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The Role of Interference in Implicit Learning of the Stroop Stimuli Sequence

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Abstract

Introduction. The effect of interference can help identify essential characteristics of the process of acquiring new knowledge. This study is the first to provide empirical evidence on the use of the effect of interference to dissociate explicit and implicit learning. We tested the hypothesis that the effect of interference arising in response to the Stroop test stimuli reduces the efficiency of explicit sequence learning and does not significantly affect implicit sequence learning.

Methods. A sample of 80 respondents took part in this study (mean age = 22.7 years). In the experiment, we used the serial reaction time tasks, when subjects were instructed to respond quickly and accurately to the sequences of stimuli. Some subjects (n = 40) viewed series of colour names written in congruent (corresponding) font colours; others (n = 40) viewed series of colour names written in incongruent (non-corresponding) font colours (Stroop stimuli). The subjects were asked to respond to font colours, without reading words. To identify explicit sequence learning, we used the recognition test.

Results. We found a significant sequence learning effect among the subjects who performed the task under congruent and incongruent conditions. Meanwhile, all subjects demonstrated a low level of explicit sequence learning (less than 51.9 % of correct responses in the recognition test). We discovered that implicit sequence learning eliminates the effect of interference (a delay in response time to incongruent stimuli).

Discussion. The results confirmed the assumption that the effect of interference does not reduce the efficiency of implicit sequence learning. The absence of significant differences between the groups that responded to congruent and incongruent stimuli makes it impossible to fully evaluate the impact of interference on explicit sequence learning. In general, the findings from this study speak in favour of the fact that the effect of interference impedes the explication of the sequence structure.

Keywords

cognitive unconscious, unconscious processes, implicit learning, explicit learning, structured sequence, sequence learning, interference, incongruent stimuli, Stroop effect, learning efficiency

Highlights

- The study considers the possibility of implicit sequence learning under conditions of interference.
- The experiment demonstrated the effects of implicit structured sequence learning.
- Implicit sequence learning may eliminate the effect of interference that arises when responding to the Stroop test stimuli.

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Introduction

The issue of sequence learning has gained considerable importance during recent decades. This is largely due to the growing interest of cognitive psychologists in implicit (unconscious) mental processes and, in particular, implicit learning. Implicit learning (IL) broadly refers to learning that occurs without intention to learn; the knowledge thus obtained is difficult to verbalize (Cleeremans, Allakhverdov, & Kuvaldina, 2019). The ability to implicitly learn regularities in sequences of stimuli and actions performed has long been discussed in scientific literature. Thus, back in the middle of the last century, K. S. Lashley noted that psychologists are mainly interested in the issue of whether the organizational processes that manifest themselves in serial actions are conscious (Lashley, 1951). However, significant advances have been made only when the experimental paradigm of the task sequence learning (TSL) was developed in the 1980s (Nissen & Bullemer, 1987). The TSL paradigm uses the method of serial reaction time (SRT), when subjects must respond to stimuli as quickly and accurately as possible; the order of the presentation of stimuli is established by a fixed and repetitive sequence (regularities) or a complex system of rules. Many authors have noted that SRT is best suited for detecting effects of implicit learning (e.g., Shanks & Johnstone, 1998; Clegg, DiGirolamo, & Keele, 1998; Frensch, Lin, & Buchner, 1998; Janacsek & Nemeth, 2012; Abrahamse, van der Lubbe, Verwey, Szumska, & Jaśkowski, 2012; Schwarb & Schumacher, 2012).

The increased interest in the SRT method is largely associated with the dual-task SRT, which explores the role of attention in learning, the impact of task complexity on learning, the neuroanatomical determinants of IL, and other aspects of learning (Hsiao & Reber, 2001). The study by Nissen & Bullemer (1987) represent a classic example of the use of the dual-task SRT, when subjects were instructed to press keys quickly and accurately in response to sequential stimuli (asterisks), while simultaneously counting low-pitched tones. Before presenting each stimulus, the subjects heard a low- or a high-pitched tone. The subjects were asked to count the number of times that low-pitched tones were presented and report the total amount after the end of the block. The results showed that additional problem-solving minimizes sequence learning. The authors explained such a result by the dependence of the implicit learning mechanism on the amount of available attention.

