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Psychology of Personality: Real and Virtual Context

HOW DO CHEMISTRY EXPERTS AND NOVICES WORK WITH CONCEPTUAL SCHEMES?

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Abstract

The level of professional competence is presumably related to task performance and eye movement strategies. We have studied eye movements in experts and novices in the process of solving chemical problems. The subjects in the study were chemists with two different skill levels: professionals with ten years of experience and university graduates. First, they read the text describing complex chemical processes and then analyzed their schematic representation and filled in the gaps found in the scheme, using separately presented answers. Eye movements were recorded using the SMI iViewX Hi-Speed 1250 tracker with head support. As a result, a characteristic oculomotor pattern associated with the analysis and completion of conceptual schemes was identified and described. Compared to reading a text, schemes were completed with longer "concentrated" fixations, and longer and faster saccades. The experts read texts and solved schematically presented problems faster and also had more correct answers. When reading texts, there was no difference in eye movements between the experts and the novices. Analysis of eye movements has shown that experts are characterized by shorter first fixations and longer fixations on significant areas of graphical tasks. Novices usually have longer first fixations and evenly distributed shorter fixations on different parts of the task. It was also found that experts make fewer transitions between areas of interests than novices. Several indices of eye movements showed that success was associated with faster overall orientation in the main pattern and more in-depth analysis of the response options presented.

Keywords: Expertise, problem solving, eye tracking, text reading, conceptual schemes, analysis of chemical processes.

1. Introduction

Change in work patterns in modern society makes us pay more and more attention to the cognitive competence of professionals, by which we mean the ability and willingness to apply knowledge to solving professional problems. One way to identify the key characteristics of competence is to compare opposite groups in terms of work-related experience and achievement: experts and novices. Experts are professionals who have sufficiently long and successful professional expertise in a particular field, for example, qualified doctors, experienced chess players, university professors, people who are proficient in foreign languages, etc (Lalumera & Tuzet, 2015). This article focuses on chemistry professionals as chemistry is one of the fastest growing and socially significant areas of scientific knowledge, which, however, has not attracted the attention of psychologists until today.

Most authors agree that one of important characteristics of experts is the possession of domain-specific knowledge and use of effective strategies for solving highly specialized problems (Feldon, 2007). One of the pioneering works in this area was a study by Chase and Simon (1973), which addressed peculiarities of the memory of chess players. Top-level players showed tremendous abilities in reproducing the arrangement of pieces on a chessboard after their short presentation. However, they did not have a significant advantage in reproducing random stimuli unrelated to chess. Further studies confirmed these results (Linhares & Freitas, 2010). The study by Chase and Simon (1973) not only demonstrated the superiority of experts but also proposed a method to identify the mechanisms that ensure this superiority: analysis of eye movements. To date, this technology has provided insights into some mechanisms of information processing that ensure successful professional activities in various fields (Blinnikova et al., 2019; Gobet, 2016).

Most modern studies which include the registration of oculomotor activity use the so-called *eye-mind* hypothesis. It connects eye movements not only and not so much with the motor activity or visual behavior but with mental work. Eye movements are considered to be objective indicators of information processing (Just & Carpenter, 1985). The oculomotor activity has usually two types of events: fixation and saccades[1]. Researchers assumed that cognitive processing occurred during eyes fixation, while saccades only transferred the gaze into the area the eye was supposed to interact with. In addition, more and more researchers are engaged in spatial analysis which compares the parameters of fixations and saccades relative to different zones of the visually perceptible space[2].

Today analysis of eye movements serves as an extensive tool to study reading, perception of figurative information, visual search, etc. The use of this method to study problem solving is much less common. The past three decades, however, have seen scientific projects in this sphere[3]. The registration of eye movements allows "seeing" the thought process, uncovering its conscious and unconscious components (Harsh et al., 2019). It has also been established that some ways or strategies for processing information are more effective than others (Tang et al., 2016).

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[1] The fixation is a state, when the eye remains still for a certain period of time. The saccade is a quick eye movement from one fixation to another (Holmqvist et al., 2011, pp. 21-23).

[2] They were called Areas of Interest (AOI).

[3] Eye movements were instrumental in the analysis of concept identifying, mental rotation of spatial configurations, graphs, searching for problems in mechanical systems, arithmetic calculations, geometric constructions, and solving various creative tasks (see Körner, 2011).

For this research, we chose chemistry problems based on the schematic representations of chemical processes. Chemistry problems are easily visualized with special figurative and symbolic information (chemical formulas). This provides great opportunities for designing tasks with eye movement registration to evaluate and describe expert knowledge characteristics in chemistry professionals.

