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RESEARCH ARTICLE

Competition between frontal lobe functions and implicit sequence learning: evidence from the long-term effects of alcohol

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Abstract Implicit sequence learning is a fundamental mechanism that underlies the acquisition of motor, cognitive and social skills. The relationship between implicit learning and executive functions is still debated due to the overlapping fronto-striatal networks. According to the framework of competitive neurocognitive networks, disrupting specific frontal lobe functions, such as executive functions, increases performance on implicit learning tasks. The aim of our study was to explore the nature of such a relationship by investigating the effect of long-term regular alcohol intake on implicit sequence learning. Since alcohol dependency impairs executive functions, we expected intact or even better implicit learning in patient group compared to the healthy controls based on the competitive relationship between these neurocognitive networks. To our knowledge, this is the first study to examine the long-term effects of alcohol dependency both on implicit learning and on executive functions requiring different but partly overlapping neurocognitive networks. Here, we show weaker executive functions but intact implicit learning in the alcohol-dependent group compared to the controls. Moreover, we found negative correlation between these functions in both groups. Our results confirm the competitive relationship between the fronto-striatal networks underlying implicit sequence learning and executive functions and suggest that the functional integrity of this relationship is unaltered in the alcohol-dependent group despite the weaker frontal lobe functions.

Keywords Implicit learning · Procedural memory · Fronto-striatal network · Competitive brain networks · Executive functions

Introduction

As the number of patients with alcohol problems has been continuously growing over the past years, it is important to discover both its short- and long-term effects. Studies have shown that almost half of the patients have residual deficits measured by explicit neuropsychological tests even after the third abstinent week; furthermore, 15 % of the patients experience these deficits even after a whole year (Zinn et al. 2004). However, the exact impact of alcohol on implicit cognition is still vaguely known. Implicit non-conscious learning and memory processes are crucial in several aspects of daily life such as everyday routine behaviors, motor, cognitive and social skills. Therefore, the present paper focuses on how alcohol dependency affects implicit learning processes.

Deeper insight into how alcohol directly affects certain brain structures might reveal a great deal of its long-term effects. Functional imaging has shown that subjects with alcohol dependency had decreased prefrontal cortical

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gray and white matter volumes compared to control subjects (Pfefferbaum et al. 1997; Bellis et al. 2005). Right, left and total thalamic, brainstem, right and left cerebellar hemispheric, total cerebellar and cerebellar vermis volumes did not differ between groups. These findings suggest that a smaller prefrontal cortex is associated with early-onset drinking problems. Similar findings have also shown the vulnerability of these areas (Medina et al. 2008); thus, it seems that the prefrontal region is highly affected by long-term alcohol consumption, and it is the most pronounced region in the brain to do so. Such declines in the prefrontal area can cause the greatly explored deficits in executive processes for alcohol-dependent patients (Goldstein et al. 2004).

Working memory refers to the mechanism during which one can online modulate information available within a certain amount of time and capacity. The original working memory (WM) model by Baddeley and Hitch (1974) proposed two main parts: the phonological loop and the visuospatial sketchpad. Some years later the central executive was also added as a new component responsible for information manipulation mechanisms such as updating, inhibition and shifting (Baddeley 1996). Measuring the decline in the central executive part of WM is a good measure of prefrontal deterioration, as it is a process which is critically involved in a number of more complex cognitive behaviors (Cowan 1999). A number of experiments have shown that the acute use of alcohol has an impact on the functioning of WM in a way that reduces the available capacity for information to be processed within a certain time frame (Curtin et al. 2001). In line with such results and further elaborating them, Finn and colleagues have come to the conclusion that alcohol intake reduced performance on a backward digit span, but only for participants with a high baseline working memory capacity. Interestingly in a later experiment (Finn and Hall 2004) based on the forward digit span task, high-span individuals were able to perform just as well while being under the effect of alcohol, as without the intoxication. It is possible that high-span individuals have more storage capacity, which is not sensitive to a more robust task such as the forward digit span task, but backward digit span performance does not stay intact due to its complexity. Both the alpha-span task and the Tower of London task resulted in similar performances under similar circumstances, such that the more complex the task gets, the worse the alcohol-dependent group responds (Noël et al. 2001). To sum up this line of thought, the more complex a WM task gets, the more the central executive part of the model (Baddeley 1994) is involved.

