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Large-scale coupling dynamics of instructed reversal learning

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ABSTRACT

The ability to rapidly learn from others by instruction is an important characteristic of human cognition. A recent study found that the rapid transfer from initial instructions to fluid behavior is supported by changes of functional connectivity between and within several large-scale brain networks, and particularly by the coupling of the dorsal attention network (DAN) with the cingulo-opercular network (CON). In the present study, we extended this approach to investigate how these brain networks interact when stimulus-response mappings are altered by novel instructions. We hypothesized that residual stimulus-response associations from initial practice might negatively impact the ability to implement novel instructions. Using functional imaging and large-scale connectivity analysis, we found that functional coupling between the CON and DAN was generally at a higher level during initial than reversal learning. Examining the learning-related connectivity dynamics between the CON and DAN in more detail by means of multivariate patterns analyses, we identified a specific subset of connections which showed a particularly high increase in connectivity during initial learning compared to reversal learning. This finding suggests that the CON-DAN connections can be separated into two functionally dissociable yet spatially intertwined subsystems supporting different aspects of short-term task automatization.

Introduction

Learning is one of the core functions of the brain, allowing humans to optimize future behavior based on past experiences. Instruction-based learning is a particularly beneficial type of learning, as relying on instructions instead of trial-and-error procedures typically makes learning more efficient and can help to avoid potentially dangerous errors (Cole et al., 2013a; Ruge et al., 2017; Wolfensteller and Ruge, 2012). Interestingly, when a novel instruction has been encoded, subsequent behavioral implementations will become increasingly effortless over time (Mohr et al., 2015; Ruge and Wolfensteller, 2010, 2016a). For example, on the first day at work, you learn from a colleague that you can get coffee from the vending machine by pressing its third button, so you can perform the correct button press right at the first implementation. This stimulus-response association (vending machine – third button) will become more and more effortless and automatic within the next few repetitions. A recent study showed that short-term automatization of stimulus-response associations is facilitated by a reconfiguration of the large-scale connectivity pattern of the brain (Mohr et al., 2016). Specifically, it was shown that the fronto-parietal network (FPN), which is typically engaged when a high level of cognitive control is required, was more active during the early phase than the late phase of 90 s practice blocks. This release of cognitive control was found to be enabled by enhanced connectivity between two task-related networks, the dorsal attention network (DAN) and the cingulo-opercular network (CON), which facilitated more efficient and direct stimulus-response transformations.

Continuing with the example, imagine the coffee vending machine has been reprogrammed and you are instructed that now you have to press the first instead of the third button to get coffee. Over time, you will get used to pressing the first button but at the beginning you will probably have a residual tendency towards the third button. In the current study, we were interested in finding out how residual stimulus-response associations from initial learning would influence short-term automatization during subsequent reversal learning. We hypothesized that impaired automatization processes during reversal learning should be reflected by altered activation and connectivity dynamics of various large-scale functional networks of the brain, building on findings of the previous study on instruction-based learning (Mohr et al., 2016). To this end, we analyzed a sample of human subjects (N = 27) who performed an instruction-based reversal learning task (Ruge and Wolfensteller, 2016b) by means of large-scale activation and connectivity analyses. In this task, subjects were instructed how to respond to four stimuli during 90 s blocks of practice. In odd-numbered blocks, novel stimuli were introduced and

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subjects learned to respond via instruction cues (initial learning condition). All even-numbered blocks were reversal learning blocks, i.e. stimuli of the previous task block were reused but different responses were instructed (reversal learning condition). As one might expect, previous analyses of behavioral data of this task have shown that reversal learning is more demanding than initial learning, expressed by increased error rates and slowed response times (Ruge and Wolfensteller, 2016b).

Based on the findings of Mohr et al. (2016), we hypothesized that the activation and connectivity dynamics of several large-scale functional networks might differ between initial and reversal learning. Specifically, we expected to find higher activation within the FPN due to increased cognitive demands during reversal learning. More importantly, we expected to find a reduced connectivity increase between the CON and DAN, reflecting the impairment of short-term automatization during reversal learning. Besides contrasting initial and reversal learning within the sample of the current study, we also compared the initial learning condition of the current sample with data from the previous study on initial learning (Mohr et al., 2016) in order to assess the robustness of these findings.

Methods

Sample

Functional and structural MRI data were collected for N = 34 healthy human subjects (Ruge and Wolfensteller, 2016b). Quality control of the imaging data led to the exclusion of two subjects due to susceptibility artifacts. Five subjects were excluded from further analyses due to high error rates (>15%) in the experimental task. Thus, the final sample consisted of N = 27 subjects (14 female) with age ranging from 21 to 35 years. The experiment was approved by the local institutional review board to be in accordance with the Declaration of Helsinki. Subjects were informed before the experiment and gave written consent.