Subsequently, researchers offered alternative explanations for a decrease in the productivity of implicit learning in the dual-task SRT. For example, Rah, Reber, & Hsiao (2000) suggested that a significant decrease in the productivity of implicit sequence learning in the dual-task SRT is not explained by distraction of attention; it is rather a result of conditions that require processing an additional set of stimuli (tones) not having predictive value. Other works have also presented different points of view on general and specific effects of interference that may arise in the SRT tasks under dual-task conditions (Cohen, Ivry, & Keele, 1990; Frensch, Buchner, & Lin, 1994; Stadler, 1995; Frensch & Miner, 1994; Heuer & Schmidtke, 1996; Schmidtke & Heuer, 1997; Frensch et al., 1998).

Interference (the effect of interference) is traditionally understood as a decrease in the productivity of learning associated with introducing an additional task. Despite the fact that the effect of interference is still poorly understood, it claims to be a phenomenon that reflects the specific processes underlying behavior under multitasking conditions or in the presence of conflicting requirements (Sozinov, Krylov, & Aleksandrov, 2013). In the study of IL, the effect of interference may help explore the role of consciousness in IL (e.g., Burmistrov, Agafonov, Kozlov, & Kryukova, 2016; Burmistrov, Kryukova, & Agafonova, 2017), the process of processing several information flows (e.g., Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Agafonov, Burmistrov, Kozlov, & Kryukova, 2018), some functional characteristics of the mechanisms forming cognitive unconscious (e.g., Waldron & Ashby, 2001; Agafonov, 2007) and other issues.

In the double-dimension serial reaction task, interference reflects the mutual influence of simultaneously processed information flows (sequences). For example, a study by Huang, Zhang, Liu, Li, & Wang (2014) examined the effect of background sequencing on implicit learning of the regularity of alternating target stimuli. The stimulus materials consisted of black letters presented on a coloured or white background. The subjects were instructed to respond to letters regardless of the background colour. The sequence of background colours was determined by either of the following conditions: (1) changed according to a rule, (2) changed randomly, and (3) the background was always white (control condition). The results showed that a random change in the background colour interferes with the letter sequence learning. The implicit learning performance in subjects who performed the task under condition 2 was significantly lower than under conditions 1 and 3. Similar effects have been described in experiments with two uncorrelated sequences (e.g., Russeler, Münte, & Rösler, 2002; Cock & Meier, 2007; Weiermann, Cock, & Meier, 2010; Meier & Cock, 2010; Weiermann & Meier, 2012). The findings from these studies showed that sequence learning can be impeded by the accompanying random or uncorrelated flow of information.

When considering the effect of interference in IL, the experiments using Stroop stimuli (words written in colours incongruent with the meaning of these words, e.g., the word ‘blue’ written in yellow) are of particular interest. In the Stroop stimuli task, subjects need to process both characteristics of stimuli (font colours and colour names). In this case, the subjects, in fact, perform two tasks simultaneously. The main one is to respond to colour, and the additional one is not to read the words (Allakhverdov & Allakhverdov, 2014). Haider, Eichler, & Lange (2011) tested the hypothesis that a significant increase in the rate of responding in the SRT test may be an indicator of explicit learning of the sequence structure. The results of the experiments showed that the Stroop interference effect disappeared only in those subjects who demonstrated explicit sequence learning. Meanwhile, the authors themselves note that these findings cannot establish the chronology between the emergence of conscious learning and a decrease in the reaction time to Stroop stimuli. In other words, the following question remains open: Which of the two effects is the cause and the result? The ability of the cognitive system to implicitly learn a sequence of incongruent stimuli is supported by the results of experiments by Deroost, Vandenbossche, Zeischka, Coomans, & Soetens (2012). The scientists have found that a delay in reaction time to Stroop stimuli disappears with implicitly acquired sequence learning. According to the authors, a decrease in reaction time to incongruent stimuli was achieved by using implicit sequence learning for implementing cognitive control functions.