In line with previous results, Saults and colleagues found that the task complexity mediates how alcohol impacts WM performance (Saults et al. 2007). In a relatively simple set of span tasks, acute alcohol intoxication had little or no effect on any general WM holding mechanism used to retain multiple concurrent items. On the other hand, it had a more pronounced effect on mnemonic strategies that are needed to maintain task items (attention demanding, consciously mediated verbal rehearsal (Baddeley et al. 1984). To sum up, alcohol affected tasks requiring only concentrated attention (consciously sustained process) compared to less consciously mediated processes.

Both short-term alcohol intake and long-term alcohol dependency have a significant impact on the performance on tasks that require frontal, parietal, temporal or mixed functions. When it comes to memory, both short- and long-term alcohol usages tend to have a temporally stable, but selective effect on implicit and explicit memory processes, respectively (Lister et al. 1991; Duka et al. 2001). Depending on the type of assessment, participants who were under the influence of a moderate dose of alcohol performed worse on an explicit stem completion task, while if the same information was acquired implicitly, their performance remained intact. The above-mentioned examples all deal with the effects of acute alcohol intake, which can be thought of as an online measurement. Our study therefore focuses on long-term alcohol dependency to see whether performance on such cognitive measurements changes over the course of constant alcohol intake.

One of the most widely used task types in measuring implicit cognitive processes is implicit sequence learning (Reber 1989). Implicit sequence learning underlies the formation of cognitive, social and motor skills and has been mostly related to the basal ganglia (Sefcsik et al. 2009), with an additional governing role of the frontal lobe (Doyon et al. 1997). These areas together form the fronto-striatal-cerebellar circuit, which has been in the focus of experiments aiming to reveal the network which governs implicit sequence learning (Doyon et al. 2009; Henke 2010; Klivenyi et al. 2012). The way in which implicit sequence learning is related to the mechanisms of the central executive working memory processes is still a topic that is currently being debated due to the possibility of shared capacities (Janacsek and Nemeth 2015). As our brain has a predetermined capacity with which it can operate with at a certain point in time, some processes can work in parallel with cooperation, while others are competing for the same resources (Poldrack et al. 2001; Albouy et al. 2008). A robust line of research claim that the weaker frontal lobe-related functions can lead to an enhanced implicit, procedural learning (Filoteo et al. 2010; Nemeth et al. 2013) based on the competition idea (Poldrack et al. 2001).

In sum, long-term alcohol usage affects frontal lobe functions such as working memory and executive functions. The effects of long-term alcohol usage can give us a better insight into how fronto-striatal-based implicit learning and DLPFC-based WM/executive functions are related in alcohol-dependent patients compared to healthy controls. To our knowledge, this is the first study to explore the effects of alcohol dependency on implicit learning. On the one hand, the possible outcome of long-term alcohol usage might result in weaker implicit learning performance if implicit learning is positively related to working memory and executive functions by sharing the same neural networks (for the debate, see Nemeth et al. 2013; Janacsek and Nemeth 2015). On the other hand, based on the previously mentioned competition idea, namely that weaker frontal lobe functions can lead to better implicit learning (Poldrack et al. 2001; Janacsek and Nemeth 2015), we predict that long-term alcohol usage has no effect or can even enhance implicit learning performance.

Table 1 Means and standard deviations (SDs) of age, education (the number refers to the level of education one has: 1—elementary school, 2—high school, 3—college) and performance on digit span, listening span, counting span and letter fluency tasks for the controls and alcohol-dependent group

	Control		Alcohol dependent		
	Mean	SD	Mean	SD	*p* value
Age	49.56	10.68	48.50	10.68	.788
Education	2.12	.72	2.07	.83	.851
Digit span task	6.27	.90	5.86	1.03	.301
Listening span task	3.86	.83	3.11	.69	.021
Counting span task	4.15	.94	3.44	.98	.080
Letter fluency task	20.82	5.29	14.78	4.76	.006

