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Research article

The rule expectancy effect on the electrophysiological correlates underlying numerical rule acquisition

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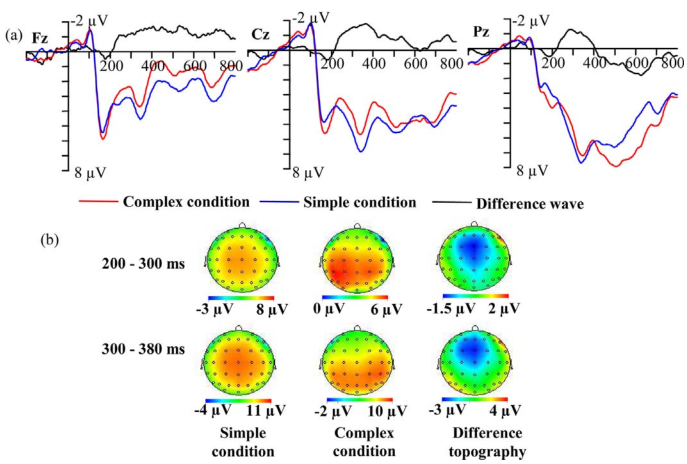
GRAPHICAL ABSTRACT



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ABSTRACT

The present study aimed to provide electrophysiological evidence about acquiring complex numerical rules when unexpected numbers were presented. Hence, we compared the neural correlates underlying the acquisition of unexpected complex rules (e.g., 12, 14, 18, 24) compared to expected simple rules (e.g., 12, 14, 16, 18). The event-related potential (ERP) results for the rule acquisition process for the third numbers showed that, in contrast to expected simple rules, unexpected complex rules elicited: an enhanced N200, reflecting the detection of a conflict between the expected numbers and the displayed numbers; a decreased P300, indicating a feeling of uncertainty accompanied by identifying numerical regularity; and an increased LPC, reflecting the working-memory updating caused by expectancy violation and rule acquisition. These results describe the precise time course of acquiring novel and complex rules when unexpected numbers were presented.

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1. Introduction

Rule acquisition, a core process of human high-order cognition, abstracts general structures from specific instances [35,36]. When complex rules require seeking second-order relationships (or operations on operations), novel and nonentrenched concepts have to be formulated [11]. This event-related potentials (ERPs) study aimed to provide electrophysiological evidence about acquiring complex numerical rules when unexpected numbers were presented.

Several studies have examined the brain potentials evoked by presenting unexpected numerical rules. Li et al. [23] has used difficult numerical rules, such as "+1, +2," which produce unexpected numbers relative to easy rules, such as "+1." Although they found the initial identification of the regularity of a number series during a rule-discovery phase was related to a larger P300 compared to nondiscovery phases, they did not report dissociated neural responses to difficult rules, which presented unexpected numbers that violated the potentially simple rules. The study also explored a rule-violation condition in which numbers incongruent with the previous rules were displayed. A larger N200 was evoked by the unexpected rules due to mismatch detection, and an enhanced late positive component (LPC) was triggered by working-memory updating when the rules were broken by the unexpected numbers.

Moreover, several ERP studies have investigated the effects of rule violation during the phase of numerical rule application, in which wrong ending numbers violated expectations based on the rules. This condition produced an LPC effect (P3b or P600), as well as the N200 [16,23,25–27,29–32]. Moreover, the numerical rule violation effect on LPC during the rule application phase was modulated by task difficulty. Núñez-Peña et al. [29,30] manipulated the difficulty of the task by varying the distance to the correct endings (rather than the hidden number rules), and found that the harder it was to integate the arithmetic rules, the greater the late positive deflection. Qin et al. [32] compared the endings of difficult rules relative to easy rules, and observed a reduced P300 amplitude for the difficult condition due to the greater information load.

