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ACCEPTED VERSION

Cautious or causal? Key implicit sequence learning paradigms should not be overlooked when assessing the role of DLPFC (Response to Prutean et al.)

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Abstract

The role of the dorsolateral prefrontal cortex (DLPFC) in implicit sequence/statistical learning has received considerable attention in recent cognitive neuroscience research. Studies have used non-invasive brain stimulation methods to test whether the DLPFC plays a role in the incidental acquisition and expression of implicit sequence learning. In a recent study, Prutean et al. has concluded that stimulating the left or the right DLPFC might not affect the expression of implicit sequence learning measured by the Serial Reaction Time (SRT) task. The authors speculated that the previous results revealing improved implicit sequence learning following DLPFC stimulation might have been found because explicit awareness accumulated with the use of Alternating Serial Reaction Time (ASRT) task. Our response presents solid evidence that the ASRT task measures implicit sequence learning that remains unconscious both at the judgment and structural level. Therefore, contrary to the conclusion of Prutean et al., we argue that the DLPFC could have a crucial effect on implicit sequence learning that may be task-dependent. We suggest that future research should focus on the specific cognitive processes that may be differentially involved in the SRT vs. ASRT tasks, and test what the role of the DLPFC is in those specific cognitive processes.

Keywords: implicit sequence learning, dorsolateral prefrontal cortex, serial reaction time task

An empirical article combined with a literature review focusing on the involvement of the dorsolateral prefrontal cortex (DLPFC) in implicit sequence learning (Prutean et al., 2021) appeared in a recent issue of Cortex. We have read the article with great interest as the authors tackled the timely and important topic of whether the DLPFC plays a causal role in incidental acquisition and expression of implicit sequence learning. The authors have presented a carefully designed experiment using the Serial Reaction Time (SRT) task to map the effects of right and left DLPFC stimulation on the expression of implicit sequence knowledge. In addition, the authors offer a systematic literature review on the effects of non-invasive brain stimulation of the DLPFC on implicit sequence learning. Based on their results and review, the authors concluded that the DLPFC might not have a role in implicit sequence learning. One of their main arguments for that conclusion was that studies reporting improvements in the expression of learning (Ambrus et al., 2020; Janacsek, Ambrus, Paulus, Antal, & Nemeth, 2015) using the Alternating Serial Reaction Time (ASRT) task had not adequately tested the implicitness of learning. "However, this outcome should be taken *cautiously*, since both studies lacked a formal assessment of the implicitness of the learning process." (Prutean et al. 2021, pp307). Thus, the authors raised the possibility that explicit awareness might have contributed to the results. While we do not dispute the fact that the lack of explicit awareness testing can be regarded as a shortcoming of the mentioned studies, in our response we would like to draw attention to the extensive literature on the implicitness of learning in the ASRT that was overlooked. Here, we summarize previous findings that provide solid evidence that ASRT is an implicit learning task and, therefore, that DLPFC stimulation might modulate implicit sequence learning in that task, even if it does not do so in the SRT.

The ASRT task was developed by Howard and Howard (1997) and has been used to measure implicit sequence learning for more than 20 years. Since its introduction, the ASRT task has been used in many studies to measure implicit probabilistic sequence learning, and its reliability has been shown to be higher than the classical serial reaction time tasks (Buffington & Morgan-Short, 2018; Stark-Inbar, Raza, Taylor, & Ivry, 2017). Moreover, the ASRT task has been shown recently to lack explicit components and to provide the purest measure for implicit procedural learning compared to similar tasks (Buffington, Demos, & Morgan-Short, 2021). To briefly recap the essence of the ASRT task: typically, four positions are presented on the screen, and a target stimulus appears at one of the four positions. The location of the target stimuli follows an eight-element sequence, which is repeated through several blocks of practice. Every other element is part of a four-element fixed sequence (if we mark the possible positions 1-4 from left to right, the sequence could be, for example, 2134), while the remaining items appear at random positions. As a result of this sequence structure, the third element of some runs of three consecutive trials (triplets) are more probable to occur. For example, if the sequence is 2r1r3r4r (where the numbers represent the predefined trials and *r* the random trials), then the last element of the triplet 2(P)-3(r)-**1(P)** is more predictable than 4(r)-3(P)-**1(r)** because the latter triplet could not be formed from two consecutive pattern elements (and one random element in the middle). Thus, to predict the n*th* trial with great probability, we only need to consider the n^{-2} trial, regardless of n^{-1} (non-adjacent second-order dependency). To sum up, the structure of the ASRT results is a noisy sequence, where the sequence is nested in random trials, which could disrupt the awareness of the repeating sequence elements (as we discuss below).