Materials and methods

Participants

Fourteen alcoholic patients (11 males/3 females) and 16 controls (11 males/5 females) participated in the experiment. The alcohol-dependent and the control groups were matched on age, gender and years of education (Table 1). The patient group was recruited from the Rehabilitation Unit of the Béla Gálfi Kht Hospital. The inclusion criterion for the alcohol-dependent group was to be completely sober at least 3 weeks prior to the experiment. Past history of alcohol dependency was diverse, and still, according to the number of relapses all participants have had at least one relapse (the *mean* of total relapses was 1.43, *SD* 0.51). Controls were individuals who did not have active neurological or psychiatric conditions, had no cognitive complaints, demonstrated a normal neurological behavior and were not taking any psychoactive medications. All participants provided signed informed consent agreements and received no financial compensation for their participation.

Tasks

The alternating serial reaction time (ASRT) task

Implicit sequence learning was measured by the "Catch the dog" version (Nemeth et al. 2010) of the ASRT task (Howard and Howard 1997b). In this task, a stimulus (a dog''s head) appears in one of the four empty circles on the screen and participants have to press the corresponding button as fast and accurately as they can. The computer is equipped with a special keyboard which only contains four heightened keys (Y, C, B and M on a Hungarian keyboard; equivalent to Z, C, B and M on a US keyboard) which are necessary for responding. These keys correspond to the target circles in a horizontal arrangement.

The appearance of stimuli follows a predetermined order, which stays unknown for the participants throughout the experiment. Stimuli are presented in blocks of 85 stimuli, from which the first five button pressings are random for practice purposes. These are followed by an eight-element alternating sequence (e.g., 2r3r1r4r, where numbers represent the four circles on the screen and "r" represents random elements), which is repeated ten times in a block. Due to the structure of the sequences in the ASRT task, some triplets or runs of three consecutive events occur more frequently (high-frequency triplets) than others (low-frequency triplets). For example, in the above illustration, 1_4, 2_3, 3_1 and 4_2 (where "_" indicates the middle element of the triplet) would occur often because the third element (bold numbers) could be derived from the sequence or could also be a random element. In contrast, 1_3 or 4_1 would occur less frequently because in this case the third element could only be random. Note that the final event of high-frequency triplets is therefore more predictable from the initial event when compared to the low-frequency triplets [also known as non-adjacent second-order dependency (Remillard 2008)]. Therefore, before analyzing the data we determined whether each item was the last element of a high-frequency or low-frequency triplet.

Overall, there are 64 possible versions of triplets (4^3, 4 stimuli combined for three consecutive events) through the task, from which 16 are high-frequency triplets (62.5 %), each of them occurring on approximately 4 % of the trials, occurring five times more often than the low-frequency triplets. The remaining 37.5 % of the remaining trials are low-frequency triplets.

Similar to previous studies (Howard and Howard 1997; Song et al. 2007; Nemeth et al. 2010), two kinds of low-frequency triplets were eliminated: repetitions (e.g., 222, 333) and trills (e.g., 212, 343). Repetitions and trills were low frequency for all participants, and participants often show preexisting response tendencies to them (Howard et al. 2004; Soetens et al. 2004). By eliminating these triplets, we could ascertain that any high-frequency versus low-frequency differences were due to learning and not to preexisting tendencies.

Previous studies have shown that as people go further in practicing the ASRT task, they respond more quickly to the high-frequency triplets compared to the low-frequency triplets, revealing sequence-specific learning (Howard and Howard 1997; Howard et al. 2004; Song et al. 2007). In addition, general skill learning—general speedup in the task, irrespective of the triplet types—can also be measured in the ASRT task.

Finally, it is important to note that the task remained implicit for the participants throughout the experiment. According to previous experiments with the ASRT task, even after an extended practice of 10 days, participants are not able to recognize the hidden sequence (Howard et al. 2004).

Digit span

The digit span task (Isaacs and Vargha-Khadem 1989; Racsmány et al. 2005) is a measure of phonological WM capacity. In this task, participants listen to an experimenter reading lists of series of numbers. The lists consist of increasingly longer series of digits which one has to repeat after the experimenter. Participants had to listen to each of these series and repeat them in order to the experimenter. Starting with three-item series, a maximum of four trials was presented at each length. If the first three trials at a particular sequence length were correctly recalled, the series length was increased by one. The maximum number of digits (i.e., series length) recalled correctly three times provided the measure of the digit span (a simple number, e.g., 6).

