RESOURCE ALLOCATION AND PROBLEM SOLVING STRATEGIES DURING A GEOMETRIC ANALOGY TASK IN INDIVIDUALS DIFFERING IN FLUID INTELLIGENCE

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ABSTRACT

In two studies, we investigated why individuals of high fluid intelligence (hf-IQ) outperform individuals of average fluid intelligence (af-IQ) in analogical reasoning tasks. In the first study, we used pupillometry to monitor the allocation of cognitive resources during a geometric analogy task. We found that hf-IQ individuals outperform af-IQ individuals in easy conditions of the geometric analogy task and in a simple choice-reaction time task without exhibiting higher cognitive resource consumption. In the most difficult conditions of the geometric analogy task, however, hf-IQ individuals recruit additional cognitive resources to achieve superior performance.

In the second study, we used eye-movement analysis to elucidate the cognitive processes and strategies used by hf-IQ individuals during the geometric analogy task. In line with previous research (Bethell-Fox & Lohman, 1984) we found that hf-IQ individuals spend more time on the representation and retrieval phase of the analogical reasoning process. They are thus more successful at collecting the relevant information for identifying the relations between the objects in the pairs of the analogy.

INTRODUCTION

It has long been known that analogical reasoning is a key component of fluid intelligence. Thus, individuals with a higher fluid intelligence solve analogy tasks more quickly and with fewer errors (French, 2002; Halford, 1992; Hofstadter, 1995; Holyoak & Thagard, 1995). However, it is less clear why the analogical reasoning process of individuals with high fluid intelligence is more successful. In this paper, we report two studies that elucidate aspects of the reasoning process and how they differ between individuals of high and of average fluid intelligence. The first study uses pupillometry to shed light on the allocation of cognitive resources during the reasoning process. The second study uses eye-movement analyses to investigate the strategies employed by individuals of differing fluid intelligence.

The concept of resources we refer to in this paper was introduced by Kahneman (1973) in his capacity theory of attention. Following his approach, Just and Carpenter (1992) have defined resources as “the amount of activation available for information storage and processing” (p.312) in the underlying cortical system. According to Just et al. (2003), there are three ways to assess the amount of cognitive resources allocated to a certain task: functional brain imaging, event-related potentials, and pupil dilation. While the former two methods are quite obvious proxies of cortical activity, pupil dilation as a measure of resource allocation – the method we used in our study – may need some further explanation.

Cognitive Resource Allocation and Pupil Dilation. All cognitive efforts, like physical efforts and sensory stimuli, cause pupil dilation (Beatty & Kahneman, 1966; Hess & Polt, 1964; Kahneman & Beatty, 1967; Loewenfeld, 1993). The more difficult a task, the more the pupil dilates (Nuthmann & van der Meer, 2005; Raisig, Welke, Hagendorf, & van der Meer, 2007; Verney, Granholm, & Marshall, 2004). For instance, in classical experiments by Hess & Polt (1964), participants displayed higher pupil dilation while solving difficult arithmetic problems, such as 11x6, than while solving easy problems, such as 4x7. While the relation of task difficulty to pupil dilation is pretty straightforward and well established within one individual, things get a little more complicated when pupillometry is used to asses resource allocation across individuals differing in their cognitive capacity. Do the more capable individuals allocate more resources to the task (higher pupil dilation), or do they rather invest fewer resources since they employ more efficient cognitive processes (lower pupil dilation)? What role do task characteristics play? Ahern and Beatty (1979) propose three hypotheses regarding these relations (see also van der Meer et al, in press):

Effort hypothesis: More intelligent individuals generally invest more resources (higher pupil dilation across all types of tasks).

Resource hypothesis: More intelligent individuals have more resources available but they invest them only when the task requires it (higher pupil dilation only in the very difficult tasks).

Efficiency hypothesis: More intelligent individuals employ more efficient processes and thus generally invest fewer resources (lower pupil dilation across all types of tasks).

In the first study, we tested these hypotheses by administering two kinds of tasks to two groups of 11th-graders, differing in fluid intelligence (M=100 vs. M=130), measured by RAPM (Raven, 1958; Heller, Kratzmeier, & Lengfelder, 1998). The first task was a very simple choice reaction time task, the second a demanding geometric analogy task.