Experimental task

Subjects performed an instruction-based stimulus-response learning task inside the scanner (see Fig. 1). The experiment consisted of 28 learning blocks. Within each block, a set of four stimuli was presented. Overall, 14 sets of stimuli were used in the experiment (7 sets of visual stimuli and 7 sets of auditory stimuli). Each set of stimuli (either 4 symbols or 4 sounds) was used twice in two consecutive blocks. Two learning types were defined: initial learning refers to learning blocks using novel stimuli (odd-numbered blocks), and reversal learning refers to learning blocks reusing stimuli from the previous block (even-numbered blocks). During reversal learning blocks, while being presented with the same stimulus material as before, subjects had to respond differently to these stimuli, i.e. a novel stimulus-response mapping was instructed.

Each block consisted of a sequence of trials. Within each trial, a stimulus of the current stimulus set was presented and subjects had to respond with a button press (left/right, middle/index finger). Subjects

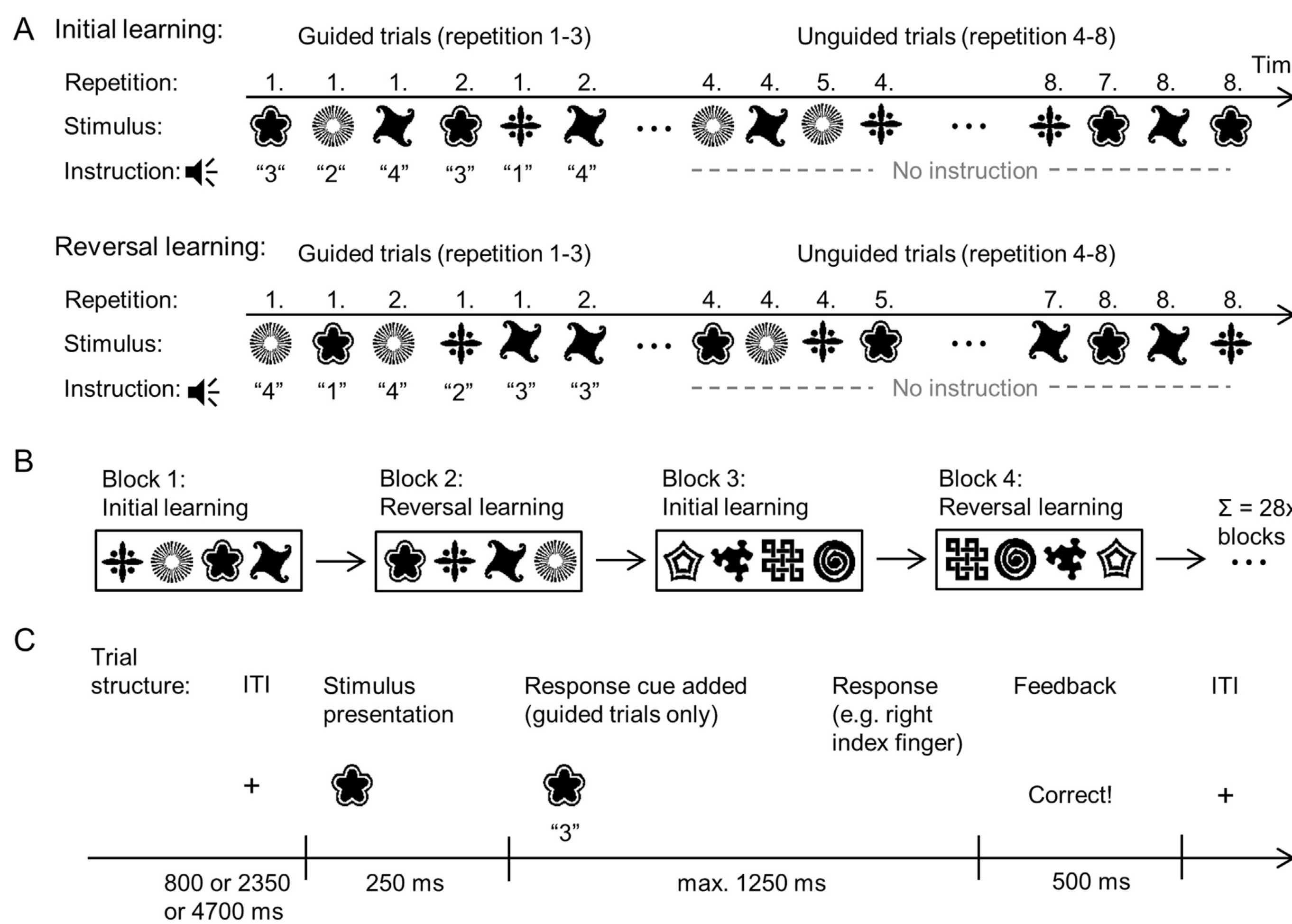

Fig. 1. Subjects performed an instruction-based stimulus-response learning task. **A:** In each task block, subjects were instructed how to response to four different stimuli. Instructions were given via response cues during the first three presentations of each stimulus. Starting with the fourth presentation, subjects had to find the correct response without response cues. **B:** In task blocks of the initial learning condition, novel stimuli were presented, whereas under the reversal learning condition, stimuli of the preceding block were reused. Visual stimuli as depicted in the figure were used in half of the 28 task blocks, while in the other half auditory stimuli were presented instead. In blocks using visual stimuli, instruction cues were presented as spoken words, whereas in blocks using auditory stimuli, instruction cues were presented on the screen. **C:** Timing of a single trial.