Listening span

The listening span task (Daneman and Blennerhassett 1984; for Hungarian version, see Janacsek et al. 2009) is a widely used complex working memory measurement. In this task, the experimenter reads aloud increasingly longer lists of sentences to the participants who have to judge whether the sentence is semantically correct or not and recall the last words of the sentences. Participant's working memory capacity was defined as the longest list length at which they were able to recall all the final words.

Counting span

The counting span task (Case et al. 1982; Engle et al. 1999; Conway et al. 2005) is a complex working memory task lacking a strong verbal component. Each trial included three to nine blue circles as targets and one to nine blue squares and one to five yellow circles as distractors on a gray background. Participants counted aloud the number of blue circles in each trial, and when finished with the count, they repeated the total number. When presented with a recall cue, participants recalled each total from the preceding set, in the order in which they appeared. The number of presented trials in a set ranged from 2 to 6. A participant's counting span capacity is calculated as the highest set size at which he or she was able to recall the totals in the correct serial order.

Letter fluency task

The letter fluency task is a widely used task to measure the central executive component of the working memory model (Baddeley 2006). In this task, participants are instructed to produce as many letters beginning with the same letter ("k" or "t") as possible in 60 s, without repetitions, synonyms or generated forms of the same word (Spreen and Strauss 1991; for Hungarian version, see Tanczos et al. 2014a, b), and the average number of correct words was used as the performance score. Higher score reflects better frontal lobe functions (Baldo et al. 2006).

Procedure

The ASRT task was administered in one session. Participants were informed that the main aim of the study was to find out just how extended practice affected performance on a simple reaction time task. Therefore, we emphasized participants to perform the task as fast and as accurately as they could. Participants were not given any explicit or implicit information about the regularity of the sequence that was embedded in the task.

The ASRT consisted of 25 blocks, which took approximately 30–40 min. Between blocks, participants received feedback on the screen about their overall reaction time and accuracy, which was followed by a rest of 10 between 20 s before starting a new block. The computer program selected a different ASRT sequence for each participant based on a permutation rule, such that each of the six unique permutations of the four possible stimuli occurred. Consequently, six different sequences were used across participants (Howard and Howard 1997; Nemeth et al. 2010).

The digit span task, the listening span task, the counting span task and letter fluency tasks were administered in a second experimental sitting in order to avoid possible confounding effects of the WM/executive function tasks and the implicit sequence learning task.

Statistical analyses

To facilitate data processing, the blocks of ASRT were organized into epochs of five blocks. The first epoch contains blocks 1–5, and the second blocks 6–10, etc. (Bennett et al. 2007; Barnes et al. 2008). As participants' accuracy remained very high throughout the test similar to previous studies (Howard and Howard 1997; Nemeth et al. 2010), we focused on reaction time (RT) for the analyses reported. For RTs, we calculated medians for correct responses only, separately for high-frequency and low-frequency triplets and for each participant and each epoch. Additionally, to the RTs, we calculated a learning index, which is the difference between the RTs for high-frequency and low-frequency triplets.

To calculate a composite score for executive function, we first transformed measures of listening span, counting span and letter fluency tasks into *z* scores. Then, we averaged these three transformed data into a composite score. Based on the median of this composite measure, we assigned half of the participants to the higher and other half to the lower executive function group. Data of executive functions were not available for five participants in the control group. Therefore, all participants were included in the first analysis focusing on sequence learning in the ASRT task, but the following analyses including the executive functions were run on the restricted sample (control group: $n = 11$, alcohol-dependent group: $n = 14$).

Results

Implicit sequence learning

To compare sequence learning between the groups, RTs were analyzed by a mixed-design analysis of variance (ANOVA) with TRIPLET (2: high vs. low) and EPOCH (1–5) as within-subjects factors and PATIENT GROUP (alcohol dependent vs. control) as a between-subjects factor. First of all, the main effect of TRIPLET was significant (F (1, 28) $= 7.366$, $\eta_p^2 = 0.208$, $p = 0.01$), such that participants responded faster to high-frequency than low-frequency triplets, revealing successful sequence-specific learning. The TRIPLET × PATIENT GROUP interaction did not reach significance (F (1, 28) $= 0.137$, $\eta_p^2 = 0.005$, $p = 0.714$), indicating that there was no difference between the alcohol-dependent and the control groups in sequence-specific learning (Fig. 1). The main effect of PATIENT GROUP alone did not reach significance either (F (1, 28) $= 2.482$, $\eta_p^2 = 0.005$, $p = 0.126$), indicating that the overall RTs of the patients and healthy controls did not differ significantly.