In the second study, we used eye-movement analyses to investigate the cognitive processes and strategies employed by individuals of high and of average fluid intelligence. Eye-movement analysis is a well-established and valid method for such an investigation because the focus of a gaze fixation corresponds to the center of visual attention (Just & Carpenter, 1976). Sprague & Ballard (2003) describe that the aim of individuals in problem solving situations is the maximum gain of information, that is, individuals tend to direct the gaze to the region with the presently largest content of information. Thus, more successful problem solvers show more purposeful and longer fixations in the relevant regions of a stimulus (c.f. Green & Lemaire, 2007; Yoon & Narayanan, 2003).

To derive hypotheses regarding differences in strategies and cognitive processes of hf-IQ and af-IQ individuals we'll briefly review literature on problem solving and analogical reasoning.

Problem solving. In general, a cognitive problem solving process can be divided into four subsequent phases (Garofalo & Lester, 1985): orientation/planning, organisation, execution, and verification. The temporal extension of a phase differs individually and can be influenced by various components, especially intelligence factors (Shore & Lazar, 1996). Differences between successful and less successful problem solvers are generally assumed to become particularly apparent in the duration of the orientation and organization phases (Span & Overtoom-

Corsmit, 1986). More precisely, successful problem solvers spend more time on planning and structuring a problem while less successful problem solvers tend to enter into the execution phase of a problem solving process more quickly and approach it with a trial-and-error-like technique.

Analogical thinking. Processing an analogy task involves core processes such as (i) building a representation, (ii) retrieving a source for the analogy (selecting relevant features and inhibiting irrelevant ones), (iii) mapping relations between source and target, and (iv) evaluating the analogy (Genter, 1983; van der Meer & Klix, 1986; van der Meer, 1996; Holyoak & Thagard, 1995; French, 2002; Kokinov & French, 2002; Holyoak, 2005).

The first two of these core processes could be equated to the orientation and organisation phase of problem solving described above. It is thus reasonable to assume that hf-IQ individuals will spend more time on identifying the relation between the objects of the source pair of the analogy before they proceed to the mapping and evaluation phases. Evidence pointing into this direction was derived by Bethell-Fox & Lohman (1984) who used eye-movement analysis to assess problem solving strategies in geometric analogy tasks. The authors found that more successful individuals mastered the given task with the help of a so-called *constructive matching strategy*, which means that the correct answer is mentally designed before it is compared with possible answer alternatives. Contrary to this, less successful individuals employ the *response elimination strategy*, which can be understood as trial-and-error-like technique, by which the participants come to the solution by the comparison of answer alternatives.

To summarize, two hypotheses regarding the gaze patterns (as an indicator of cognitive process and strategies) of hf-IQ and af-IQ individuals can be derived from the literature:

First, in any given object, hf-IQ participants will be better in the identification of relevant stimulus areas, that is, they will focus on the areas with the largest content of information (Sprague & Ballard, 2003).

Second, h-IQ participants will spend more time on the representation and retrieval phases of the analogical problem solving processes, that is, they will analyze the relations between the patterns of a pair more thoroughly before comparing the pairs and their relations.

Study 1: Pupillometry

METHODS

Participants

Thirty-seven students (11^{th} graders from schools specialized in mathematics and natural sciences) took part in the experiment, 29 men and 8 women, with a mean age of 17 years (*SD* = 0.6). Three months prior to the experiment, all participants were screened for their fluid intelligence (f-IQ) by administering the RAPM (Heller, Kratzmeier, & Lengfelder, 1998). Participants were divided into two groups based on their RAPM scores (whole sample: M(f-IQ) = 117.5, SD = 16.9).
Five female and 14 male participants were assigned to the af-IQ group (M(f-IQ) = 102.6, SD = 8.5), whereas 3 female and 15 male participants were assigned to the hf-IQ group (M(f-IQ) = 133.1, SD = 4.7).

Materials and Procedure

Choice reaction time task. In this low-level cognitive task, each trial started with a fixation cross presented in the middle of the screen for 1,000 ms (pre-trial baseline phase). Following the fixation cross, a vertical line was shown in the middle of the screen. After 500 ms, a dot appeared either to the left or right of the vertical line. Participants had to decide as quickly and accurately as possible whether the dot was presented to the left or right of the vertical line.

Geometric analogy task. In this high-level cognitive task, participants were presented with stimuli quadruplets. Each quadruplet consisted of a source pair (A:A') and a target pair (B:B') of geometric chessboard-like patterns (cf. Figure 1). Six different patterns were used. A pilot study had been conducted to select patterns of similar complexity. Three types of relations between patterns were possible within the source and target pair, respectively: mirroring on the vertical, the horizontal, or the main diagonal axis. These types of relation vary in difficulty (low [vertical] < medium [horizontal] < high [main diagonal]; Offenhaus, 1983; Royer, 1981; van der Meer, 1996). Source pair and target pair had either the same type of relation (analogy items) or different types of relation (distractor items) (Figure 1).