2. Problem Statement

Recent years have, therefore, seen an increase in studies comparing the oculomotor activity of experts and novices in the process of solving various problems. However, it must be noted that the data, which have accumulated exponentially, are full of contradictions. Many studies demonstrate that experts solve problems taking one glance at them (Kundel et al., 2007; Reingold et al., 2001), whereas in other studies experts make a great number of fixations (Konstantopoulos, 2009; Litchfield et al., 2008). Some authors suggest that the oculomotor pattern of experts has shorter fixations (Rayner, 2009), whereas others report the opposite (Bertrand & Thullier, 2009).

These contradictions are related to three significant aspects of problem solving. First, professional knowledge has domain specificity, it is shared by a narrow circle of professionals, and each group of professionals can apply unique strategies to achieve success. This undermines the idea of universal patterns. This issue can be addressed through the use of universal forms of tasks. One of such universal forms is the process scheme that can be analyzed by specialists in any field (Ratwani et al., 2008). Second, tasks are heterogeneous, they have a structure, therefore differences between experts and novices may not concern the entire space of the task but only some of its parts. Haider and Frensch (1999) argue that with an increase in professionalism, specialists better distinguish between relevant and irrelevant parts of the problem and therefore concentrate on processing the most important information. Third, most studies do not take into account the success factor in individual trials or of individual performers. Experts and novices are mainly distinguished by the duration of their professional experience. Some novices, however, can be highly successful, especially in individual trials, and experts, by contrast, sometimes fail. Studying these aspects will help to understand better what is behind the so-called superiority of experts, which makes it possible to solve professional problems faster and with fewer errors.

3. Research Questions

Our investigation compares eye movements of experts and novices a) when reading a chemical process description and filling in gaps in a schematic representation of this process; b) considering two different parts of the schematic problem: the space proper to the scheme and the space of answer options; c) in more or less successful trials. Chemists were picked for analysis since this field of knowledge requires special methods of processing and representing the information which are necessary to solve professional problems (Tang & Pienta, 2012). One of significant questions of this research is identifying peculiarities of problem solving by chemistry professionals as they rarely become subjects of psychological studies

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4. Purpose of the Study

The purpose of the experimental study is to identify the characteristic patterns of eye movements of chemistry experts and novices when they analyze schematically presented problems and to assess their solution. We supposed that chemists with ten years of work-related experience (experts) would use more appropriate cognitive strategies, reflected in eye-movement patterns, and solve problems more efficiently than university graduates (novices). It was presumed that there were differences in cognitive architecture in more successful trials and in less successful ones. In addition, this study tested the hypothesis that experts and novices achieve success through different ways of cognitive processing.

5. Research Methods

5.1. Subjects

The study involved 35 chemists with different levels of competence (the mean age was 35 years) with two different levels of expertise: 18 chemistry experts (mean work related experience: 10 years), 17 novices (chemistry students, mean work-related experience: 0.5 years).

5.1. Stimuli

The subjects were presented with four texts describing chemical processes: the production of varnishes, hydrogen peroxide, vinyl chloride, foam polyurethane. After each text, a graphic representation of the described processes was given (the example in Figure 01). The schemes had several cells where the chemical compounds were replaced by letters. These cells were to be filled in with answer options located in a separate zone to the right (the answer area separated from the scheme area).

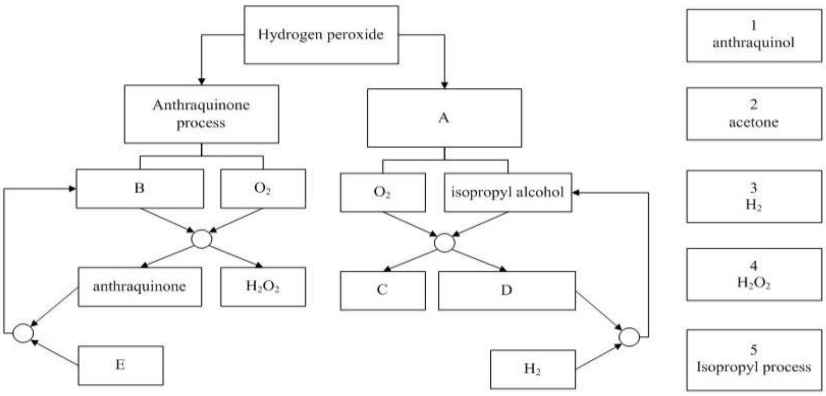

Figure 01. An example of the presented problem for arranging skipped components. The left part of the figure is the scheme area (AOI-1), the right part of the figure is the answer area (AOI-2).

