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Contents

Linear and Non-linear Patterns of Eye Movements in Lexical Search: Expert Versus Novice Language Learners

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Abstract. In the current study linear and non-linear eye movement patterns of lexical search were distinguished, based on the combination of intersaccadic angle and saccade direction measures, which proved to differ in subjects with different vocabulary knowledge. Participants, who were classified as experts and novices by their vocabulary test score, were asked to find 10 foreign language words in letter matrices. Eye movement data – peak saccade velocity and blink rate – indicated higher level of cognitive load in subjects with lower vocabulary test results. Subjects with minor vocabulary knowledge tended to adopt a non-linear eye movement pattern, characterized by frequent change of saccade direction and lack of prevalent direction, whereas proficient language learners were more inclined to demonstrate a more structured search pattern with prevailing either horizontal or vertical directions. The results confirmed our hypotheses: subjects with lower, intermediate and higher vocabulary expertise demonstrated different performance, different rates of cognitive load markers and different eye movement patterns. The acquired data, combined with the results of our previous study, support the argument that experts' advantage in professional tasks is mediated by cognitive control.

Keywords: Experts and novices · L2 learners · Visual search · Eye movement patterns · Intersaccadic angle · Saccade direction

1 Introduction

Features of experts' and novices' information processing is a challenging area of eye movement research. Experts have extensive and in-depth knowledge and skills in domain-specific areas as compared to novices. When solving cognitive tasks, they demonstrate faster and more accurate execution. The key concept of the experts-novices studies is that solving visual tasks differs in people with different level of expertise: in general, the feature of experts' eye movements is their "fluency" of viewing and focus on relevant details, which is based on their extensive knowledge of the subject [1] and the attention distribution in favor of the target areas of interest, while ignoring irrelevant areas [2]. This common idea notwithstanding, evidence of experts' and novices' basic eye movement parameters seem to be domain-specific. In some cases, experts were

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reported to make more short fixations, as compared to novices, e.g. in reading mathematical proofs [3], while other research report a more efficient gaze behavior indexed by lower fixation rates, e.g. as in laparoscopic surgery training environment [4, 5].

Integrative eye movement measures are often used to solve this discrepancy, such as the ratio of fixation duration and saccadic amplitudes, that characterizes the preference of either ambient or focal visual systems [6]. This metric has been used in a number of comparative studies of expert and novice cognitive performance. [7, 8]. Other possible measures of visual search task performance, which can be used to study the nature of scanning process, are the saccadic direction and intersaccadic angles [9]. This particular measuring technique was applied in this research.

Visual search in a complex environment is a common task for experts and novices in any domain. In the current research we modelled a lexical search task, where subjects were supposed to find familiar, but undefined words among randomly assigned letter charts. As visual search involves both looking (moving the gaze to new locations) and seeing (distinguishing between targets and non-targets), the identification of eye movement patterns involves defining to which degree each process was involved. As demonstrated in previous research, structured and unstructured search patterns can reflect the use of different cognitive strategies, such as the choice between looking versus seeing strategy. The latter are connected with the active managed search [10] and high cognitive control rates [11].

In our previous study [12] we defined three scanning patterns, based on the interrelation of saccade direction and intersaccadic angle. These patterns proved to be connected to the levels of impulsivity and executive or cognitive control involvement. Subjects who tended to demonstrate a steady linear eye-movement pattern ("Horizontal sequential") also showed low Impulsivity indices. In this case, subjects' search was organized in left-right, bottom-top manner. In contrast, the subjects with high impulsivity indices demonstrated a less structured search. Therefore, executive and cognitive control manifested itself in linear characteristics of eye movement patterns.

The question of which scanning method leads to higher performance remains open. Some studies show that unstructured search movements lead to faster responses with less error rates, while others show the opposite trends. It is also not completely clear how the scanning methods are related to the level of expertise [13]. Some authors insist that experts use less structured and more intuitive strategies, while others hold the opposite opinion.

The current study is aimed at identifying visual lexical search patterns in subjects with different expertise in foreign languages. We hypothesized that subjects will demonstrate different performance scores, different rates of cognitive load markers (peak saccade velocity, blink rate) and cognitive control in a lexical search task depending on their foreign language vocabulary knowledge. These parameters should be reflected in their eye movement patterns: linear or non-linear.

2 Method

32 Russian-speaking subjects took part in the research. Before the main task the subjects did a WAT test [14] to estimate their English vocabulary level. The subjects had to find

10 English 4-letter words in 15*15 matrices containing English letters (randomized by frequency) in 40 s (a relatively easy task for skilled English learners and a reasonably hard, but solvable one for novice learners).