A trial consisted of four phases. It started with a fixation cross, which was presented for 1,000 ms (pre-trial baseline phase). Then, the item was presented (stimulus presentation phase). Participants had to decide as quickly and accurately as possible whether there was the same type of relation in both the source and the target pairs and indicate their decision by a button press. As soon as a response button was pressed, the item disappeared from the screen to prevent subsequent processing or rumination. The item was followed by a mask with the same luminance as the test items for 2,000 ms (relaxation phase). After the relaxation phase a smiley appeared on the screen indicating that participants were now allowed to blink and could start the next trial by pressing one of the response buttons (blinking phase).

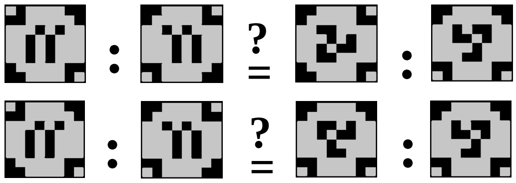

Figure 1.
Sample items of the geometric analogy task. Above: a valid analogy; below: no analogy

Apparatus

Stimuli were presented using the experimental control software Presentation 9.01 (Neurobehavioral Systems Inc, Albany, CA) running on a Microsoft® Windows® XP operating system. Pupillary responses were continuously recorded using an iView system (SensoMotoric Instruments GmbH, Teltow, Germany; sampling rate: 240 Hz).

RESULTS

Choice reaction time task. Individuals with high fluid intelligence responded faster, RT: means (M) and standard deviations (SD): M = 317.70 ms, SD = 40.34 and with higher accuracy, error rate: M = 1.11%, SD = 2.14, than individuals with average fluid intelligence, RT: M = 356.37 ms, SD = 68.87; error rate: M = 1.58%, SD = 3.75. The RT difference was significant ($F(1,35) = 4.28$, $p = .05$).

Although the hf-IQ group showed superior performance, task-induced pupillary dilations did not differ (hf-IQ: M = 0.32 mm, SD = 0.14; af-IQ: M = 0.28 mm, SD = 0.12; $F(1,35) = 0.65$, $p = .43$).

Geometric analogy task. Figure 2 shows the mean response times and error rates of the hf-IQ and the af-IQ group.

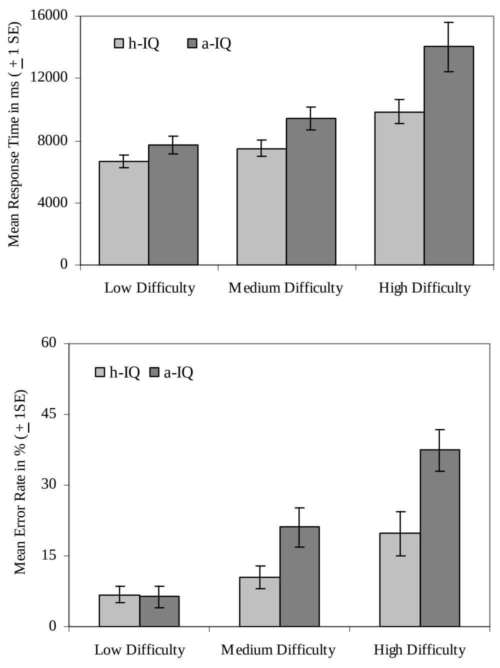

Figure 2.
Mean response times (above) and mean error rates (below) in the geometric analogy task; bars indicate standard error

In the easiest condition (mirroring on the vertical axis), performances of the hf-IQ and the af-IQ group did not differ significantly, neither regarding speed (t(35) = 1.48, p = .15) nor accuracy (t(35) = -0.14, p = .889). In the more difficult conditions (mirroring on the horizontal or diagonal axis), however, the hf-IQ group outperformed the af-IQ group, both regarding speed (medium difficulty: t(35) = 2.10, p = .04; high difficulty: t(35) = 2.32, p = .03) and accuracy (medium difficulty: t(35) = 2.16, p = .038; high difficulty: t(35) =2.639, p =.01).

Figure 3 shows the task induced pupillary dilations.