The potential explicitness of learning in the ASRT can be formally tested at different levels of knowledge. We should differentiate between the conscious status of the knowledge that an item comes after another (is the current element legal?) and the knowledge of the rule (why is the current element legal?) (Fu, Dienes, & Fu, 2010). The first type of knowledge describes the judgment knowledge of an element, while the latter the structural knowledge. Even if some control is verified over the use of judgment knowledge, structural knowledge can remain unconscious (Fu et al., 2010). In ASRT studies, these two aspects of knowledge have been tested by assessing whether participants are able: 1) to verbalize the regularity (judgement knowledge), 2) to produce the regular and non-regular patterns voluntarily (structural knowledge), and 3) to recognize regular patterns and differentiate them from non-regular patterns (structural knowledge).

Awareness of knowing the structure (judgement knowledge) can be verified by *subjective reports* of the participants, typically with the help of questions about the participants' strategies, observations, and confidence. The original article of Howard and Howard (1997) reported in detail post-experiment subjective reports that revealed that participants were unable to correctly describe any regularity even if they reported deliberately searching for one. Similar post-experiment questions have been used in more than 30 experiments and none of the studies reported participants to be able to verbalize knowledge about the regularity (Bennett, Howard, & Howard, 2007a; Bennett, Madden, Vaidya, Howard, & Howard, 2011; Bo, Peltier, Noll, & Seidler, 2011; Bo & Seidler, 2010; Csabi, Varszegi-Schulz, Janacsek, Malecek, & Nemeth, 2014; Dennis, Howard, &

Howard, 2003, 2006; Feeney, Howard, & Howard, 2002; Hallgató, Gyori-Dani, Pekár, Janacsek, & Nemeth, 2013; Hedenius et al., 2011; Howard, Dennis, Howard, Yankovich, & Vaidya, 2004; Howard, Howard, Japikse, & Eden, 2006; D. V. Howard et al., 2004a; Janacsek, Borbély-Ipkovich, Nemeth, & Gonda, 2018; Janacsek, Fiser, & Nemeth, 2012; Japikse, Negash, Howard, & Howard, 2003; Kiss, Nemeth, & Janacsek, 2019; Kóbor, Horváth, Kardos, Nemeth, & Janacsek, 2020; Kobor, Janacsek, Takacs, & Nemeth, 2017; Selam Negash et al., 2007; Selamawit Negash, Howard, Japikse, & Howard, 2003; Nemeth, Csábi, Janacsek, Várszegi, & Mari, 2012; Nemeth, Hallgató, Janacsek, Sándor, & Londe, 2009; Nemeth & Janacsek, 2011; Nemeth et al., 2011, 2010; Romano, Howard, & Howard, 2010; Schwartz, Howard, Howard, Hovaguimian, & Deutsch, 2003; Song, Howard, & Howard, 2007a, 2008, 2007b; Song, Marks, Howard, & Howard, 2009; Stillman et al., 2013; Tóth et al., 2017; Unoka et al., 2017; Zavecz, Horváth, Solymosi, Janacsek, & Nemeth, 2020). One study did report evidence of explicit knowledge for a few participants on a post-experiment questionnaire (Sævland & Norman, 2016). However, the questionnaire they used did not ask the participants to formulate structure, only to judge whether the previous position of the sequence might have influenced the current position, and some participants did not exclude this possibility. Taken together, the learned regularity in the ASRT seems to remain non-verbalizable for the participants across most studies.