All procedures performed in the study were in accordance with the ethical standards of the ethics committee of Lomonosov Moscow State University and with the Helsinki declaration.

Recorded Data. We recorded the search success rate and eye movement data. Eye movements were sampled monocularly at 250 Hz using the SMI iView X RED 4 (FireWire) tracking system with on-line detection of saccades and fixations and a spatial accuracy $< 0.5°$.

Visual search patterns of eye movements were defined on the basis of saccade directions and intersaccadic angles. SMI BeGaze data about the starting (Saccade Start Location X, Y) and ending (Saccade End Location X, Y) coordinates of the saccades (identified by SMI BeGaze by velocity and acceleration thresholds) were used.

We used the procedure of saccadic direction angles computation similar to the one described by Amor et al. [9], where the horizontal angle for the *i*-th saccade (α_i) is computed as:

$$\arctan(a_i) = \arctan\left(r_i, y / r_i, x\right),$$

where r_i,y = |Location End Y - Location Start Y|, and r_i,x = |Location End X - Location Start X|.

The obtained angles (0°–90°) we attributed to 8 directions according to substraction values of y_i and x_i, where y_i = Location End Y - Location Start Y, and x_i = Location End X - Location Start X. Similarly to the previous research [13], we distinguished 8 possible directions. The percent of saccades in every direction was counted up for every trial.

The angle between the *i*-th saccade and the successive saccade (β_i) was computed as: in case both saccades were directed upwards or both directed downwards

$$\beta_i = 180 - (|a_i - a_i + 1|),$$

in case one saccade was directed upwards and the other downwards:

$$\beta_i = 180 - a_i - a_i + 1$$

The percent of 0–45°, 45–90°, 90–135°, 135–180° angles was counted up for every trial.

Data Processing. The total of 288 trials was recorded. The data were calculated and subjected to factorial ANOVA using IBM SPSS Statistics 20.

3 Results

Cluster analysis was used to categorize the subjects on the basis of their WAT performance. We opted a 3-cluster solution: lower score (cluster center = 55,75, 8 subjects), intermediate score (cluster center = 97,46, 13 subjects), higher score (cluster center = 132,06, 11 subjects). The groups varied in their verbal search performance: the average of 0.86 words was identified in the low WAT score group; intermediate WAT score group found 1.35 word per trial; 1.95 words were found on average in the high WAT score group. The differences proved to be significant ($F(2; 286) = 28.33$; $p < 0{,}01$).

Thus, it was found that subjects with a lower level of language competence demonstrate poor performance and find fewer lexical units in random letters. In addition, it was found that for this group of respondents solving the task is associated with higher cognitive load, manifested in an increase in the number of blinks and the peak saccade velocity. Subjects with lower WAT scores demonstrated higher blink rate and higher peak saccade velocity as compared to subjects with intermediate and high WAT score (see Table 1).

Table 1. Eye movement data of subjects with different vocabulary knowledge

	Blink rate (total count per trial – 40s)	Peak saccade velocity ($^{o}/_{s}$)
Low WAT score	7.4 (4.5)	212 (72)
Intermediate WAT score	4.2 (3.1)	206 (56)
High WAT score	4.1 (2.9)	169 (55)
The results are significant at	$F(2;288) = 6{,}6$, $p < 0{,}01$	$F(2;288) = 12{,}9$, $p < 0{,}01$

As it was expected, the obtained results indicated that the subjects with lower linguistic competence achieve less success and spend more effort while solving lexical problems. It was much more interesting to find out what strategies of search activity are used by people with different linguistic experience and different levels of performance, and to what extent these strategies are subject to conscious cognitive control.

In order to identify the scanning patterns, we analyzed saccadic directions and intersaccadic angles for each trial. If a saccade is represented as a vector, the horizontal angle to the x-axis is its direction, and the angle between two consecutive saccadic events is the intersaccadic angle, which is a marker of the change in eye movement direction. Further, cluster analysis was used to define search patterns based on saccade direction and intersaccadic angle measures. We opted for a 3-cluster solution, which corresponded to the 3 patterns of visual search in our previous study (see Table 2).

Therefore, three search patterns were identified: “Horizontal” - mostly horizontally oriented directions, intersaccadic angle values with little change in direction (0°–45°), a few “backtrack” 135°–180° angles (49 trials); “Vertical” – more vertical (mostly downward) directions, intersaccadic angle values, indicating little change of direction and occasional “backtrack” 135°–180° angles (44 trials); “Non-linear” - a relatively even distribution of saccade directions and intersaccadic angles, with slight prevalence of horizontally oriented saccades (136 trials). The use of Non-linear pattern was associated with higher saccadic amplitude and peak saccade velocity (see Table 3).