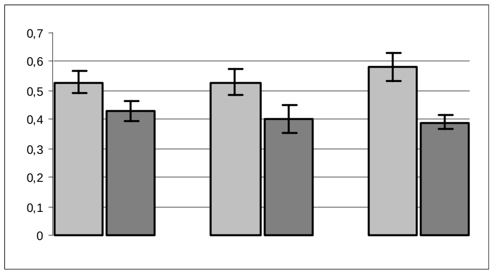

Figure 3.
Task induced pupillary dilations in the geometric analogy task;
light grey: hf-IQ group, dark grey: af-IQ group (left: easy, middle: medium, right: difficult)
bars indicate standard error

The hf-IQ group displays higher pupillary dilations in all difficulty conditions. Statistically, this is a tendency in the easy (F(1,35) = 3.88, p = .06) and the medium (F(1,35) = 3.785, p = .06) condition and a significant difference in the most difficult condition (F(1,35) = 11.70, p < .01).

DISCUSSION

The hf-IQ individuals outperformed the af-IQ individuals in both the easy choice reaction and the more difficult geometric analogy task. Cognitive resource consumption, indexed by pupillary dilation, was equal in both groups in the choice reaction time task. In the geometric analogy task, however, hf-IQ individuals showed higher cognitive resource consumption, especially in the most difficult condition. Relating this pattern of results to the three hypotheses derived from Ahern & Beatty (1979), it is in clear contradiction to the *efficiency hypothesis.* If hf-IQ individuals performed all kinds of cognitive processes with higher efficiency we should have seen smaller pupillary dilations in the hf-IQ group in both administered tasks. Actually, however, we found higher pupillary dilations, but not in all tasks, as would be predicted by the *effort hypothesis*, but only during the most difficult demands. This result is in favour of the *resource hypothesis*, that is, hf-IQ individuals have more resources available but invest them only when the task requires it. Our results suggest that in the geometric analogy task we used, and probably in other tasks of similar complexity, hf-IQ individuals achieve superior performance by recruiting more cognitive resources. This finding is in line with a growing body of neuroimaging studies that find highly intelligent individuals recruiting more brain areas during a variety of cognitive tasks (e.g. O'Boyle et al., 2005; Lee et al., 2006; but see also Rypma, 2006, for a critical discussion).

Study 2: Eye-movement analysis

METHODS

Participants

In the second study, the sample consisted of thirty-two students, divided into two groups according to the same criteria as described for study one. The af-IQ group included four female and eight male participants (M(f-IQ) = 103.8, *SD* = 7.8), whereas two female and 18 male participants were assigned to the hf-IQ group M(f-IQ) = 129.7, *SD* = 7.9).

Materials and Procedure

The second experiment took place at the Berlin NeuroImaging Center. The experiment was embedded into a functional Magnetic Resonance Imaging (fMRI) study during which the eye-movement data, which we report here, were recorded.

The task was the same as in study 1 except that the number of trials was increased from 60 to 150 and that another possible alignment for the patterns was included, namely mirroring on the secondary diagonal axis.

All patterns were comprised of a center and a periphery (see Figure 4). For some patterns, it was sufficient to compare the centers of the patterns within a pair to identify the relation between them with certainty (for example see the patterns depicted in Figure 1). For other patterns, comparison of the centers was not sufficient to unambiguously identify the relation. For instance, judging entirely by the center, the right-hand patterns in Figure 4 could be either vertically or horizontally mirrored. In those cases, information from the periphery has to be collected to make a secure judgment about the relation of the pair. Thus, individuals who spend much time on the representation and retrieval phase of the analogical problem solving process would be expected to regard both the center and the periphery of the patterns to retrieve the relation within a pair with certainty.

Dependent Variables

Additionally to RTs and errors, eye-movements were recorded. They were analyzed in regard to the frequency of fixations at pre-defined areas of interest (AOI) and the frequency of scan-paths between those areas. Regarding the AOI, we distinguished between the patterns' center and the patterns' periphery (see Figure 4). A *scan-path* is defined as a sequence of fixations and saccades (Noton & Stark, 1971). A typical scan-path within a pair of patterns is depicted in Figure 5.