5.2. Procedure

First, the subjects were asked to carefully read the text. Then, instructions were given to solve problems presented in the form of graphical schemes, where the subjects using computer mouse clicks were to place the missing chemical compounds into empty cells. Time was not limited either for reading or for solving problems.

5.3. Equipment

Stimuli were presented on a 23-inch screen with a 1920x1080 pixel resolution, using the software Experiment Center from SensoMotoricInstruments. Eye movements were recorded with an SMI iViewX Hi-Speed 1250 tracker (sampling rate 500Hz) with head support and the corresponding SMI software iVewX. A chin rest was used to fix the head.

5.4. Recorded indicators

In the experiment, the following indicators were recorded: I - indicators of the problem solving performance, such as the runtime and the number of correct answers; II - indicators of the oculomotor activity, in particular, the number, frequency and duration of fixation; the number, frequency, velocity and amplitude of saccades, as well as the scanpath. All indicators were recorded automatically with the Experimenter Center program. The answers of the subjects were also put down in the protocol by the experimenter. Statistical data processing was carried out with ANOVA using SPSS Statistic'20.

6. Findings

6.1. Comparison of main performance indicators and indices of oculomotor activity of experts and novices

The solving of the problem involved several stages: reading a text, studying a conceptual scheme, studying answer options (which were to fill the gaps in the scheme), and filling in empty cells. The research design allowed analyzing time indicators, performance indicators and parameters of eye movements related to different components of the problem.

The experts read texts much faster than the novices: 79,9 s vs 125,9 s (differences are significant: F(1,138)=69,88, p<0,01). All indices related to the runtime, such as the number of fixations and saccades, the total duration of the scan, were also significantly bigger for the novices than for the experts. In general, these data show that novices spend more cognitive resources on the reading part. There was no difference between the professionals and the students in terms of the average duration of fixations, the average duration, amplitude and velocity of saccades and the frequency of oculomotor events. This suggests that the nature of the cognitive processing of work-related textual material is similar in chemistry experts and novices.

Descriptions of chemical processes, being key elements in texts, were represented as areas of interests (AOI). The experts appeared to spend significantly less time in these areas and, most importantly, to make as few returns as possible to these significant units of texts. Differences in these indices are highly significant: in the time spent in the area of interest, (F (1,138 = 51.9, p <0.01); in returns to the area of interest, (F (1,138 = 48.1, p <0, 01). Thus, we can conclude that experts read texts faster as they are less likely to return to what they have already read, whereas novices reread the text, returning to the most significant units. Why does this happen? Novices return to key points to memorize information better for further usage. Experts do not need this return since they already have the information about the described chemical processes in their memory. Therefore, they only actualize knowledge in the long-term memory and use both information from the perceptual system and information from long-term storages to create a representation of the problem.

We see a similar pattern in the fill-in-the-gap task. The experts coped with this problem faster (53,57 s vs 95,49 s) and with fewer errors (7,65% vs 44,15% wrong answers). The experts and the novices differed significantly in the performance time (F (1,138) = 59.2, p <0.01) and in the percentage of correct answers (F (1,138) = 10.8, p <0.01). The experts had lower oculomotor indices that were connected with the duration of the slide (the length of the scanning path, the number of fixations and saccades, the total duration of fixations and saccades, the total amplitude of saccades). No significant differences were found either in the average duration of fixations, or in the average amplitude, duration, and velocity of saccades.

A comparison of the oculomotor activity indices of the experts and the novices in separate areas of interest (scheme area and answer area) revealed certain differences. The data are presented in Table 01. In both areas, the experts spent less time and made fewer fixations. There was a slightly significant difference in the duration of the first fixation between the experts and the novices in the scheme area. The experts had a lower first fixation rate, which indicates that they oriented in the task more quickly. The duration of the first fixation is believed to reflect the processes of recognition and identification of presented material. In particular, the duration of the first fixation was shown to be longer on unfamiliar and poorly understood objects (Graef De et al., 1990). In our case, neither the experts nor the novices had previously seen the presented schemes. Therefore, the fact that the experts' first fixation was shorter indicates that they understood the information presented earlier in the text better.