Thus, in the study of IL the effect of interference can be represented as a) a factor that reduces (impedes) the efficiency of IL when performing two tasks in parallel or while processing two uncorrelated information flows and b) a means (tool) for studying various aspects of implicit learning. This study *aims* to identify the effects of implicit sequence learning under interference conditions. In particular, we are going to consider the impact of the effect of interference on implicit and explicit sequence learning. Since interference occurs in individual consciousness (Allakhverdov & Allakhverdov, 2014), we may assume that this factor will reduce the efficiency of explicit learning without significantly affecting implicit learning.

Methods

This study used the serial reaction time tasks.

Participants

The experiment involved 80 subjects, including 45 females. The subjects were randomly distributed into 4 groups – two experimental groups (EG1, n = 20; EG2, n = 20) and two control groups (CG1, n = 20; CG2, n = 20). The mean age was 22.7 years (SD = 2.94). All subjects had normal or corrected-to-normal visual acuity and colour vision.

Equipment and stimulus materials

Stimuli: 1) names of 4 colours (green, yellow, red, and blue) printed in congruent font colours; 2) names of the same 4 colours printed in incongruent font colours (the word 'yellow' printed in green, the word 'green' printed in yellow, the word 'blue' printed in red, and the word 'red' printed in blue). All stimuli had a height of 1.5 cm and a width from 8 to 11 cm (depending on the number of letters in words). The stimuli were displayed in the center of a screen against a gray background. At the bottom of the screen, 4 squares coloured green, yellow, red, and blue with a side length of 2 cm were presented. The squares showed the colour of keys for responding (A, Z, K, and M). In each task, the colour of the squares was randomly changed. The subjects used middle and index fingers of both hands for responding. The experiment was carried out using a laptop with a 13.3-inch screen and a standard keyboard. The distance from the subject's eyes to the computer screen was approximately 60 cm.

Procedure

The experiment started with instructions. The subjects from EG1 and CG1 were instructed that the names of 4 colours, written in fonts of different colours, would be alternately presented on the screen. The task was to press a key which colour would correspond to the font colour as quickly as possible, regardless of the name of the colour (incongruent condition). The subjects from EG2 and CG2 were instructed to respond to the font colours but not ignoring the colour names (congruent condition).

First, the subjects were asked to respond to a training block of 25 trials, similar to those used in the main task. At the beginning of each task 4 coloured squares appeared at the bottom of the screen; they were displayed until the subject pressed a key. Then, 100 ms later a stimulus was presented for 100 ms. If the subject pressed a key that did not correspond to the colour of the stimulus, then the word 'error' appeared on the screen for 100 ms. The pause between trials was 300 ms. The main procedure consisted of 12 blocks of 73 trials (876 trials in total). There was a rest break between the blocks (15 seconds), during which the average reaction time and the number of mistakes in the block were shown on the screen. For all groups, the sequence of presentation of stimuli was random in the first three trials of each block. Starting from the fourth trial, in EG1 and EG2 the sequence of the target parameter of stimuli (font colour) in all blocks (except 9 and 12) was determined by the second order conditional structure, which included the following 10 elements: D–B–C–A–C–B–D–C–B–A (a sequence adapted from Nissen & Bullemer, 1987). Colour designations were as follows: A – yellow, B – green, C – blue, and D – red. In blocks 9 and 12, stimuli were presented in a pseudo-random sequence which was generated considering the following two constraints: (a) the same stimuli were not repeated twice in a row, and (b) the proportions of stimuli did not differ from those in the blocks which used the sequence. In CG1 and CG2, the sequence of presentation of stimuli was pseudo-random throughout the whole procedure.