Some have argued that verbal reports are insufficient to evaluate explicit knowledge. In response, tests that do not depend on verbal reports have been developed to measure potential sequence knowledge. For example, *free generation* or *production tests* can be used to determine whether participants can voluntarily produce and/or suppress learned regularities (e.g., Jiménez, Méndez, & Cleeremans, 1996). In these tests, participants are asked to generate a sequence of responses that resembled the sequence they experienced during the ASRT task. On such post-learning production tests, participants tend to produce more high- than low-probability triplets (Dennis et al., 2003; Howard & Howard, 1997; D. V. Howard et al., 2004b; Japikse et al., 2003; Marvel, Schwatz, Howard, & Howard, 2005; Schwartz et al., 2003; Song et al., 2007a, 2008, 2007b). However, production tests likely reflect a combination of implicit and explicit processes (Destrebecqz & Cleeremans, 2001) and thus they do not provide evidence that the sequence regularity was explicitly available. To determine if the advantage for high-probability triplets reflects implicit knowledge, production tests with inclusion and exclusion conditions can be used. In such tasks, participants are asked to generate a sequence that differs from what they experienced during the ASRT (exclusion condition) in addition to the usual inclusion condition. According to the Process Dissociation Procedure (PDP, Jacoby, 1991), explicit knowledge is required to produce a sequence that differs from what was experienced, whereas production of pattern-consistent responses in the inclusion condition can be achieved by implicit or explicit knowledge. Studies that used both inclusion and exclusion conditions in the production tests demonstrated the lack of explicit knowledge following the ASRT task (Dennis et al., 2006; Horváth, Török, Pesthy, Nemeth, & Janacsek, 2020; Kiss et al., 2019; Kóbor et al., 2020; Kobor et al., 2017; Sævland & Norman, 2016; Szegedi-Hallgató et al., 2017; Vékony, Marossy, et al., 2020; Vékony, Török, et al., 2020).

Another indication of explicit structural knowledge occurs when participants can recognize regular patterns in a *forced-choice recognition task*. Here, participants are asked to categorize test sequences (or triplets) as consistent or inconsistent with what they experienced in learning. ASRT studies using forced-choice recognition tasks have shown that participants are unable to recognize the regular patterns in a forced-choice recognition test (Bennett, Howard, & Howard, 2007b; Bennett et al., 2011; Bo & Seidler, 2010; Dennis et al., 2006; Gamble, Lee, Howard, & Howard, 2014; Howard et al., 2004; Howard, Howard, Dennis, & Yankovich, 2007; Howard et al., 2006; Japikse et al., 2003; Marvel et al., 2005; Selamawit Negash et al., 2003; Romano et al., 2010; Song et al., 2007a, 2008, 2007b, 2009; Szegedi-Hallgató et al., 2017). These findings provide further support for the fact that performing the ASRT does not lead to structural knowledge of the sequence.

Perhaps the most convincing evidence for the implicit nature of the ASRT task comes from studies that compared implicit and explicit (cued) versions of the task. For instance, Song et al. (2007) developed a color-cued version of the ASRT to facilitate sequence recognition and compared the performance to the implicit (standard, non-cued) version of the task. In the free generation tasks, no participants who learned with the implicit version of the task were able to generate the pattern. Moreover, on recognition tests, neither group was able to differentiate between the previously high- and low-probability triplets, demonstrating the lack of explicit structural knowledge. Similar results were obtained in three other studies of Song et al. (2007, 2008, 2009). These results support the idea that although informing the participant about the sequence may allow the individual to know some part of the pattern (that every second item is part of a pattern), it still does not develop a degree of structural knowledge that would allow the distinction between high and low-probability triplets. This is of particular importance because in the conventional analysis of ASRT, high- and low-probability triplets are compared and the extent of learning is determined by the difference between the two. These findings then support the notion that participants are not capable of recognizing the regularity explicitly in the ASRT task.

Taken together, the findings summarized above make it unlikely—contrary to the suggestion of Prudean and colleagues (2021)—that the DLPFC effect previously shown in the ASRT is due to the task evoking explicit awareness of the sequence. Instead, we propose to reformulate the question to focus on the differences between the different versions of the SRT and ASRT that may influence the role of the DLPFC in learning. That is, why does the DLPFC seem to play a role in the ASRT but not in the SRT (Ambrus et al., 2020; Janacsek & Nemeth, 2015; Nemeth, Janacsek, Polner, & Kovacs, 2013; Virag et al., 2015)? Since no experimental task is truly process-pure (Jacoby, 1991), attention should be focused on the specific cognitive processes that are involved in the two tasks, and what the role of DLPFC is in those specific cognitive processes.

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