The main effect of EPOCH was also significant, indicating that participants showed general skill learning (i.e., they became generally faster) as the epochs went on (F (4, 25) $= 39.235$, $\eta_p^2 = 0.584$, $p < 0.001$). The EPOCH × PATIENT GROUP (F (4, 25) $= 0.322$, $\eta_p^2 = 0.011$, $p = 0.863$) interaction was not significant, which indicates that the two groups were not differing on general skill learning.

In a following ANOVA, we also included EXECUTIVE GROUP (low vs. high) as a between-subjects factor. Here, the TRIPLET × EXECUTIVE GROUP interaction showed a strong trend toward significance (F (1, 21) $= 3.988$, $\eta_p^2 = 0.160$, $p = 0.059$), indicating that executive functions had an effect on sequence-specific learning in the ASRT task. Participants with lower executive functions showed higher sequence-specific learning compared to the participants with higher executive functions (9.77 vs. 1.87 ms, respectively). Interactions involving both PATIENT GROUP and EXECUTIVE GROUP did not reach significance, suggesting that the level of executive functioning did not have a differential effect in the alcohol-dependent and control groups.

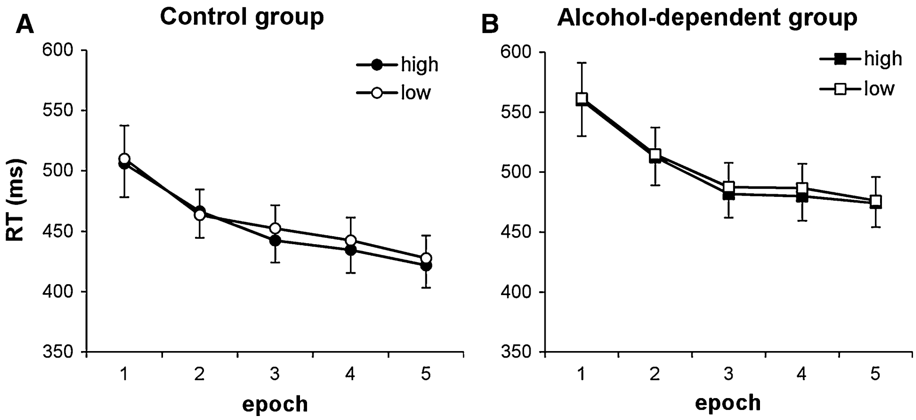

Fig. 1 Reaction times (RTs) in the ASRT task for the control (**a**) and the alcohol-dependent groups (**b**). There was no difference between the two groups either in sequence-specific learning (RT difference between high-frequency and low-frequency triplets) or in general skill learning (overall RT improvement across time). *Error bars indicate* standard error of mean (SEM)

Correlations between sequence learning and executive functions

To further explore the relationship between sequence-specific learning and executive functions, we ran correlation analyses for all participants, as well as for the controls and alcohol-dependent group separately. We calculated sequence-specific learning measures for the whole session as an RT difference between responses for high- and low-frequency triplets for each epoch separately and then averaging these difference scores across epochs. This overall sequence-specific learning score showed a moderate, negative correlation with the executive function scores ($r(25) = -0.420$, $p = 0.037$) when the alcohol-dependent and the control groups were analyzed together (Fig. 2a). Within-group correlations showed similarly moderate, negative correlation in the control group ($r(11) = -0.499$, $p = 0.118$; Fig. 2b) and a relatively strong negative correlation in the alcohol-dependent group ($r(14) = -0.635$, $p = 0.015$; Fig. 2c). In addition, we ran further correlation analyses controlling for phonological working memory (measured by the digit span task) and found a strong, negative correlation between sequence-specific learning and executive functions in both groups (controls: $r(11) = -0.624$, $p = 0.054$; alcohol-dependent group: $r(14) = -0.630$, $p = 0.021$). Importantly by comparing the two correlations measured on independent groups of subjects, the difference of correlations for the patient group and the healthy controls did not reach significance ($Z = -0.492$, $p = 0.622$). Thus, these correlation analyses further strengthen the results found in the ANOVA in that participants with lower executive functions tend to exhibit higher sequence-specific learning.