Thus, we used a 2x2 factorial experiment design. The first factor was the sequence of presentation of stimuli – structured in EG1 and EG2 or pseudo-random in CG1 and CG2. The second factor was congruence between colour names and font colours – incongruent stimuli in EG1 and CG1 and congruent ones in EG2 and CG2. All subjects performed the task under one of four conditions.

After completing 12 blocks of the SRT task, all subjects were asked, "Do you think the font colours of the words changed randomly or were determined by a certain sequence?" They had to choose one of the following four answer options: (a) "The font colours of the words changed randomly"; (b) "Perhaps, the sequence of alternation of the font colours of the words was not random, but I am not sure about that"; (c) "I noticed a regularity in changing the font colours of the words, but did not use it when responded"; and (d) "I discovered a rule in changing the font colours of the words and can partially or completely describe it".

Then we informed the subjects that the sequence of presentation of stimuli was determined by a special rule. To examine the degree to which the subjects learned the regularity, we asked them to perform the recognition test for sequence fragments. This test of explicit learning is more sensitive to relevant knowledge than any version of a generation task (e.g., Perruchet & Amorim, 1992; Willingham, Greely, & Bardone, 1993; Stadler, 1995). The recognition test consisted of 40 series of 3 trials (120 trials in total), similar to those used in the main procedure. In 20 out of 40 series, the sequence of stimuli corresponded to the rule. The series alternated randomly. After each series of trials, the subjects were asked to choose whether it corresponded to the rule or not. The subjects did not receive feedback informing about the correctness of the answers.

Results

The RStudio environment (RStudio Team, 2016) and the R programming language (R Core Team, 2019) were used for statistical analysis. To process the results, we used analysis of variance.

ANOVAs are useful when comparing more than two groups, exploring the impact of both intragroup and intergroup factors, and analyzing the data from a pretest–posttest design (repeated-measures analysis of variance).

The results of the subjects who made more than 20 % errors in task with incongruent stimuli (2 from EG1, 2 from CG1) and more than 10 % in task with congruent stimuli (1 from EG2) were excluded from further analysis. The first 10 responses in each block were excluded as well. From the remaining data, we excluded erroneous answers (M = 49.78, SD = 30.98) and responses deviating from the average response time for 3 standard deviations (1.99 %), which amounted to 8.4 % of the total responses. Accordingly, further we compared the average response time (RT) of correct answers among 75 subjects. The dependent variable (RT) was measured in milliseconds (ms).

Sequence learning

To analyze the effects of sequence learning we calculated changes in RT (a) in the learning phase (from 1 to 8 blocks) and (b) at each of the two segments when the structural sequence changed to a pseudo-random one (8 and 9, 11 and 12 blocks). The comparison was carried out separately for EG1 and EG2. One-way ANOVA showed significant differences in RT between the blocks for EG1 ($F (4. 68) = 55.69$, $MSe = 2670$, $p < 0.001$, $\eta_p^2 = 0.54$) and EG2 ($F (4. 72) =$ 36,95, $MSe = 1505$, $p < 0.001$, $\eta_p^2 = 0.52$). RT comparisons between the blocks were carried out according to Tukey HSD test. When comparing blocks 1 vs. 8, we observed a decrease in RT in EG1 (by 223.9 ms, $p < 0.001$) and EG2 (by 133.7 ms, $p < 0.001$). When comparing blocks 8 vs. 9 and 11 vs. 12, there was an increase in RT. In EG1, RT in block 9 increased by 76.8 ms ($p = 0.027$) and in block 12 – by 105.6 ms ($p < 0.001$). In EG2, RT in block 9 increased by 48.3 ms ($p = 0.022$) and in block 12 – by 41.7 ms ($p = 0.067$).

