Clinical Neurophysiology 130 (2019) 2166–2168

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Editorial

Implicit learning in the developing brain: An exploration of ERP indices for developmental disorders

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The human brain innately possesses implicit-learning (IL) abilities that contribute to the acquisition of a range of knowledge such as that related to language, music, and action. The IL is the learning of statistical properties in information (Perruchet and Pacton, 2006) and does not require any intention to learn or awareness of what has been learned. The term IL has interchangeably been referred to as statistical learning, although statistical learning is generally defined as the learning of transitional probability in sequences (Saffran et al., 1996). IL is, on the other hand, likely to be interpreted in the broad sense, including artificial grammar learning (Reber, 1967), sequential learning, word learning (Smalle et al., 2017), and probability learning (Reber, 1993). Here, based on the definition by Peter et al. (2019), I use the term IL to discuss a broad range of issues on gating and predictive functions in the developing brain. In particular, the present article focuses on how the learning effects are reflected in event-related potentials (ERPs) and event-related magnetic fields (ERFs).

1. Neural bases of implicit learning and the individual difference

The ERP/ERF modalities directly measure brain activities during IL, and seem to represent a more sensitive method for evaluating IL effects than behavioral observation does (Paraskevopoulos et al., 2012). For example, the IL is typically reflected in the priming-related ERP/ERF components underlying gating and predictive functions. The brain automatically filters out statistically redundant information such as repetitive and predictable stimuli. In the end, IL effects manifest as suppression of the neural response to these stimuli compared with novel or unpredictable stimuli. Recent literature has shown increased interest in individual differences of IL capacities to predict other cognitive abilities or disabilities (Siegelman et al., 2017). For example, persons with developmental disorders (Saffran, 2018) such as dyslexia (Arciuli and Simpson, 2012) and amusia (Peretz et al., 2012) are impaired in IL ability, whereas it may be facilitated in other types of developmental disorders such as Tourette syndrome (Dye et al., 2016) and synesthesia (Forest et al., 2019). It has generally been thought that developmental disorders begin early in the developing brain. Hence, these findings may suggest that specific developmental processes that occur during early periods such as infancy and childhood modulate the IL ability. Given the limitations of attention and discrimination capacities in infancy and children, the neural evaluation of IL ability during early developmental periods has an advantage over behavioral observation, and could open a perspective for early detection and intervention for individuals suffering from developmental disorders.

A number of studies have reported that the ERP/ERF provide important indices of the individual difference in IL ability. For example, the IL effects are larger in musicians than non-musicians in the early components of P1 (Paraskevopoulos et al., 2012) as well as N1 (Schön and François, 2011). The gating function is also reflected in an early component (Boutros and Belger, 1999): a stimulus generates local inhibitory activity that suppresses the early neural response to a second identical stimulus in order to avoid overstimulation. In this issue of *Clinical Neurophysiology*, the results of Peter et al. (2019) may partially agree with these previous findings. They found that the gating in earlier, but not later, components was reduced in individuals with dyslexia. Furthermore, this reduction was linked to their poor performance in word learning. The adaptation failures in earlier components have also been seen in autism spectrum disorder (ASD) (Madsen et al., 2015) and schizophrenia (Freedman et al., 1996), and may also be related to attention deficit hyperactivity disorder (ADHD) (Hendren et al., 2018), which is frequently comorbid with dyslexia (Germanò et al., 2010). Thus, it is hypothesized that the earlier components provide important indices of the individual difference in IL ability, including developmental disorders such as ASD, schizophrenia, and dyslexia. Another study, on the other hand, detected that the IL effect on a later component of N400 is also larger in musicians than in non-musicians (Francois and Schön, 2011). The N400, compared with earlier components, is considered to reflect higher levels of sensory processing such as semantic learning in language and music (Koelsch et al., 2004). It is believed that the N400 effects of IL may represent different stages of learning processes across implicit knowledge and semantic knowledge. A previous study examined ERPs for paired tones (Choudhury and Benasich, 2011) in ages ranging from six months to four years, and also included a group of children at risk for specific language impairments. The results indicated that the positive mismatch response, which peaked at approximately 250 ms after the pitch change, is the dominant response in infants and children up to the age of four years. Thus, the later as well as earlier components are also essential indices for young individuals.