However, it is not clear whether the rule expectancy effect on numerical rule application can be extended to the process of numerical rule acquisition. Hence, the primary goal of our research was to provide electrophysiological evidence of acquiring hierarchical rules when unexpected numbers were presented. Two relational levels of number-series completion tasks were used to achieve this goal, as suggested by Holzman et al. [11]: (1) a simple condition that consisted of easy mental arithmetic problems (e.g., 12, 14, 16, 18) whose rules could be ascertained by mental calculation or automatic number fact retrieval [12,17,18]; and (2) a complex condition that entailed mental arithmetic problems with gradually varied magnitudes. As the complex condition presented numbers that were incongruent with the simple rules, the expectancy of the obligatory rules would be violated and novel numerical rules would need to be formulated. For instance, the rule of “14, 13, 11” is “−1 then −2,” which violates the simple rule of “−1.” Li et al. [23] suggested that underlying rules can only be discovered after the presentation of the third number in a series. We recorded electrophysiological data as the third number of a series was presented to investigate the processing of numerical rule acquisition, as the numerical rule should be acquired at this point.

The complex condition presented third numbers that violated the expectations of the obligatory rules. However, the participants still had to formulate potential rules. Therefore, they would inevitably retrieve relevant numerical knowledge and map it onto the present situation, leading to the generalization of complex numerical rules. Hence, the response for the complex condition should reflect the generalization process of complex rules after the expectancy of the simple rules were violated. Based on the findings of previous number-reasoning studies [16,23,29–32], we expected that the expectancy violation effect would modulate both the N200 and LPC, reflecting mismatch detection and working- memory updating, respectively.

2. Materials and methods

2.1. Participants

Twenty-two paid, right-handed college students (12 males, 23.5 ± 3.5 years) from Shanxi Normal University participated in this study. Participants had no history of a neurological or psychiatric disease, and all had normal or corrected-to-normal vision. An informed consent form was signed by each participant, and the study was approved by the local ethics committee.

2.2. Experimental design

Prior to the main experiment, a pilot study was conducted to determine the proper presentation times of the stimuli and the proper intervals, in which the participants were required to press buttons for each number in the series. The design of the actual experiment consisted of two conditions. Each condition consisted of 80 trials that were presented in a random order. Each trial contained four numbers against a black background, written in 38 pt. Courier New font. The first three numbers were written in white, and the forth number, which was presented as a probe number, was emphasized in yellow.

The two conditions consisted of number series formulated by the rule expectancy effect. The rule expected condition contained simple problems, which included simple addition and subtraction, for example, “20, 18, 16,” wherein the rule was “−2.” The rule unexpected condition contained complex problems, in which the operands changed hierarchically. For example, “5, 7, 11,” wherein the rule was “+2 then +4 then +6,” and so on (repeatedly increasing the addition by 2). The operands varied from ± 1 to ± 4 in the simple condition, while the operands changed gradually in the complex condition, such as "+1 then +2 then +3." None of the numbers in the series were larger than 20. Considering the potential limitation of the participants’ mental arithmetic ability, the types of problems were restricted to addition and subtraction, in a similar manner to previous studies [14,30].

The participants were given practice trials to familiarize themselves with the task before the formal experiment began. There were five blocks of 32 trials each, which were randomly presented in the simple and complex conditions. Each trial was conducted as follows: a crosshair was presented in the center of the screen for 500 ms followed by three successive numbers, which were each presented for 500 ms. The inter-stimulus interval (ISI) was 800–1200 ms. After a blank screen, which lasted 1300–1700 ms, the probe number was displayed. Half of the probes were congruent with the hidden rule and half were not congruent with the hidden rule in both the simple and complex conditions. The participants were required to decide whether the probe number was congruent with the hidden rule by pressing one of two keys within 2000 ms. The response keys were counterbalanced across participants. The ratio of correct to incorrect probe numbers was 1:1. The distance between the participants’ eyes and the screen was approximately 60 cm during the experiment

2.3. Electrophysiological recording

The recording and analysis of ERPs were performed with a 64-channel electroencephalogram (EEG) recording system (Brain Products GmbH, Germany). Average mastoid electrodes served as a reference, and a forehead electrode was used as the ground. Both the vertical (two electrodes placed above and below the right eye) and the horizontal electrooculogram (EOG; two electrodes placed at the external canthi) were recorded. The electrode impedance was kept below 5 kΩ. The EEG and EOG were amplified using a 0.01–80 Hz bandpass and were digitized with a digitalization rate of 500 Hz. All trials exceeding ± 80 μV and trials with response errors were excluded from the ERP average.