Correlations between interference and sequence learning factors

To analyze correlations between sequence learning and interference, we compared the data from EG1 and EG2. Two-way repeated-measures (Block – intragroup factor) ANOVA was used (Group x Block) (Table 1). There was a significant influence of the 'Group' factor ($F (1.35) = 9.441$, $MSe = 11880$, $p = 0.004$, $\eta_p^2 = 0.52$), 'Block' factor ($F (4. 140) = 91.643$, $MSe = 2071$, $p < 0.001$, $\eta_p^2 = 0.14$), and factors interaction ($F (4. 140) = 7.021$, $MSe = 2071$, $p < 0.001$, $\eta_p^2 = 0.08$) on the response time. Multiple comparisons using Tukey HSD test showed significant differences between groups in block 1 ($p < 0.001$). At the same time, compared to EG2, EG1 showed higher RT scores (by 99.5 ms). In block 8, the difference between the groups decreased to 9.3 ms ($p = 0.99$). As a result of transition from the structural sequence to the pseudorandom one in blocks 9 and 12, RT in EG1 increased more than in EG2. In block 9, the difference between the groups was 28.5 ms ($p = 0.727$), in block 12 – 63.9 ms ($p = 0.005$). Figure 1 shows the average response time in blocks for the four groups.

To determine the impact of the independent variable (sequence learning) separately from the additional variable (practice in performing the task), we compared the dynamics of RT in the learning phase (from block 1 to block 8) in the experimental and control groups. The decrease in RT (from block 1 to block 8) was 223.9 ms in EG1, 121 ms in CG1, 133.7 ms in EG2, and 82.3 ms in CG2. The difference was 102.9 ms between (EG1 and CG1) and 51.4 ms (between EG2 and CG2). One-way ANOVA revealed significant differences between the groups ($F (3. 71) = 10.81$, MSe = 6183, $p < 0.001$, $\eta_p^2 = 0.31$). According to Tukey HSD test, significant differences were found between EG1 and CG1 (p = 0.001).

Table 1
Two-way ANOVA for RT in blocks 1, 8, 9, 11, and 12 (EG1 and EG2)

Factors	SS	MS	df1	df2	F-criterion	p-value
Group	112162	112162	1	35	9.441	0.004
Block	759054	189763	4	140	91.643	< 0.001
Group x Block	58150	14538	4	140	7.021	< 0.001

