of visual abductive reasoning. At this point, we cannot say whether this is due to methodological issues or to the fact that the process itself does not differ substantially between individuals with different working memory abilities but 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. Careful manipulations on task difficulty could shed further light on this question. For instance, implementing a spatial second task could help to investigate the trade-off between functional eye movements and a less fine – grained representation. Another possible next 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 paper with regard to different (e.g., verbal) abductive tasks or even task that are deductive or inductive is of interest. The results we found may not be specific for abduction but 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. As there is, to our knowledge, not much research on reasoning using process tracing methods, our study provides some of the first evidence of how memory has an influence on complex reasoning tasks. Looking at nothing proved to be an useful process measure to analyse the influence of memory on abductive reasoning (10). Based on our results, future research on looking at nothing and reasoning should not stop 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 reasoning experiments and showed that spatial storage abilities affect abductive reasoning- the outcome as well as the process. Our participants used 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 is connected to successful reasoning. The verbal storage modality of working memory does 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. In this vein, we want to end as we began, with a quote from Sherlock Holmes: “Education never ends, Watson. It is a series of lessons, with the greatest for the last.” (Sir Arthur Conan Doyle, *His Last Bow*).

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