Table 01. Comparison of oculomotor parameters of the novices and the experts in the scheme area and in the answer area

AOI	Groups	Dwell time[4] (ms)	N of fixations	First Fixation Duration (ms)	Average Fixation Duration (ms)
Scheme area	Novices	55087,25	240,57	211,96	202,17
	Experts	30397,52	130,54	184,53	200,94
	F (1, 138)	56,58	58,85	2,68	0,79
	Significance level	*p* < 0.001	*p* < 0.001	*p* = 0.05	-
Answer area	Novices	33409,35	137,1972	189,7690	222,7338
	Experts	20493,57	76,3676	193,3529	244,1603
	F (1, 138)	34,4	48,34	0,05	10,31
	Significance level	*p* < 0.001	*p* < 0.001	-	*p* < 0.001

The experts' fixations were longer in the answer area (F (1,138) = 8.77, p <0.01). At first glance, this result may seem paradoxical, since in most studies experts have shorter fixations. Here, long-term fixations may indicate a deeper visual information processing (Holmqvist et al., 2011), which in this case implies the correlation of information in the answer area with the representation of the stored scheme.

The pattern of eye movements in the experts had fewer transitions between two areas of interest: the space of the scheme and answer options (F (1,138) = 88, p <0.01). On average, the novices made 38.86 movements between areas of interest, and the experts, in turn, made 17.99 movements. The novices also

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[4] Dwell time is the total duration of fixations in the area of interest (AOI).

had a higher return frequency: per second they made 0.47 return movements, while experts made only 0.38 (differences are significant: F (1,138) = 17.6, p <0.01) This is an important index, which shows the subject's ability to use not only information from perceptual systems but also information stored in mental representations of short-term and long-term memory[5].

A longer fixation time in the answer area and a fewer number of transitions between the areas of interest in experts can be interpreted as evidence that they, unlike novices, use mental representations to a greater extent in solving problems. If novices seek to correlate the answer with the scheme, shifting the gaze from one part of the task to another. Previously we showed that novices when solving difficult tasks prefer to expand their perceptual span (Blinnikova & Izmalkova, 2017; Blinnikova et al., 2019). Experts correlate the answer options with the mental representation of the scheme. Thus, they hold their gaze longer on one or another answer option and do not need to return to the image of the chemical process scheme.

6.2. Comparison of samples with varying degrees of performance accuracy

The number of errors that occurred in each trial depended both on the competence of the subject and on how well the chemical process was analyzed. We divided the trials by the number of correct answers into two clusters: a cluster with a low number of correct answers (m = 53%) and a cluster with a high number of correct answers (m = 85%). A cluster with a higher percentage of correct answers was also characterized by a faster problem solving (F (1. 138) = 18.08 p <0.001), as well as a shorter latency time for the first answer.

It is important to note that trials with a higher percentage of correct answers were executed with fewer fixations: 238,94 vs 349,41 (differences are significant: F(1,138)=19,65, p<0,01), but the fixations are longer on the average: 216,56 ms vs 208,94 ms (although the difference is not very significant F(1,138)=2,88, p=0,05). The duration of the fixations, as we noted above, indicates the depth of processing. It turns out that a deeper cognitive processing leads to a faster and more successful problem solving. We can correlate the average duration of fixations with the duration of the problem solving and obtain the cognitive processing efficiency factor.

We obtained a similar result when we compared the oculomotor indices related to the scheme area and to the answer area. The dwell time and the number of fixations in both areas of interest are significantly less in trials with a high percentage of correct answers. At the same time, we found out that a high percentage of correct answers was associated with a shorter first fixation in the scheme area (179,57 ms vs 214,68 ms) and longer fixations in the answer area (242,17 ms vs 224,76 ms). The differences are significant: F(1,138)=4,42, p<0,05 for the first fixation duration and F(1,138)=5,26, p<0,05 for the average fixation duration. In other words, the probability of finding the correct answer increases if the subject is ready to carry out a faster scan of the conceptual scheme and a slower and deeper analysis of the answers.

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[5] Rau et al. (2014) demonstrated that a large number of transitions is a result of surface processing of information.

6.3. Comparison of main performance indicators and indices of oculomotor activity of the experts and the novices in trials with varying degrees of success

At the last stage of data processing, we decided to analyze the interaction of two components of professional experience: duration of professional activity and the success or effectiveness of this activity. We compared the oculomotor patterns of the experts and the novices in successful and unsuccessful trials. We expected the experts and the novices to use different strategies for achieving high results in solving problems.

The interaction of the two factors was significant for a small number of indices. No significant interaction was obtained for indices of eye movement relative to the entire slide. However, the interaction between the factors was significant for indices of the duration of the first fixation and the average duration of fixations in some areas of interest (see Figure 02). It is worth noting that both of these indices are related directly to cognitive processing.