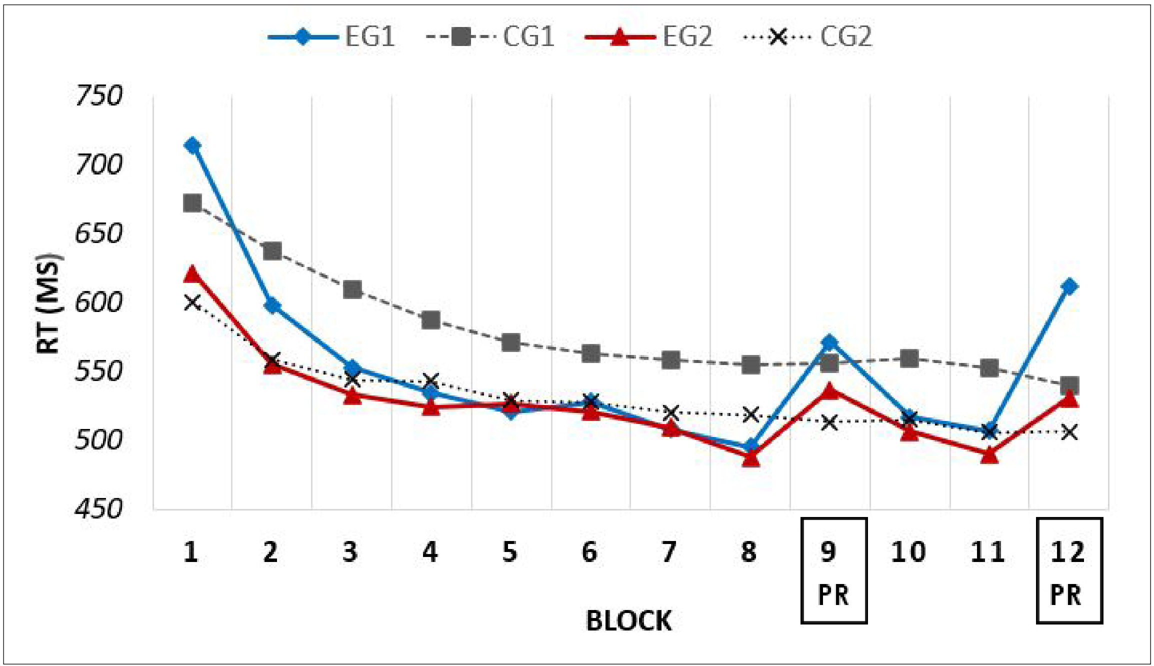

Figure 1. Average response time in the blocks calculated for all subjects

Legend: PR refers to the pseudorandom sequence.

Explicit and implicit sequence learning

Table 2 presents the number of subjects who chose one of the first three answers (no one chose the fourth option) to the question about the use of the rule that determined the alternation of the font colours of words and the rate of correct answers in the recognition test. The comparison of the average number of correct answers for each of the experimental groups with pooled data from the control groups (CG) was carried out using one-way ANOVA and showed a significant influence of the 'Group' factor on the rate of correct answers (F (2. 72) = 3.618, MSe = 43.04, p = 0.032, η_p^2 = 0.091). Multiple comparisons according to Tukey HSD test showed significant differences between EG2 (M = 47.1 %) and CG (M = 51.7 %): p = 0.039. EG1 (M = 51.9 %) and EG2 (p = 0.07) differ at a level of significant tendencies. EG1 did not significantly differ from the control groups (p = 0.99).

Table 2
The number of subjects who chose answers 1, 2 or 3 and the results of the recognition test

Groups	Answers			Test
	1	2	3	
EG1	9 (50 %)	7 (38.9 %)	2 (11.1 %)	51.9 %
CG1	10 (55.6 %)	6 (33.3 %)	2 (11.1 %)	52.4 %
EG2	8 (42.1 %)	10 (52.6 %)	1 (5.3 %)	47.1 %
CG2	11 (55 %)	7 (35 %)	2 (10 %)	51.1 %

The next step in the analysis of explicit and implicit sequence learning was the comparison of RT in the main procedure among the subjects who showed the result up to 20 correct responses (50 %) in the recognition test (9 from EG1 and 14 from EG2), and subjects with the result of more than 20 correct responses (9 from EG1 and 5 from EG2) (Table 3). Two-way repeated-measures ('Block' – intragroup factor) ANOVA (Group x Block) revealed a significant impact of the 'Group' factor (F (3. 33) = 3.796, MSe = 11894, p = 0.019, η_p^2 = 0.17), 'Block' factor (F (4, 132) = 92.857, MSe = 2044, p < 0.001, η_p^2 = 0.53) and the interaction of factors (F (12, 132) = 3.192, MSe = 2044, p < 0.001, η_p^2 = 0.105) on RT. Multiple comparisons according to Tukey HSD test did not show significant differences in EG1 and EG2 between the subjects who gave up to 50 % of correct responses in the recognition test and those with the efficiency of more than 50 % of correct responses (p > 0.1).

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Table 3
Average RT among the subjects from EG1 and EG2 who gave correct responses in the recognition test at the chance level (CL) and higher (> CL)

Blocks	EG1		EG2	
	9 (CL)	9 (> CL)	14 (CL)	5 (> CL)
1	751.8	691.2	607.7	662.1
8	502.3	492.9	485.8	495.1
9	594.2	554.6	528.6	558.7
11	510.3	507.2	490.9	490.8
12	612.9	615.7	523.1	559.1

Discussion

The experiment tested the following two hypotheses: (a) the interference factor does not have a significant impact on implicit sequence learning and (b) the interference factor impedes explicit sequence learning. To test the first hypothesis, we analyzed the data reflecting sequence learning, the impact of interference (before and after sequence learning) and the degree of awareness of the acquired knowledge. To test the second hypothesis, we compared the results of the recognition test for sequence fragments obtained in EG1 and EG2.