Table 2. Cluster analysis results

	Horizontal pattern (49 trials)	Vertical pattern (44 trials)	Non-linear pattern (136 trials)
Angles 0–45° (%)	45.76	41.62	31.97
Angles 45–90° (%)	13.98	17.45	20.13
Angles 90–135° (%)	11.74	14.97	18.93
Angles 135–180° (%)	28.51	25.96	28.97
Direction right-upward (%)	24.74	15.02	17.07
Direction upward-right (%)	5.15	9.32	9.51
Direction upward-left (%)	5.04	10.47	9.59
Direction left-upward (%)	13.06	10.86	12.94
Direction left-downward (%)	17.40	12.91	14.04
Direction downward-left (%)	5.37	13.61	9.89
Direction downward-right (%)	5.65	12.94	10.20
Direction right-downward (%)	23.59	14.86	16.76

Table 3. Saccade velocity and amplitude measures in search patterns

	Peak saccade velocity ($^{o}/_{s}$)	Saccadic amplitude (°)
Horizontal	161 (37)	2.1 (1.1)
Vertical	179 (46)	2.9 (2.9)
Non-linear	202 (71)	5.5 (6.0)
The results are significant at	$F(2;288) = 9,9$, $p < 0,01$	$F(2;288) = 12,9$, $p < 0,01$

Next, using the coefficient of contingency, we attempted to find out if there was a relationship between the level of language competence and the patterns of eye movements. The coefficient of contingency between WAT score cluster and eye-movement cluster equals 0.21, $p < 0,01$ (see Table 4). The result maintains that subjects with different levels of linguistic competence use different strategies for scanning the search space. The data in Table 4 show that subjects with lower WAT score tended to use the non-linear pattern more frequently, while higher WAT results were associated with increasing use of linear horizontal and vertical patterns. At the same time, the strategies themselves obviously differed in order and control during implementation. The implementation of a horizontal or vertical scanning pattern implied the use of a higher level of cognitive control. In contrast, the non-linear pattern reflected a chaotic, poorly controlled search.

Table 4. Crosstabulation results (n trials) for use of the patterns in subjects with different WAT score

	Low WAT score	Intermediate WAT score	High WAT score
Horizontal pattern	5.8%	19.5%	29.9%
Vertical pattern	14.7%	18.5%	21.8%
Non-linear pattern	79.5%	62%	48.3%

4 Discussion

The results of the study indicate that language expertise can be traced in eye movement patterns in visual search task. Notably, blink rate and peak saccade velocity, acknowledged markers of cognitive load [15] increase in subjects with lesser language competence, which can be attributed to the laborious vocabulary task. The obtained results correspond to the vast amount of research on the eye movement strategies of experts and novices in terms of providing eye movement evidence for higher cognitive load of novices [16], which is especially manifested in saccade metrics [17].

Although oculomotor measures have long been used in relation to search efficiency [18], expert-novice research in different domains demands introduction of novel complex eye movement patterns, such as the way of identifying structured and unstructured search patterns. In the present study subjects with lower lexical test score demonstrated more frequent use of a non-linear scanning pattern, while the use of linear patterns increased in more efficient language learners.

As shown in previous research, structures and unstructured search patterns can reflect the use of different cognitive strategies, such as choosing “looking” versus “seeing” strategy [10]. Therefore, the question, raised by the current research, is whether the revealed eye movement patterns are determined by cognitive strategies, which, in turn, are induced by experience, or whether they can be accounted for by the increased cognitive load.

The results of our previous research, where non-linear eye movement pattern was associated with higher impulsivity index [12], support the latter hypothesis to a certain extent. As higher peak saccade velocity is supposed to be related to higher cognitive load and as it has also been registered in impulsive subjects, the use of Non-linear pattern can reflect reduction of cognitive control.

The acquired data can contribute to a challenging discussion in cognitive psychology on the features of experts’ cognitive activity [19]. Although experts retrieve relevant information quicker, their execution is not entirely effortless and intuitive. However, the distinct feature of experts is the higher cognitive control, which is reflected in more structured eye movement patterns.

5 Conclusions

The present study documented eye movement features of expert and novice language learners in vocabulary search task, which a) indicate higher level of cognitive load in subjects with lower vocabulary test results (higher peak saccade velocity and blink rate in less proficient subjects) and b) different visual lexical search patterns on the basis of eye movement data on intersaccadic angles and saccade direction (which were named Horizontal, Vertical and Non-linear).

The described patterns correspond to the patterns obtained in preceding research [12], which had also been shown to correspond to cognitive control factor. The current study displayed the relation of cognitive load and the preference of using the linear and non-linear pattern. According to the empirical data, these patterns are more or less manifested in subjects according to their expertise in foreign languages.

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