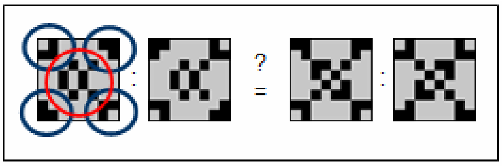

Figure 4.
Center and periphery areas of the patterns
red circle = center, blue circles = periphery

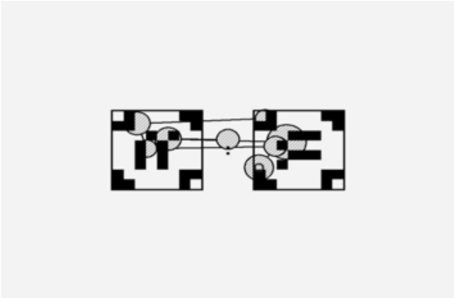

Figure 5
Example of a typical scan-path of one participant; the circles represent the location of fixation; the bigger a circle the longer the duration of a fixation.

Apparatus

Stimuli were presented using the software Presentation (Version 10.2; Neurobehavioral Systems Inc, Albany, CA).

Eye-movements were recorded by infrared-oculography of the right eye with the MRI-compatible eye-tracking system iView-X™ MRI-LR (SensoMotoric Instruments GmbH, Teltow, Germany) at a frequency of 50 Hz. At the beginning of each experiment a five-point calibration procedure was used to allow between-subject comparisons of eye-movements.

RESULTS

Behavioral Data. The presentation of the results will concentrate on eye-movement parameters, because our behavioral findings turned out to basically confirm the results of the first study, namely: In general RTs increased and accuracy decreased with increasing task difficulty. The hf-IQ group was faster than the af-IQ group, although these differences failed to reach significance in this study. The hf-IQ group outperformed the af-IQ group regarding accuracy in the most difficult relations (main diagonal: $t(32) = 3.52$; $p < 0.01$; secondary diagonal: $t(32) = 2.71$; $p = 0.01$).

Eye-movement Data. In comparison to the af-IQ-group, the hf-IQ-group explored the periphery of a pattern more and the center of the pattern less frequently. Concerning the periphery of a pattern, these findings are significant for the mirroring on the horizontal ($t(32) = 3.05$; $p = 0.01$), the main diagonal ($t(32) = 2.87$; $p = 0.01$), and the secondary diagonal axis ($t(32) = 2.28$; $p = 0.03$). Concerning the center of the pattern, these findings could be seen for the mirroring on the horizontal ($t(32) = -2.26$; $p = 0.03$), the main diagonal ($t(32) = -2.07$, $p = 0.05$), and the secondary diagonal ($t(32) = -2.14$; $p = 0.04$).

Compared to the af-IQ group, the hf-IQ group had significantly less scan-paths between the source pair and the target pair of the patterns ($t(32) = -2.14$; $p = 0.05$).

DISCUSSION

Roughly in line with the results of study 1, the hf-IQ group outperformed the af-IQ group, although this was only significant in the most difficult conditions (mirroring on the two diagonal axes).

On the basis of eye-movement analyzes, it was possible to draw conclusions on successful and less successful problem solving strategies: The hf-IQ group explored the patterns' periphery more than the af-IQ group. Because in many of the patterns, scanning the center was a necessary but not a sufficient condition for finding the right solution, the gaze pattern of the hf-IQ group can be characterized as orientation toward the relevant information (Sprague & Ballard, 2003; Green & Lemaire, 2007; Yoon & Narayanan, 2003).

Furthermore, h-IQ individuals showed less scanpaths between the source and the target pair of the patterns. In line with Bethell-Fox & Lohman (1984), this result indicates that more successful individuals make a greater effort to mentally design the relation *within* a pair before comparing those relations *between* pairs. They master the task with the so-called *constructive matching strategy*, while af-IQ individuals tend to employ a *response elimination strategy*. In other words, hf-IQ individuals tend to spend more time on the representation and retrieval phase of the analogical reasoning process at the expense of the mapping and evaluation phases.

GENERAL DISCUSSION

In two studies, we investigated the impact of fluid intelligence on the allocation of cognitive resources and problem solving behavior during a geometric analogy task. Individuals of high fluid intelligence showed superior performance in both studies.

In the first study, we found that the hf-IQ individuals outperform af-IQ individuals because they have more cognitive resources available which they allocate to the analogical reasoning process when task demands require it. The second study showed that hf-IQ individuals differ from af-IQ individuals by spending more time on the representation and retrieval phase of the analogical reasoning process at the expense of the mapping and evaluation phases. They scan the objects of the analogy more thoroughly to extract the relevant information for identifying the relations between them. The combination of pupillometry and eye-movement analysis thus helps to better understand processes of cognitive resource allocation and problem solving strategies in participants differing in fluid intelligence.

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