A decrease in RT (from block 1 to block 8) in EG1 and EG2 and an increase in RT in blocks 9 and 12 indicates the presence of sequence learning by the subjects of both groups. The difference in RT in block 1 between EG1 and EG2 indicates the impact of interference preceded sequence learning. The analysis of the results from the subsequent blocks showed that as the sequence was learned, the delay in RT caused by the impact of incongruent stimuli gradually decreased until it completely disappeared in the block 5 (Fig. 1). In turn, compared to EG2, a more significant increase in RT in blocks 9 and 12 in EG1 shows that the effect of interference returns with a change in the sequence. This explanation is consistent with the results of experiments by Deroost et al. (2012), who found a reduction in the Stroop effect at the learning phase and its complete return after changing the sequence.

The acquisition of practical skills leads to a decrease in the effect of interference (e.g., Kline, 1921; Stroop, 1992). Therefore, we compared the results of the learning blocks performed by the subjects of the experimental and control groups. Differences in the dynamics of decrease in RT during the learning phase indicates that subjects from EG1 learned the sequence. In turn, sequence learning made it possible to significantly reduce the effect of interference when responding to incongruent stimuli.

The analysis of answers to the question about the existence of a regularity in the order of presentation of stimuli showed an extremely low subjective assessment of awareness of the sequence in all groups (Table 2). Only 7 subjects, including 4 from the control groups, chose the third answer – "I noticed a regularity in changing the font colours of the words, but did not use it when responded". No one chose the fourth answer – "I discovered a rule in changing the font colours of the words and can partially or completely describe it". This assessment coincides with the results of the recognition test – the average number of correct responses is at a level close to chance level in each group. The absence of significant differences in RT between the subjects who gave less than 50 % of correct responses and those who gave more than 50 % of correct responses in the recognition test indicates that explicit learning did not have a significant impact on the result of the main task. We admit that some subjects acquired explicit knowledge of separate fragments of the sequence. However, this knowledge did not affect RT.

The comparison of the results of the recognition test between EG1 and EG2 did not confirm the hypothesis that interference has a negative impact on the acquisition of explicit knowledge of the used rule. Both experimental groups showed no clear signs of sequence awareness. This may be explained by using random alternation of key colours for responses. As noted above, two uncorrelated sequences can give rise to the effect of interference. In this experiment, a random sequence of motor responses could reduce explicit sequence learning of perceptual stimuli. Moreover, some decrease in efficiency of explicit learning was probably caused by using a pseudorandom sequence of stimuli in the last block of the procedure. The subjects could memorize the combinations of stimuli from the last block (edge effect) and mistakenly indicate them as corresponding to the rule in the recognition test. Since EG1 did not show the presence of explicit sequence learning, the result obtained does not falsify the second hypothesis. Further research using different tests will provide a better understanding of the impact of interference on explicit and implicit learning.

Conclusion

This study aimed to examine the process of sequence learning under the conditions of interference. Our findings enabled us to draw the following conclusions: (a) firstly, Stroop interference does not have a significant impact on implicit sequence learning and (b) secondly, the acquisition of implicit knowledge helps eliminate the effect of interference. The first conclusion is consistent with the idea that cognitive unconscious can independently process different flows of information, in particular, semantic and perceptual ones. The second conclusion shows that implicit learning can be investigated not only in terms of the influence of various factors (e.g., resources of attention or working memory) on this process, but also as a factor that has a significant impact on other mental processes.

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S. N. Burmistrov developed the experimental design and the computer program for conducting the experiment, carried out the experiments, and analyzed and interpreted the empirical results.

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A. D. Fomicheva processed, analyzed, and presented the empirical results and edited the manuscript.
Yu. E. Shilov organized the experimental procedure, selected the subjects, and wrote the literature overview.

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