Discussion

Our main goal was to investigate how relatively long-term alcohol usage might impact implicit sequence learning and whether executive functions can modulate it. We found that the alcohol-dependent and the control groups did not differ in sequence-specific learning and general skill learning performance. Moreover, we found an inverse relationship between sequence-specific learning and executive functions—such that participants with lower executive functions showed higher learning performance in both alcohol-dependent and control groups.

Since the long-term effects of alcohol usage on implicit sequence learning are unknown to date, we compared our results to studies manipulating with acute alcohol intake only. In line with previous results on how alcohol impacts implicit processes (Duka et al. 2001; Kirchner and Sayette 2003), one explanation for the intact implicit sequence learning can be such that the learning process does not rely on the same frontal circuits as executive functions do, and therefore, it is not affected by alcohol consumption. Kirchner and Sayette (2003) differentiated between the automatically and conceptually driven aspects of an implicit task. Their main finding showed a dissociation between these two aspects in a way that alcohol intake had a significant effect on the conceptually driven aspect while it had no impact on any of the automatically driven processes. Thus, acute alcohol intake has a more clear impact on explicit/more executive like processes, while its effects on implicit processes are either not present or still unknown (Duka et al. 2001). The above-mentioned literature is also in line with researchers proving that implicit learning processes are spared during Korsakoff syndrome (Fama et al. 2006; Oudman et al. 2011), which is a chronic disorder often

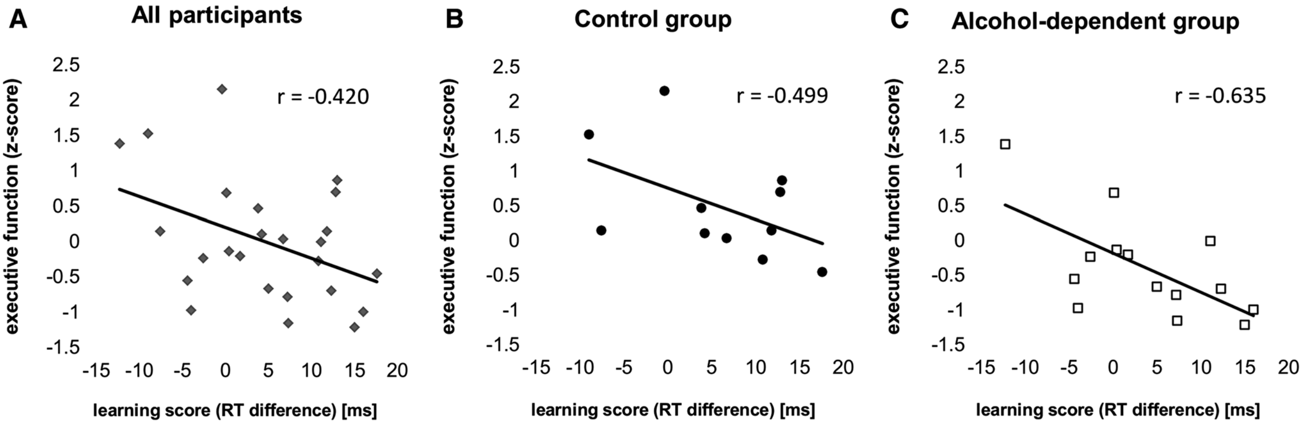

Fig. 2 Relationship between sequence-specific learning and executive functions. There was a moderate to strong negative correlation between these measures for all participants (**a**), as well as in the controls (**b**) and alcohol-dependent group (**c**) separately. Thus, weaker executive functions correlated with better sequence-specific learning performance

caused by long-term alcohol dependency, affecting mainly the hippocampus and frontal areas of the brain.