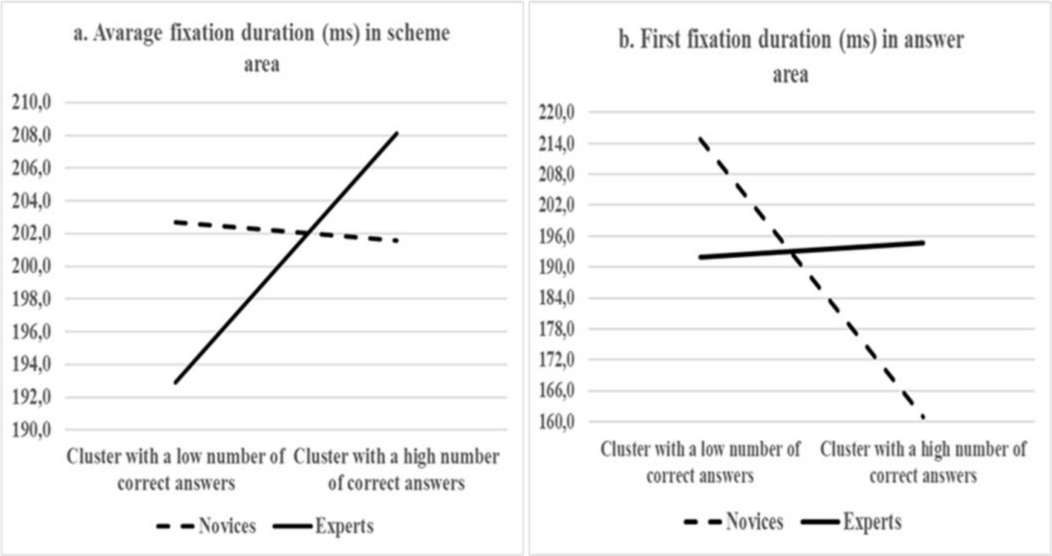

Figure 02. The eye movements parameters which differ significantly in experts and novices in clusters with a high and low number of correct answers.

In the scheme area, the average fixation time index showed an interaction between the performance factor and the expert factor (F (3, 136) = 3,6; p<0,05). These data suggest that in more successful trials experts have longer fixations, whereas this index is slightly lower for novices. We have already discussed the value of a longer fixation; this index reflects the depth of information processing. Thus, when it comes to scheme analysis, experts achieve higher results as they perform deeper processing and link perceptual information to the information stored in memory. Already our previous study showed that the processing depth was a cognitive resource of experts (Blinnikova et al., 2019).

In the answer area, the first fixation index showed an interaction between performance and the factor of the experiment duration (F (3, 136) = 3,43; p<0,05). These data demonstrate that in more successful trials novices had a shorter first fixation, whereas this index is slightly higher for experts. The duration of the first fixation, as we have already noted, indicates orientation in the task or in one of its parts. This suggests advantage for those novices who are better oriented in the answer zone.

7. Conclusion

Reading texts and solving fill-in-the-gap tasks in chemical process schemes showed significant differences in the execution time between the experts and the novices. Besides, the experts gave more correct answers than the novices. In general, these data, as in many other studies, demonstrate the superiority of experts, which means that more experienced professionals solve problems faster and make fewer mistakes. In order to understand what is behind the superiority of experts, we analyzed the characteristics of their oculomotor activity. It turned out that the advantage of experts is, first of all, in quick orientation in the task space, as well as in resorting to cognitive strategies of execution. Cognitive strategies rely on knowledge stored in memory (both long-term and short-term). This is proven by a smaller number of returns to the same information both in the process of reading, and in the process of scheme analyzing and choosing an answer.

The scheme completing task presupposed studying the scheme and answer options that were offered in the task. The study of eye movement parameters related to the scheme area and the answer area showed that the subjects first studied the scheme image and processed more information in this space. However, they performed a deeper processing in the answer area. In this area of interest (AOI), the average duration of fixations was significantly higher. Eye movements in more successful and less successful trials were analyzed. Success correlated with a faster overall orientation in the main scheme (defined by the duration of the first fixation in the scheme area) and a deeper analysis of the presented answer options (defined by the mean duration of fixation in the answer area).

Comparison of eye movement indices in successful and unsuccessful trials by experts and novices showed that, in general, novices benefit from faster ways of information processing, whereas experts, by contrast, benefit from the departure from fast and largely stereotyped processing. These findings create new possibilities of developing educational programs as well as methods that assess the professional skill level in chemistry professionals.

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