https://doi.org/10.1016/j.clinph.2019.09.001

2. Key insight: from content to context

Language and music have a variety of hierarchical structures. Our brains can learn these structured contexts through IL (Daikoku, 2018c). It is, however, unknown how these contexts modulate IL effects on ERP/ERF. Recent studies indicate that persons with developmental disorders such as dyslexia (Du and Kelly, 2013) and amusia (Omigie and Stewart, 2011; Omigie et al., 2012, 2013) are not impaired for first-order, but instead for higher-order (more complex) IL. The computational studies also suggested that individual differences of implicit knowledge between persons gradually emerge from the lower- to higher-order IL models (Daikoku, 2018b, 2019). These findings may suggest that ERP components could be an indicator by which to objectively understand intact and impaired IL performance in persons with developmental disorders, and how structures in sequences modulate their IL performances. To clarify the neural correlates of IL of structured sequences, it is necessary to establish experimental paradigms with various structures and regularities.

One of the key insights into this issue may be entropy. The complexity of structured sequences has frequently been evaluated from entropy based on information theory (Pearce, 2006; Daikoku, 2018a) as shown by Shannon (1948). Particularly, conditional entropy can be calculated from transitional-probability distribution and interpreted as uncertainty. From the information theoretical perspective, it is more difficult to learn a transitional-probability distribution with higher conditional entropy. Neural studies have used this value to understand how brains perceive the uncertainty of statistical distributions during IL of the sequences (Harrison et al., 2006). It is suggested that the degree of conditional entropy modulates the predictability of each content of stimulus sequences (Nastase et al., 2014; Hasson, 2017; Agres et al., 2018). In other words, these findings may suggest that "*context*" in sequences affects the prediction of each "*content*". The uncertainty encoding is mainly processed in modality-general systems including the medial temporal lobe (MTL) (Hasson, 2017). When modality-general systems are impaired, the persons may show disabilities of uncertainty encoding as well as modality-general cognitive function. A previous study also indicated that IL effects on ERP are reduced in individuals with impairment of the MTL (Schapiro et al., 2014). It is hypothesized that the neural generators of the earlier ERP components are in primary cortices, whereas the generators of the uncertainty encoding and gating processes preceding the earlier components may occur in modality-general systems such as the MTL (Grunwald et al., 2003; Perrachione et al., 2016). Most studies have focused on the IL of sequences that consisted of a specific regularity such as pseudo-word concatenation. As described above, however, different structures may represent different IL effects. Hence, how structures in sequences modulate their IL performances is an important key to understanding other cognitive abilities or disabilities and hidden developmental problems. Recent studies propose an experimental paradigm to investigate how physically and statistically deviant stimuli are reflected in ERP components (Koelsch et al., 2016; Tsogli et al., 2019). The authors suggested that the different types of deviants, that is, physical (i.e., direction) and statistical (i.e., contextual) deviants, induced mismatch negative responses around 150–250 ms. This paradigm may also be a candidate for understanding how structures in sequences modulate their IL performances in the developing brain, and how intact and impaired IL performance in persons with developmental learning disorders is reflected in ERP components. In conclusion, Peter et al. (2019) found that the gating in earlier, but not later, components was reduced in individuals with dyslexia. I would also like to emphasize, however, that the later components are also essential indices for young individuals. To clarify ERP/ERF indices for developmental disorders, further studies are needed to establish experimental paradigms with various structural regularities. The neural evaluation of IL ability during early developmental periods could provide a new perspective for early detection and intervention for individuals suffering from developmental disorders.

Acknowledgements

The present study was supported by Suntory Foundation. The funders had no role in decision to publish and preparation of the manuscript.

Declaration of Competing Interest

The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tatsuya Daikoku *

Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Germany

* *Address: Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstraße 1a, 04103 Leipzig, Germany.*

E-mail address: tdaikoku-tky@umin.org

Accepted 1 September 2019

Available online 10 September 2019