Further interpretations involve that alcohol leaves not only frontal areas intact that are crucial for implicit sequence learning, but the related fronto-striatal-cerebellar network as well. Until now, no experiments have yet proven that alcohol has a significant effect on implicit processes related to the striatum. According to our results, alcohol not only leaves implicit learning intact, but has a definite effect on frontal/executive functions showing a dissociation between processes that mainly rely on frontal capacities (executive functions) compared to processes rely on the striatum (implicit sequence learning). Importantly, further studies need to explore the role of these functional brain networks with neuroimaging methods more accurately. Here, we showed a negative relationship between implicit sequence learning and executive functions. The background of such a relationship can be explained by the competition between two learning mechanisms, namely the PFC/MTL-mediated hypothesis-testing attention-dependent processes versus the striatum-dependent less attention-dependent, procedural learning (Ashby et al. 1998; Poldrack et al. 2001; Filoteo et al. 2010; Henke 2010). In line with our results, studies showed that weakening the interconnectivity between frontal lobe and other brain structures, in addition to the disruption of the frontal lobe engagement, can improve sequence learning (Filoteo et al. 2010). For example, a recent finding of Nemeth et al. (2013) is in line with this idea, demonstrating that manipulations reducing the reliance on specific frontal lobe-dependent processes can improve procedural-based learning performance (Filoteo et al. 2010; Galea et al. 2010). One such manipulation can be hypnosis, a tool which temporarily disconnects certain frontal areas from the anterior cingular cortex and other brain areas, disturbing the frontal attentional control and executive system (Kaiser et al. 1997; Egner et al. 2005; Gruzelier 2006). This temporal disconnection might be a key factor in the improvement in implicit sequence learning (Nemeth et al. 2013), as it is possible that it eliminates certain frontal areas that would compete for the same capacity. Such a process results in heightened sensitivity to statistical probabilities, which is essential for automatic procedural mechanisms (Janacsek et al. 2012). This interpretation is consistent with the result that participants with better executive functions showed decreased sequence learning in the waking alert condition, due to a possible competition for the same frontal capacities (Nemeth et al. 2013). However, if this disruption is present for a longer period of time—which is the case with alcohol dependency—and the brain gets irreversibly degraded, implicit learning processes can also become impaired due to the damage to fronto-striatal networks.

The above-mentioned literature shows that the question of how implicit processes and working memory/executive functions are related is still under debate (Janacsek and Nemeth 2013, 2015). One way to resolve this problem is by noting that not all working memory and executive functions can be localized to only frontal regions (Carpenter et al. 2000), and furthermore, it is possible that the striatum plays a role in WM/executive functions by modulating the inhibition of the PFC (Ashby et al. 2010). Therefore, if alcohol blocks mainly frontal capacities, it is also possible that it does not have such a pronounced effect on all WM processes. This could also be a reason for intact implicit processes, or even implicit performance increases due to the blocking of certain frontal areas by TMS (Galea et al. 2010) or by other tools (Frank et al. 2006; Nemeth et al. 2013). We believe that our results are not due to the storage component of the working memory but more related to the executive functions because after controlling for storage capacity, the negative relationship between implicit sequence learning and complex WM index even became stronger.

The rehabilitation of patients with alcohol problems is a very challenging process as these people have to cope with a number of cognitive deficits, such as problems with memory, attention. Determining the impaired brain networks involved in cognitive processing is extremely helpful in predicting the progress of cognitive decline, as well as for later recommendations for learning strategies and trainings. If we know which functions stay intact while others show a decrement due to the dependency, we can also determine the functions upon which therapies and compensating strategies can be built on. Since implicit learning is involved in acquiring new skills, and it is a cognitive process which seemingly stays intact even after long-term alcohol usage, it can be one of the foundation stones. Also, implicit learning strategies are also involved in the process of habit change, which is essential for changing one's drinking habits.

To our knowledge, the present study is the first to investigate whether long-term alcohol usage affects implicit sequence learning and how these indices correlate with performance on executive functions. We found weaker executive functions, but intact implicit learning in the alcohol-dependent group. Thus, in spite of the common expectation that alcohol disrupts most cognitive functions, we showed that at least one function, specifically implicit sequence learning, is intact. Our results shed light on the different or partly overlapping fronto-striatal networks that have a different role in implicit processes and executive functions, moreover showing a competitive relationship among them.

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